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MIXING ZONE MODELING AND DILUTION ANALYSIS FOR WATER-QUALITY-BASED NPDES PERMIT LIMITS

Health and Environmental Sciences Department
Publication Number 4664
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American Petroleum Institute

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Mixing Zone Modeling and Dilution Analysis for Water-Quality-Based NPDES Permit Limits

Health and Environmental Sciences Department

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PREFACE

The American Petroleum Institute (API), through its Water Technology Task Force, has sponsored technical studies over the past several years to evaluate and identify practical, cost-effective and environmentally sound technology options for handling, treating, and disposing of waters generated at petroleum facilities, particularly product distribution terminals. The results of these studies are intended to provide industry and regulatory agencies with technical information to make informed decisions on appropriate alternatives for individual petroleum facilities.

The Task Force has sponsored and published a significant amount of work in prior years on handling and treating facility waters. Other facets of this work include the analysis of the impact of these waters and the extent of treatment required at the facility to meet water quality objectives. The work contained in this report is intended to provide guidance to petroleum facility engineers and others on choosing the appropriate methods to evaluate the mixing zone impact of the final effluent discharge on the receiving waters. Treated wastewater effluents from municipal, commercial, and industrial facilities enter the receiving waters via open channels, pipelines, or sewer systems. Much progress has been made in recent years to model and design diffuser systems so that the effluent's residual contamination, when mixed, dispersed and assimilated into the receiving waters will meet watershed or general water quality requirements consistent with the uses of the water. However, modeling the mixing zone and dilution effects of effluents can be technically complicated. For this reason, the Task Force sponsored a study to summarize and simplify the available approaches for performing this modeling work.

Mixing zone dilution calculations and estimation are important to all dischargers of treated wastewaters and stormwaters and can have a significant impact on wastewater treatment facility costs and infrastructure. Typically, a facility has an effluent discharge permit that is negotiated with government agencies. The permit sets forth the allowable wastewater effluent temperatures and contaminant quality parameters (e.g., salt concentrations) to ensure that receiving water quality will not be impaired for its intended uses. The effluent permit may factor in a mixing zone dilution of the effluent into the receiving water body, allowing concentrations in the effluent that are higher than the general water quality requirements needed in the bulk of the water body. In short, the discharge of a small effluent flow (e.g., from a petroleum terminal) into a large water body could have temperatures or concentrations of a contaminant many times higher than the bulk of the water body, without impairment, because the effluent is rapidly diluted into the water body. This mixing zone dilution can be controlled somewhat by designing the proper outfall pipe and diffusers. Hence, by effective mixing zone modeling and diffuser design, reasonable, but not excessive, wastewater treatment processes can be employed at the facility and still not impair the quality of the receiving water body or watershed. To ensure that receiving water quality is not impaired, state regulatory agencies may limit or deny a mixing zone dilution when necessary to prevent lethality to passing aquatic organisms, bioaccumulation of pollutants, and significant risk to human health.

Prior studies sponsored by the Task Force have shown that operations and water characteristics at petroleum facilities can vary significantly, as do regulatory requirements in different geographical jurisdictions. The characteristics, size and uses of the affected water bodies must be considered when planning new facilities or upgrades of existing ones. This report will greatly assist facility engineers and planners in the use of mixing zone models and calculations. The value and impact of this work may be more useful in the future with government agencies considering more factors in effluent permits, such as a discharger's affect on the global watershed, sediments and aquatic life, and the possibility of watershed discharger effluent emission trading.

Studies Sponsored by the Water Technology Task Force

Publ 1612 Guidance Document for Discharging of Petroleum Distribution Terminal Effluents to Publicly Owned Treatment Works, First Edition, November 1996

Publ 4581 Evaluation of Technologies for the Treatment of Petroleum Product Marketing Terminal Wastewater, June 1993

Publ 4582 Comparative Evaluation of Biological Treatment of Petroleum Product Terminal Wastewater by the Sequencing Batch Reactor Process and the Rotating Biological Contractor Process, June 1993

Publ 4602 Minimization, Handling, Treatment and Disposal of Petroleum Products Terminal Wastewaters, September 1994

Publ 4606 Source Control and Treatment of Contaminants Found in Petroleum Product Terminal Tank Bottoms, August 1994

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ABSTRACT

In the United States, National Pollutant Discharge Elimination System (NPDES) permits for wastewater discharges to surface water include effluent limits based on available treatment technology. More stringent limits may be set on a site-specific basis to protect local receiving water quality. The derivation of water-quality-based permit limits may consider effluent dilution within a "mixing zone" near the outfall. Mathematical water quality models are generally used to estimate such dilution.

Although the concept of a mixing zone is straightforward, its application to a specific discharge situation often raises technical and policy concerns. This report presents a summary of available information on the role of dilution analysis and mixing zone models in the NPDES permitting process. It is intended as guidance for those who manage or evaluate mixing zone studies in the course of obtaining water-quality-based NPDES permits. The document includes an analysis of the mixing zone regulations and policies of the United States Environmental Protection Agency (EPA) as well as 14 states. Basic concepts are presented to describe the physical interaction of effluent discharges and ambient waters. The application of these concepts to outfall design and mixing zone model selection is discussed.

Ten EPA-developed mixing zone models are presented in detail. These range from simple analytical equations to sophisticated computer programs. The discharge and ambient conditions appropriate for each model are described. A structured approach is presented for the selection, validation, and strategic use of mixing zone models in the NPDES process. Dye tracer studies are discussed as supplements or alternatives to modeling. Case histories illustrate the role of mixing zone models and tracer studies in real-world permitting situations. References are provided for model documentation as well as electronic access via the Internet.

EXECUTIVE SUMMARY

In the United States, wastewater discharges to surface water are regulated through the National Pollutant Discharge Elimination System (NPDES) permit program. NPDES permits are issued and enforced either by the United States Environmental Protection Agency (EPA) or by state agencies under authority delegated by EPA. NPDES permits generally include technology-based effluent limitations; more stringent limits are applied on a case-by-case basis if necessary to protect receiving water quality.

Water-quality-based NPDES permit limits are set so that the fully diluted effluent will not exceed ambient water quality criteria. However, EPA and many states recognize that a receiving water can be protected without requiring an effluent to meet water quality criteria at the point of discharge. Water-quality-based permits often include mixing zone allowances to account for the dilution that takes place around an outfall.

A mixing zone may be established by computing a dilution factor or it may be delineated as a spatial area with fixed boundaries. In either case, it is an allocated portion of a receiving water in which a discharge is rapidly diluted. Water quality criteria may be exceeded within a mixing zone but must be met at its boundaries.

Dilution credits are typically calculated using a mathematical model based on discharge and receiving water conditions assumed to represent critical (i.e., poor) mixing conditions. The dilution factor derived from the model is then used to calculate environmentally-protective NPDES permit limits. Conservatisms inherent in computing the dilution factor will directly result in more restrictive effluent limits.

While the concept of a mixing zone is straightforward, the actual determination of dilution credits for a specific discharge raises potentially difficult issues for both regulatory agencies and NPDES permittees. To participate meaningfully in permit development, dischargers need to be aware of the technical and policy options available to them, as well as the advantages and disadvantages of various mathematical modeling approaches for mixing zone analysis.

This guidance document was commissioned by the American Petroleum Institute (API) to summarize available information on the role of dilution analysis and mixing zone models in NPDES permitting. The following major topics are discussed:

- Regulatory basis for mixing zones.
- Hydrodynamics of effluent dilution and outfall diffuser design.
- Availability and strategic use of mixing zone models.
- Dye tracer studies and other field study methods as alternatives or supplements to mixing zone models.

This document is not aimed at experienced water quality modelers. Rather, it is intended primarily for the benefit of those who manage or evaluate mixing zone studies in the course of obtaining water-quality-based discharge permits. The goal is to equip this user group with information and strategies to successfully negotiate site-specific NPDES permits which account for available dilution in the environment.

Regulatory Basis for Mixing Zones

EPA has established its position on mixing zones through two major regulations and a series of guidance documents and policies issued over the last 25 years. The most significant of these are discussed in Chapter 2, with the following key themes emerging:

- Mixing zones are consistent with the objectives of the Clean Water Act (CWA) and should be considered by regulatory authorities when NPDES permits are developed.
- Dischargers are not automatically entitled to a mixing zone. This is a discretionary activity on the part of the permitting authority and is subject to EPA review and approval.
- State regulatory agencies can decide to limit or deny a mixing zone on a site-specific basis. Mixing zones should be limited when necessary to prevent lethality to passing aquatic organisms, bioaccumulation of pollutants, and significant risk to human health.

- States should adopt written mixing zone polices as part of their water quality standards regulations. However, current EPA regulations do not specify minimum technical requirements for state mixing zone policies. The practical result is that the application of mixing zones in NPDES permits varies widely across the United States.

In addition to policy guidance, the EPA documents reviewed in Chapter 2 offer numerous technical recommendations on mixing zone implementation. These include specification of receiving water critical low flows for dilution calculations, default assumptions for effluent dilution in open waters such as large lakes, and benchmarks for mixing zone size and shape.

Chapter 2 also includes a survey of the mixing zone policies of 14 states. These states were selected to cover the major petroleum refining centers of the United States as well as to represent a wide geographic distribution and a variety of receiving water environments. This survey demonstrates that some states have very prescriptive mixing zone policies. Others allow substantial flexibility, offering dischargers an opportunity for technical input and negotiation during NPDES permit development.

Often, but not always, input parameters and critical assumptions for mixing zone modeling are specified in state water quality standards or policy documents. However, in some states, permit writers may simply take these parameters uncritically from EPA guidance documents, textbooks, other precedents, or customary professional practice. Dischargers should be aware that those model inputs not set by state regulation or written policy are negotiable and can often be changed on the strength of good technical arguments or field data.

Mixing Zone Physics and Outfall Diffuser Design

Chapter 3 introduces several basic concepts which describe the physical interaction of effluent discharges and receiving waters within mixing zones. These include:

- Classification of effluents as either "jets" or "plumes" and the dilution pattern for each type of discharge.

- Distinctions between "near field" and "far field" mixing processes and the factors dominating effluent dilution in each region.

- The role of effluent buoyancy in promoting mixing and the limiting effect of ambient density stratification on dilution of positively buoyant discharges.

- Relatively rapid and uniform vertical mixing of effluents in rivers. Lateral mixing, on the other hand, occurs over longer distances and is dependent on factors such as current speed, channel morphology, and the presence or absence of rapids.

- The importance of ambient currents and tidal effects for complete effluent mixing.

A grasp of these fundamental principles is essential for the proper design of outfall diffuser systems, the selection of an appropriate mixing zone model for a given discharge, and the interpretation of model output.

The basic components of a high-energy effluent diffuser are introduced in Chapter 2, including the outfall pipe, the diffuser pipe, and smaller diameter discharge ports and diffuser nozzles. Equations governing diffuser hydraulics are presented, and design techniques are described to ensure equal flow distribution along the entire length of a multiport diffuser.

Configuration of the diffuser ports and nozzles will also dictate the effectiveness of initial mixing. Important factors include size, spacing, and horizontal as well as vertical orientation relative to ambient currents. It is generally recommended to direct diffuser nozzles perpendicular to the centerline of the diffuser pipe and in the direction of the strongest ambient current. For discharges to marine or brackish waters, it is also important that diffuser ports be sized to achieve sufficient exit velocities and prevent saltwater intrusion under low flow conditions. Empirical design criteria are presented to address these concerns.

Materials of construction and outfall location are the two primary construction considerations for diffuser systems. Material selection must be based on the characteristics of both the effluent and the receiving water as well as risks associated with geotechnical conditions and physical exposure. Acceptable pipe materials include plastics (polyvinyl chloride and high density polyethylene), fiberglass, welded steel, ductile iron, and reinforced concrete. Metal fittings must be made of marine-grade stainless steel or other corrosion-resistant materials. The diffuser should be constructed so that it is protected from physical hazards, floating debris, wave and current action, and, in some cases, seismic activity. Construction techniques are described to mitigate these risks.

Availability and Strategic Use of Mixing Zone Models

The availability and strategic use of mixing zone models are discussed in Chapter 4 through Chapter 6. A consistent emphasis throughout these chapters is that users should strive for the least complex modeling approach possible to achieve the objective of environmentally-protective and cost-effective NPDES permit limits. There is a trade-off between cost and model accuracy. Simple models tend to err on the side of overprotective permit limits, while more complex models bring additional costs related to data collection and consultant support. Each discharger must determine whether the costs of implementing a more rigorous model are likely to be recouped via a less restrictive discharge permit.

Chapter 4 introduces several important technical issues to consider when selecting a mixing zone model. These include the following:

- Stages of mixing. "Near field" models focus on the mixing that occurs in the immediate vicinity of the outfall and may be useful when a mixing zone is physically defined in terms of area or volume around the discharge point. This type of mixing is controlled primarily by the momentum and buoyancy of the discharge itself. "Far field" models consider the mixing that occurs farther away from the discharge point. This stage of mixing is dominated by ambient turbulence in the receiving water.

- Spatial resolution. Mixing zone models are available which consider water quality changes over zero (completely mixed), one, two, or three dimensions in space. Model complexity increases with the number of spatial dimensions considered. Guidance is provided regarding situations where each type of model is – and is not – appropriate.

- Temporal resolution. Models can also be categorized in terms of how they consider changes in pollutant concentrations over time. The advantages of steady state and time variable mixing zone models are discussed, along with the use of tidally averaged steady state models to evaluate mixing in dynamic estuarine systems.

- Deterministic vs. probabilistic models. A deterministic mixing zone model predicts a single environmental response to a fixed set of inputs intended to represent critical mixing conditions in the receiving water. This approach may result in overly conservative dilution factors, especially when mixing is governed by several independent variables. On the other hand, probabilistic models predict the distribution of environmental responses over a full range of input conditions. These types of models should be considered when the frequency of expected water quality criteria violations is a critical issue in NPDES permitting.

Chapter 4 also presents ten mixing zone models developed and/or currently supported by EPA. These range from simple desktop calculations to sophisticated computer programs requiring significant input data and expert support. The structure, assumptions, complexity, output, and computer hardware requirements for each model are described. The range of appropriate discharge and receiving water conditions is discussed for each model, along with typical errors in model application. Guidance is provided on the applicability of specific mixing zone models to typical discharge situations, including shallow and deep rivers, estuaries, and open waters such as large lakes and marine systems. Finally, three case histories illustrate use of the mixing zone models discussed in Chapter 4 in actual NPDES permitting situations. These examples show how information is factored into model selection and how the models can be used iteratively in setting permit limits.

Chapter 5 describes how to obtain additional information on the specific mixing zone models introduced in Chapter 4. References are provided for model documentation as well as electronic access via the Internet.

A structured approach for mixing zone model selection is discussed in Chapter 6. Important considerations may be grouped into three broad categories:

- Regulatory requirements. Mixing zone regulations and policy applicable in a specific state must be thoroughly understood to take full advantage of any available regulatory flexibility as well as to eliminate consideration of modeling approaches which are not acceptable to the permitting authority.

- Discharge characteristics. Key variables include type of discharge (surface, submerged single port diffuser, submerged multiport diffuser) as well as effluent flow rate, density, and chemical characteristics.

- Ambient conditions. The physical and chemical characteristics of the receiving water will also determine the extent of effluent mixing. The most important variables in this category include water body type (shallow river, deep river, estuary, lake, or open ocean), width and depth of the receiving water, receiving water flow rate and velocity profile, ambient density variation with depth, and background or upstream water quality. Data sources are identified for many of these receiving water variables.

Such preliminary information should be summarized in a general narrative format and compared against the capabilities of the EPA-supported mixing zone models described in Chapter 4. In most cases, this will limit selection of a mixing zone model to one or two choices.

Validation requirements should also be considered when selecting a mixing zone model. The user must be able to demonstrate that a model accurately describes the system being evaluated. Such demonstrations may take several forms:

- Justification of model selection and inputs. This is the most fundamental validation requirement and it may be accomplished by the use of EPA-supported models, demonstrating that the selected model is appropriate for a given receiving water and discharge situation, and documentation of all user-specified model inputs. Supporting references should be made to the technical literature or similar previous studies wherever possible.

- Sensitivity analysis. Simulations with input parameters at the extremes of their expected ranges are useful to define the uncertainty range in dilution predictions. Such sensitivity analyses are often required by regulators before model results are accepted for NPDES permitting.

- Calibration against field data. The calibration process consists of adjusting model inputs to achieve a satisfactory comparison between predictions and actual field data. Tracer studies (discussed below) provide the best means for evaluating mixing zone model calibration.

- Verification with independent data sets. Verification compares the predictions of a calibrated mixing zone model against the effluent dilution observed in one or more independent sets of field data. This is the strongest type of model validation. Although the costs of model verification are high, this expense may be justified by the additional reliability – and ultimately, regulatory acceptability – of the predictions of a verified model.

Requirements for model validation will vary for individual dischargers. It is not uncommon for technical problems to arise during the validation process as the selected model is developed and initial simulations are conducted. The output of all mixing zone models should be carefully examined. Unrealistic dilution predictions may indicate that the selected model cannot appropriately simulate a specific receiving water and discharge configuration. In these situations, an alternative model should be considered for more realistic effluent dilution predictions.

Dye Tracer Studies and Other Alternatives to Modeling

Dye tracer studies may be used as supplements or alternatives to mixing zone modeling. A conservative tracer is injected into the discharge and measured at various points in the receiving water to quantitatively characterize effluent dilution under actual field conditions. Dye study results are frequently used to calibrate mixing zone models or verify model predictions. Once the credibility of a model has been established with field data, greater confidence can be placed in its ability to simulate dilution with different effluent characteristics, a new outfall diffuser, or seasonal variability in the receiving water. The other primary rationale for conducting a dye study is to demonstrate compliance with mixing zone requirements and water quality criteria after an NPDES permit has been issued. A field demonstration of effluent mixing is often included as a condition in NPDES permits.

Chapter 7 presents an introduction to effluent dye tracer studies. To provide useful results, a plume characterization study requires a substantial effort in planning, logistics, field execution, data processing, and reporting. Tables are provided in the guidance document which list factors to consider and possible approaches to execution of tracer tests in different types of receiving waters, including free-flowing rivers, tidally-influenced rivers, bays, and estuaries. Available tracers are discussed, along with criteria for tracer selection. Other important issues include selection of an injection point which allows rapid and complete mixing of the effluent and the dye prior to discharge; procedures for sampling and measuring dye concentration in the effluent; and positioning systems, sampling methods, and analytical procedures for measuring tracer dispersion in the receiving water. Concurrent measurement of additional receiving water parameters, including density profiles, currents, and tidal heights, is often necessary to document conditions during the field test and to provide input for many mixing zone models.

Other types of tracer studies are reviewed in addition to dye dilution tests. These include conductivity measurements and thermal plume mapping. The use of high-resolution conductivity measurements to track wastewater plumes and calculate dilution is particularly well-suited for freshwater systems (such as rivers and lakes) and well-mixed coastal waters. A case history is presented to illustrate the successful use of conductivity measurements to demonstrate mixing zone compliance and evaluate the impacts of alternative effluent limits for a municipality discharging to a small river. The results of the dilution study were used to modify the conservative assumptions and inputs used in standard mixing zone models.

Field programs to measure effluent dilution typically cost between $20,000 and $75,000 per sampling mobilization. While costs will vary between sites, a large multi-disciplinary dilution study conducted over several seasons can easily cost several hundred thousand dollars. Because these costs are significant, dischargers should clearly define the expected benefits of a tracer study before work begins and compare these against the likely expense of field testing as well as alternatives such as modeling.

CHAPTER 1

INTRODUCTION

In the United States, wastewater discharges to surface water are regulated through NPDES permits issued and enforced either by EPA or by state agencies under authority delegated by EPA. Generally, the CWA requires that NPDES permits reflect technology-based effluent limitations. However, more stringent limits may be applied on a case-by-case basis if necessary to protect receiving water quality.

Much information is available to help regulators and dischargers establish environmentally-protective mixing zones and dilution factors. API retained the team of Brown and Caldwell and Limno-Tech, Inc. (LTI) to summarize this information and develop a guidance document on the role of dilution analysis and mixing zone models in the NPDES permitting process. To participate meaningfully in permit development, dischargers need to be fully aware of the range of technical and policy options available to them, as well as the advantages and disadvantages of various modeling approaches for mixing zone analysis. Therefore, this document has been written primarily for the benefit of those who may manage or evaluate mixing zone and dilution studies in the course of obtaining water-quality-based NPDES permits. The goal of the authors is to equip this user group with technical information and strategies to negotiate site-specific NPDES permits which properly account for available dilution in the environment.

Water-quality-based permit limits are set so that the fully diluted effluent under critical environmental conditions (e.g., low flow, slack tide, etc.) will not exceed ambient water quality criteria. As discussed in Section 1.1 below, these criteria are promulgated by the states as part of their water quality standards regulations and are intended to protect human health and aquatic life.

Water-quality-based NPDES permit limits have become more common in recent years as states have adopted ambient criteria for numerous toxic pollutants. In issuing such permits, EPA and many states recognize that the designated uses of a water body can be maintained without requiring effluents to fully meet water quality criteria at the point of discharge. Allowances are available which consider the mixing and dilution that take place in the vicinity of an outfall. This concept is illustrated by the following simplified algebraic expression:

$$C_{eff,allow} = C_{WQC} \; x \; S_{crit} \qquad (1\text{-}1)$$

where:

$C_{eff,allow}$	=	allowable effluent concentration
C_{WQC}	=	ambient water quality criterion
S_{crit}	=	dilution factor under critical conditions

As shown by this equation, the calculated permit limit may, depending on the size of the dilution factor, be substantially greater than the corresponding ambient water quality criterion.

A mixing zone may be determined by computing a dilution factor or it may be delineated by a regulatory agency as a spatial area with fixed boundaries. In either case, it is an allocated region within a receiving water in which the effluent is rapidly diluted due to its own momentum and buoyancy (which create a sharp velocity gradient and shear stress between the effluent and ambient water), as well as ambient turbulence. Water quality criteria may be exceeded within a mixing zone but must be met at its boundaries.

Dilution credits are typically derived from a mathematical model applied to a set of discharge and receiving water conditions believed to represent a critical (i.e., poor) situation for mixing. As shown in Equation 1-1, this dilution factor can then be used to calculate end-of-pipe NPDES permit limits which protect the biological integrity of the receiving water. Equation 1-1 also illustrates the general concept that any conservatism inherent in the computed dilution factor will directly result in more restrictive effluent limits.

1.1 Water Quality Criteria and Standards

As defined in the Code of Federal Regulations (CFR), a water quality standard is a regulation promulgated by a state or EPA which designates the use or uses to be made of a water body as well as criteria to protect the designated use [40 CFR 131.3(i)]. The CWA describes various uses for surface waters which are considered desirable. These include public water supply, industrial and agricultural water supply, recreation, and propagation of fish, shellfish, and wildlife. States are free to designate more specific uses (e.g., cold water and warm water aquatic life habitat) or to designate uses not mentioned in the CWA, with the exception that waste transport and assimilation is not an acceptable designated use [40 CFR 131.10(a)].

At 40 CFR 131.11(a)(1), states are required to establish water quality criteria which, when met in ambient waters, will protect each designated use. These criteria "must be based on sound scientific rationale" and are subject to EPA review and approval. For waters with multiple use designations, the enforceable criteria are those which protect the most sensitive use. Although criteria may be expressed as narrative statements, states must also adopt numerical values for individual chemicals or constituents based on national guidance developed by EPA. Numerical water quality criteria to protect aquatic life are generally developed to address both short-term (acute) and long-term (chronic) effects.

EPA water quality criteria guidance includes three components for each regulated pollutant (EPA 1991):

- Magnitude (the allowed concentration in ambient water)
- Duration (the averaging period over which the ambient pollutant concentration is compared to the allowed value)
- Frequency (how often the criterion may be exceeded)

Two numerical values are specified by EPA in the aquatic life criterion for each pollutant. The acute criterion maximum concentration (CMC) is a value which cannot be exceeded in ambient waters for a 1-hour averaging period more than once every 3 years. The criterion continuous concentration (CCC), or the chronic toxicity criterion, represents a 4-day average concentration which may not be exceeded more than once every 3 years. The critical ambient and effluent conditions selected for purposes of mixing zone modeling and dilution analysis should reflect the duration and frequency considerations inherent in the definition of the CMC and the CCC.

1.2 Mixing Zones

States may, at their discretion, adopt mixing zone policies and procedures as part of their water quality standards regulations (40 CFR 131.13). Such policies are subject to EPA review and approval.

EPA guidance (EPA 1991) acknowledges that the biological integrity of a water body as a whole can be maintained even if ambient pollutant concentrations exceed water quality criteria in small areas near an outfall. However, to ensure water quality protection, EPA also seeks to minimize mixing zones, either by limiting the allowed spatial extent of the impacted area or the magnitude of the dilution factor. In evaluating proposed mixing zones, EPA specifically requires a determination on the part of the permitting authority that there will be no lethality to passing aquatic organisms and, considering likely exposure pathways, that there will be no significant human health risks.

Two types of mixing zones may be established, corresponding to the two-number aquatic life criteria discussed in Section 1.1. This concept is illustrated on Figure 1-1. In the zone immediately surrounding the outfall, neither the CMC nor the CCC is met. The size of this "acute" mixing zone is limited by proper design of the outfall diffuser. EPA also requires that the travel time of drifting organisms through the "acute" mixing zone be well less than the 1-hour average exposure associated with the CMC. The CMC must be met at the edge of this first mixing zone and throughout the next mixing zone. The CCC is met at the edge of the second, or "chronic," mixing zone. According to EPA, conditions within the entire mixing zone would prevent lethality to aquatic life but may not necessarily ensure growth and reproduction of all organisms that might otherwise attempt to reside continuously in the vicinity of the outfall.

There are a number of other issues which should be considered in evaluating effluent dilution and developing NPDES permit limits. These include the following (EPA 1991):

- Background or upstream pollutant concentrations.
- Potential for effluent to attract, rather than repel, aquatic organisms.
- Maintenance of zones of passage for swimming organisms into tributary streams as well as the main water body.
- Potential for overlapping mixing zones among adjacent dischargers and the total area of all allowed mixing zones in relation to the water body as a whole.
- Potential for a mixing zone to impact critical habitat areas or drinking water intakes.
- Discharge of bioaccumulative pollutants in areas used for fish harvesting, especially shellfish beds.

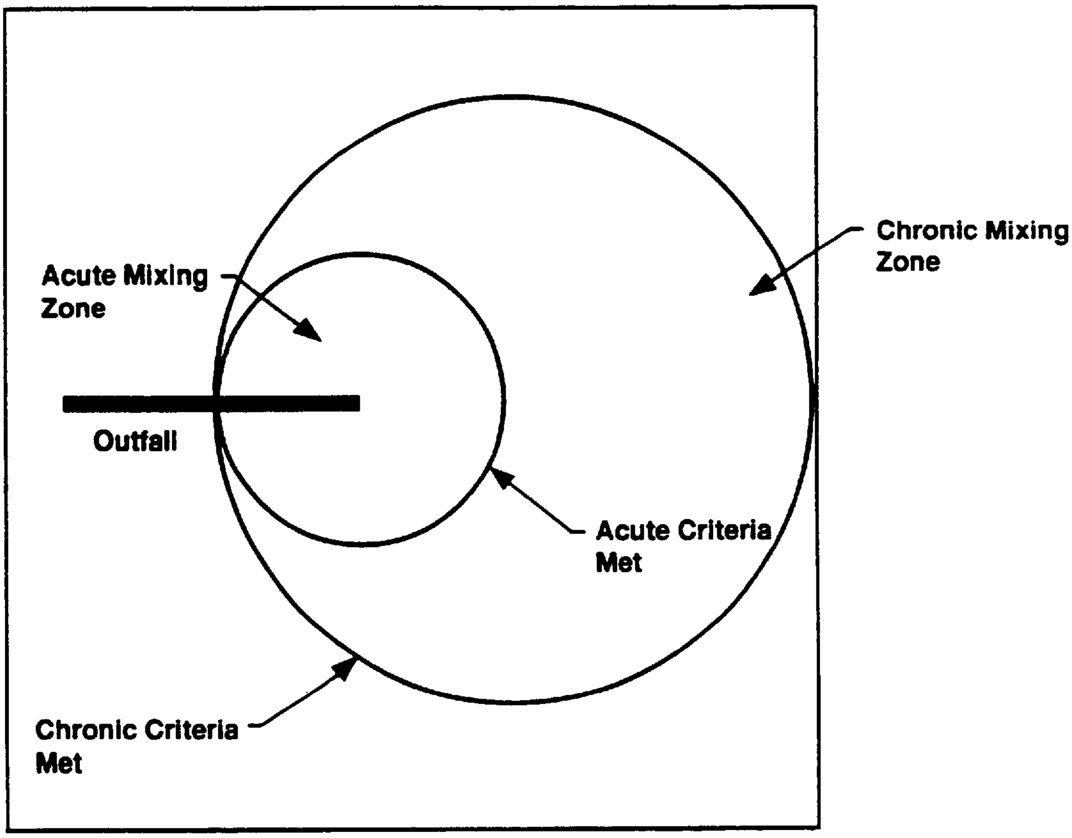


Figure 1-1. Diagram of the Two Parts of the Mixing Zone

Factors such as these may provide reasons for a permitting agency to allow a smaller mixing zone than would otherwise be justified by the mixing zone and dilution models discussed in subsequent chapters of this document. According to EPA, it may even be appropriate to deny a mixing zone in some site-specific circumstances (EPA 1991).

1.3 Report Organization

This guidance document is divided into eight chapters, including this introduction. Chapter 2 provides an overview of EPA policies and technical guidance on the role of mixing zones in the NPDES permitting process. Mixing zone regulations, policies, and guidance from selected states are also presented. Chapter 3 introduces important concepts related to the hydrodynamics of effluent dilution in receiving waters and the design of outfall diffusers. Available mixing zone models are presented and reviewed in Chapter 4. Chapter 5 identifies EPA sources for mixing zone models, and Chapter 6 discusses a number of strategic issues for dischargers to consider when applying models. The use of dye tracer studies as alternatives or supplements to mixing zone models is described in Chapter 7. References are provided in Chapter 8.

Three appendices are also included with this report. Appendix A gives one-page summary descriptions of the mixing zone models presented in Chapter 4 and Chapter 5. Instructions for electronic access to EPA-supported mixing zone models are provided in Appendix B. Samples of mixing zone model output are provided in Appendix C.

CHAPTER 2

REGULATORY BASIS

The preceding chapter introduced the regulatory framework within which mixing zones and dilution factors are considered in developing water-quality-based NPDES permit limits. This chapter will present key EPA policies and technical guidance related to mixing zones. Mixing zone regulations, policies, and guidance from selected states will also be discussed.

Mixing zone implementation differs widely across the United States. Some states have very prescriptive policies and procedures for establishing mixing zones and calculating dilution factors. Others allow substantial flexibility, offering dischargers an opportunity for technical input and negotiation. While the guidance provided in this document has general value to NPDES permittees, dischargers must make the effort to understand and follow the established process for determining mixing zone boundaries and allowable effluent dilution in their specific jurisdictions.

It is also important to understand those elements of mixing zone and dilution analysis which are negotiable with the permitting agency, as well as those which are not. Sophisticated mixing zone modeling studies and field measurements of effluent dilution can be expensive. Time and money should not be spent on these activities unless the discharger has reasonable assurance that the permit writer will consider the study results in calculating permit limits.

A third important point is that the input parameters and assumptions used for dilution modeling directly affect model output. This will become apparent as specific models are discussed in subsequent chapters of this document. Often, but not always, critical assumptions such as upstream flow are specified in state water quality standards regulations or in agency policy documents. However, in some cases, these parameters may simply be taken uncritically from textbooks, EPA guidance documents, other precedents, or customary professional practice. Dischargers should be aware that those model inputs not set by regulation or written policy are generally negotiable and can often be changed on the strength of good technical arguments or field data. However, even if significant modeling assumptions can be modified through negotiation, developing the necessary supporting data will often entail substantial costs.

Finally, dischargers should be aware that many NPDES permit writers, especially less experienced ones, may be reluctant to take full advantage of the flexibility available in EPA guidance and state regulations when specifying mixing zones. This reluctance may stem from philosophical or technical concerns. Consequently, it is important for dischargers to understand the permit writer's perspective regarding mixing zones and dilution credits. Permittees should also be prepared to support the permit writer by providing detailed technical and policy justification for any flexibility that is applied in the development of a specific mixing zone. Ideally, such discussions between the discharger and the permit writer should occur well before negotiations begin over effluent limits for specific wastewater constituents. The extent of the allowed mixing zone and dilution credit should certainly be settled before a draft NPDES permit is made available for public review and comment.

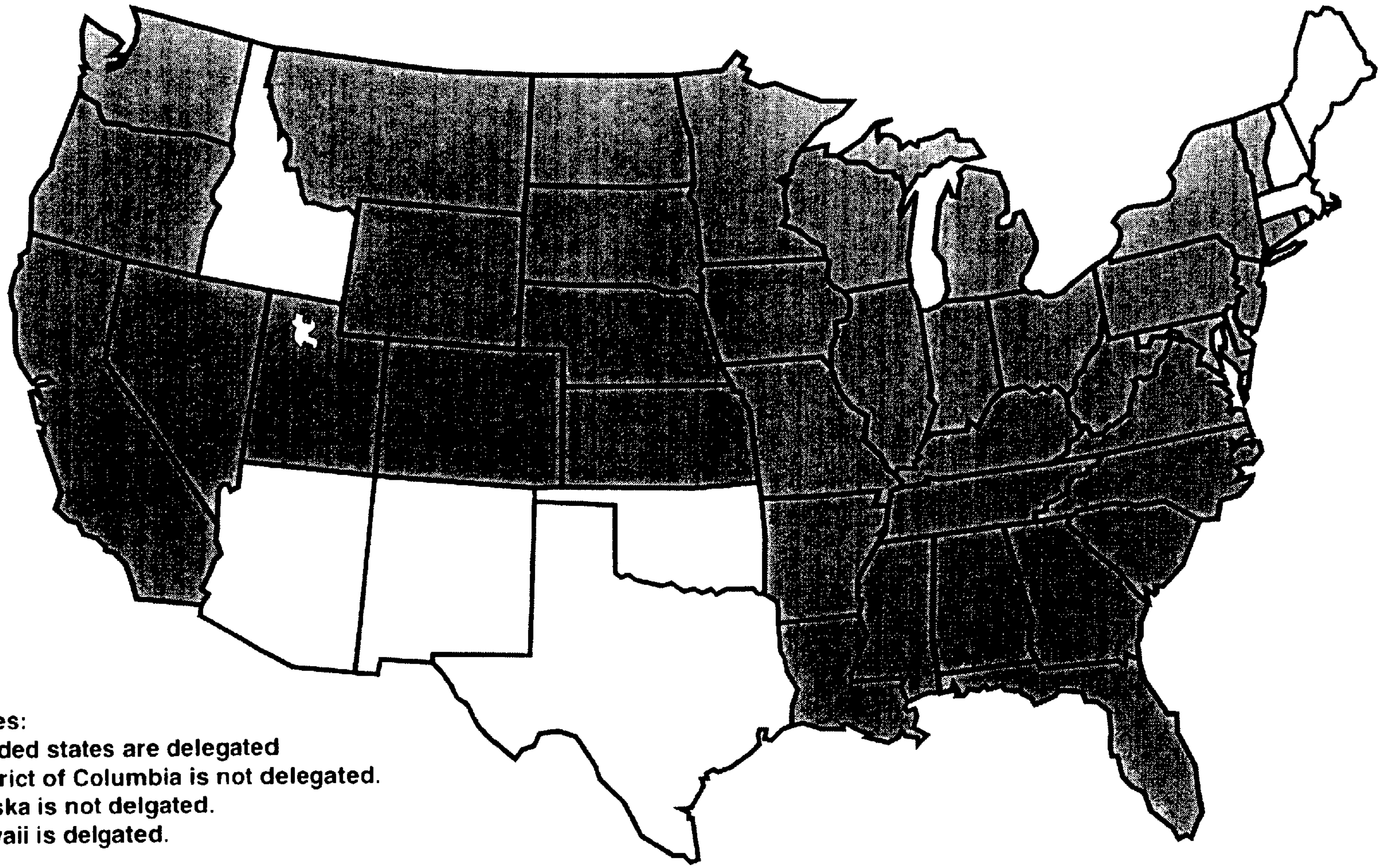
2.1 Water-Quality-Based NPDES Permits

Under the CWA, an NPDES permit is required for discharge from a point source to the surface waters of the United States. The NPDES permit establishes the legal conditions for the discharge. Typical permit conditions regulate the quality of the effluent, either in terms of pollutant concentrations or mass discharge rate, establish monitoring requirements, and determine the content and frequency of reporting to regulatory agencies. In some situations, the NPDES permit may also place a limit on effluent flow rate.

The NPDES permit must contain effluent limits which reflect technology-based requirements. For major industrial categories, such as petroleum refineries, these limits have been established by EPA in the form of promulgated effluent guidelines regulations. Many, but not all, of EPA's effluent guidelines set discharge limits for individual facilities on the basis of size or historical production rates. For smaller facilities, such as marketing terminals, technology-based effluent limits are determined by individual NPDES permit writers on the basis of best professional judgement. For any type of facility, the permit writer may also set more stringent discharge requirements if necessary to maintain compliance with state water quality criteria.

As shown on Figure 2-1, most states have been delegated authority by EPA to develop, issue, and administer NPDES permits. In 9 nondelegated states, EPA retains authority for the NPDES permit program. However, even when EPA prepares the NPDES permit, the state must

Figure 2-1. States Delegated NPDES Permitting Authority



Notes:
Shaded states are delegated
District of Columbia is not delegated.
Alaska is not delgated.
Hawaii is delgated.

still certify that the effluent limits will assure compliance with applicable water quality standards regulations, including any mixing zone requirements.

Section 1.2 introduced the concept of a mixing zone as a limited portion of the receiving water, in the vicinity of the outfall, in which effluent is diluted to meet ambient water-quality criteria. Credit for this dilution may be considered by the permit writer in developing water-quality-based discharge limits which will ensure compliance with ambient criteria at the mixing zone boundaries.

Mixing zones may be determined in a number of ways. Examples include assigning a fixed percentage of river flow for dilution, establishing boundaries for the mixing zone based on distance from the outfall or area around the diffuser, or allowing mixing within a fraction of the receiving water area. Regardless of the method employed, mixing zone boundaries are determined from assumed critical dilution conditions in the receiving water. Some often-used assumptions regarding critical conditions are debatable. One primary example is the use of the 7-day average low flow with a 10-year recurrence frequency (7Q10) as the critical river flow for dilution. Subsequent chapters will show how these critical assumptions influence dilution estimates.

2.2 Federal Mixing Zone Policy and Guidance

EPA has established its position on the role of mixing zones in the NPDES permit process in two major regulations and a series of guidance and policy documents issued over the last 25 years. This section will review the most important of these documents, with an emphasis on regulatory applications of mixing zones. EPA technical guidance on specific mixing zone models is discussed in Chapter 4 through Chapter 6.

Underlying the EPA guidance and policy documents is the assumption that, for purposes of effluent mixing and dilution, it may be appropriate to allow ambient pollutant concentrations to exceed water quality criteria in small areas near an outfall. However, the size of a mixing zone must be limited to prevent lethality to passing organisms and significant risks to human health. State regulatory agencies can decide to allow or deny a mixing zone on a site-specific basis. For a mixing zone to be permitted, the burden is on the discharger to show that state water quality standards are satisfied, including any mixing zone requirements (EPA 1991).

2.2.1 Water Quality Standards Regulation. EPA's water quality standards regulation is codified at 40 CFR 131. This regulation describes minimum requirements and procedures for development, review, and approval of the state water quality standards programs required by the CWA.

The basic framework of 40 CFR 131 as it exists today was promulgated by EPA in a November 1983 Federal Register (FR) notice (48 FR 51400). This 1983 rulemaking was very general with regard to the role of mixing zones in establishing NPDES permit limits. Mixing zones were simply listed at 40 CFR 131.13 among the discretionary polices which states could use to implement their water quality standards regulations. However, if mixing zone policies are included in state water quality standards or other implementing regulations, such policies must be submitted to EPA for review and approval. In addition, EPA has separate authority to review individual mixing zone determinations used to develop facility-specific NPDES permits. EPA's rationale is that state mixing zone policies and specific permit decisions are inseparable from the implementation of state water quality standards and criteria. As such, they must be reviewed by EPA for technical merit and consistency with the CWA.

One section of 40 CFR 131 does contain specific EPA requirements regarding mixing zones. In December 1992, EPA promulgated federal water quality criteria for toxic pollutants in 14 states and territories which had failed to fully comply with CWA Section 303(c)(2)(B). This action was known as the National Toxics Rule. At 40 CFR 131.36(c)(2), EPA codified for the affected states and territories the critical low flow to be assumed in a receiving water when evaluating mixing zones for priority toxic pollutants. Specifically, a 1Q10 or 1B3 low flow is to be used in mixing and dilution analyses to prevent exceedances of the CMC in ambient waters. Similarly, a 7Q10 or 4B3 low flow is required when determining ambient compliance with the CCC. To evaluate ambient water quality for compliance with human health criteria, mixing zone analyses are to use a 30Q5 low flow and a harmonic mean flow for evaluating non-carcinogens and carcinogens, respectively.

Note that the 1B3 and 4B3 values are "biologically based" low flows determined using EPA's DFLOW model (EPA 1991). The averaging periods and exceedance frequencies specified in the CMC and CCC for individual pollutants, along with historical flow data for the receiving water, are used to calculate 1B3 and 4B3 low flows. Thus, the 1B3 value corresponds to a water quality criterion exceedance once every 3 years, while the 4B3 value is associated with an allowable exceedance for 4 consecutive days once every 3 years. The harmonic mean flow used to evaluate ambient water quality against human health criteria is a long-term mean value for the receiving water calculated according to procedures outlined by Rossman (1990) and EPA (1991).

On February 27, 1996, EPA announced the availability of an interim draft Advanced Notice of Proposed Rulemaking (ANPRM) discussing possible revisions to 40 CFR 131 (Davies 1996). EPA's stated intent in releasing this draft was to seek input from interested parties prior to formal FR publication of the ANPRM. On the subject of mixing zones, the interim draft ANPRM revealed that EPA is considering changes that would expand the current provisions of 40 CFR 131.13 and impose more specific requirements on the states. Specific subject areas identified by EPA for review include the following:

- Current regulations do not establish any EPA requirements for the content of state mixing zone policies. EPA is now considering that states explicitly address several such issues, including mixing zone prohibitions in certain waterbodies or under specific conditions, circumstances in which only chronic mixing zones would be allowed (i.e., no acute mixing zones such as illustrated in Figure 1-1), and a listing of site-specific factors to be considered in authorizing mixing zones for individual facilities.

- As will be illustrated in Section 2.3, some states do not have very specific requirements in their mixing zone policies. EPA is concerned that state mixing zone determinations may not be consistent from site to site or technically defensible. Therefore, EPA is considering including specifications for state mixing zone policies in the 40 CFR 131 revision. For example, states may be required to define certain program elements such as mechanisms to identify complete and incomplete mixing of effluent and receiving water, default critical low flows for effluent dilution analyses in complete mixing situations, effluent design flows, and special mixing zone conditions for bioaccumulative pollutants. According to EPA, these types of provisions would not change the Agency's current approach to state mixing zone policy reviews under 40 CFR 131.13. Rather, they would codify current practice.

- EPA could require that states explicitly prohibit mixing zones which could impinge on public water supply intakes, recreation areas, or sensitive wildlife habitats.

- EPA is considering a requirement that state water quality standards include a description of the methods used to specify the location, geographic boundaries, size, shape, and in-zone water quality of mixing zones.

- EPA is particularly concerned about instances of slow effluent mixing with receiving waters and discharge plumes which extend for significant distances downstream from the outfall. In such situations, computation of a dilution factor from the entire critical low flow may be too simplistic for calculating effluent limits. EPA may stipulate that states conduct more thorough mixing zone analyses in these cases to demonstrate that NPDES permit limits fully protect water quality.

In the February 1996 interim draft ANPRM, EPA emphasized that it was not necessarily committed to revising 40 CFR 131. A potential alternative may be additional guidance documents or policy in lieu of regulatory changes. Nevertheless, the specificity of the issues raised by EPA in the interim draft ANPRM suggests that at least some states could lose flexibility in future mixing zone decisions, whether through promulgated changes in the water quality standards program or increased EPA scrutiny of individual NPDES permit decisions.

2.2.2 Water Quality Guidance for the Great Lakes System. On March 23, 1995, EPA published final Water Quality Guidance for the Great Lakes System (60 FR 15366), commonly known as the Great Lakes Initiative (GLI) guidance. This rule was codified at 40 CFR 132. It was required by Section 118(c)(2) of the CWA, which mandates that EPA publish guidance on minimum water quality standards, anti-degradation policies, and implementation procedures for the Great Lakes system. The rule outlines provisions that must be adopted by Illinois, Indiana, Michigan, Minnesota, New York, Ohio, Pennsylvania, and Wisconsin as these states revise water quality standards regulations affecting streams, rivers, and lakes within the drainage basin of the Great Lakes. The eight GLI states may also adopt portions of these regulations in standards for waters outside the Great Lakes Basin. In addition, various aspects of the GLI guidance may be considered by EPA for nationwide application through possible future revisions to 40 CFR 131 (Davies 1996).

The GLI guidance addresses several mixing zone issues which are relevant to this report. First, EPA has established a 12-year phase-out of mixing zones for existing discharges of bioaccumulative chemicals of concern (BCCs) in the Great Lakes basin. (BCCs are defined as those chemicals which bioaccumulate by a factor of 1,000 or more and include, but are not limited to, 22 specific pollutants listed in the regulation. The listed pollutants are primarily organochlorine pesticides, polychlorinated biphenyls, mercury, and dioxin.) Limited exceptions to this phase-out are allowed based on water conservation or technical and economic considerations. As of March 1997, mixing zones for new discharges of BCCs to the Great Lakes basin are no longer allowed.

Second, the GLI guidance specifies the critical low flows and assumptions to be used by state regulatory agencies in calculating effluent dilution factors and drafting water-quality-based

NPDES permit limits. For implementation of chronic aquatic life criteria, the GLI establishes 7Q10 or 4B3 as the low stream flow. A 1Q10 flow value is to be used in conjunction with acute aquatic life criteria, the harmonic mean flow is to be used with human health criteria, and the 90Q10 low flow is specified for use with water quality criteria for protection of wildlife. (Wildlife protection criteria are another new feature of the GLI guidance.)

Third, the GLI guidance allows states to use default assumptions of available dilution in the absence of site-specific mixing data. For the open waters of the Great Lakes, a default assumption of 10:1 effluent dilution may be used. In no case can a mixing zone for the open waters of the Great Lakes exceed the area in which near field mixing occurs (see Section 4.1.1 for a description of near field mixing processes). For flowing waters, states may use up to 25 percent of the appropriate low stream flow for effluent dilution when calculating NPDES permit limits based on chronic water quality criteria. Acute mixing zones are capped at a maximum 2:1 dilution in the receiving stream.

Finally, the GLI guidance allows dischargers the option of conducting an alternate demonstration for the purpose of establishing larger mixing zones than provided by these default assumptions. Such mixing zone demonstrations must be approved by EPA and conducted to meet specific requirements outlined in the GLI guidance. For example, these studies must describe effluent mixing behavior at a particular site, estimate actual dilution at the boundaries of any proposed mixing zone, address background water quality and streambed morphology within the mixing zone, determine whether or not adjacent mixing zones overlap, show that the mixing zone does not block passage of fish or other aquatic life, address whether the mixing zone will attract aquatic organisms, and demonstrate that a proposed mixing zone will not extend to critical wildlife habitats or drinking water intakes. Mixing zone studies must be based on the assumption that pollutants are not degraded within the mixing zone unless technical information is provided which shows otherwise. The GLI guidance also requires mixing zone demonstrations to show that existing and designated uses of the receiving water will be protected and that an expanded mixing zone not result in objectionable deposits, color, odor, taste, or turbidity.

2.2.3 Water Quality Standards Handbook. EPA originally published the Water Quality Standards Handbook (Handbook) to help states interpret and implement the 1983 water quality standards regulations codified at 40 CFR 131. The second edition of the Handbook was published in 1994 (EPA 1994). This document is a compilation of EPA policy guidance and technical information related to the water quality standards program. While intended primarily for state agencies, it does provide NPDES permittees with valuable insights regarding EPA's approach to mixing zones.

The Handbook restates EPA's long-held position that states may allow effluent mixing zones in the vicinity of an outfall and still protect the integrity of the receiving water as a whole. However, EPA (1994) also reiterates that mixing zone allowances are a matter of discretionary state policy subject to EPA review and approval (40 CFR 131.13).

EPA (1994) recommends that states have a definitive statement in their water quality standards regulations as to whether or not mixing zones are allowed. Where mixing zone provisions are part of state standards, there should be a clear description of procedures for determining the location, size, and shape of mixing zones. EPA (1994) makes the following recommendations on these issues:

- **Location:** Biologically important areas are to be identified and protected, and zones of passage for migrating fish and other aquatic organisms should be preserved. Therefore, EPA (1994) recommends that state standards specifically identify those portions of receiving waters in which mixing zones are not allowed to prevent adverse impacts to critical resource areas and migrating fish.

- **Size:** According to EPA (1994), limitations on the dimensions or allowed area of mixing zones provide another way for states to protect migrating fish. Therefore, the Handbook encourages states to adopt size limits for mixing zones in their water quality standards regulations. For streams and rivers, EPA generally expects state policies to limit mixing zones on the basis of widths, cross-sectional areas, and/or critical low flow available for dilution. The lengths of mixing zones in rivers are generally determined on a case-specific basis. In lakes, estuaries, or coastal waters, EPA (1994) indicates that mixing zones can be limited by surface area, width, cross-sectional area, or volume.

  The Handbook also introduces the concept, illustrated in Figure 1-1, that independently established acute and chronic mixing zones of different sizes may apply to the same outfall. The acute mixing zone may be sized to prevent lethality to passing organisms, with the chronic mixing zone sized to protect the ecology of the receiving water as a whole.

  Other benchmarks provided by EPA (1994) for sizing mixing zones include the following:

i. It is not necessary to meet the CCC within a mixing zone, only at the edge. Thus, conditions within the mixing zone may not ensure the survival, growth, and reproduction of all aquatic organisms that might otherwise attempt to reside continuously in that portion of the receiving water allocated for effluent dilution.

ii. Lethality to passing organisms can be avoided if the CMC is exceeded for no more than a few minutes in a parcel of water leaving an outfall. This is the basis for the Handbook's outfall design criteria described below.

iii. Travel time for drifting and swimming organisms through the acute mixing zone should generally be less than 15 minutes to avoid exceeding the CMC over a 1-hour averaging period.

These criteria provide "rules of thumb" used by EPA in evaluating both statewide mixing zone policies as well as individual NPDES permit decisions.

- **Shape:** EPA (1994) recommends that the shape of a mixing zone be a simple configuration that is easy to locate in a body of water and avoids impacts on biologically important areas. In lakes, a circle with a specified radius around the outfall is generally preferable, according to the Handbook, but other shapes may be allowed in unusual circumstances. EPA (1994) also states that "shore-hugging" plumes are to be avoided in all water bodies.

The Handbook devotes considerable attention to methods that state permitting agencies can use to prevent lethality to aquatic organisms in a mixing zone. Four options are provided:

- Set effluent limits so that the CMC is never exceeded in the discharge itself. For example, EPA (1994) states that this option should be used for effluents continuously discharged to intermittent streams.

- Require that the CMC be met within a short distance of the outfall during chronic low flow conditions in the receiving water. This condition can be met through proper outfall design. EPA (1994) states the initial discharge velocity should be 3 meters per second or greater and the mixing zone should be limited to 50 times the discharge length scale in any direction. The discharge length scale is defined as the square root of the cross-sectional area of any outfall or diffuser pipe.

- Where a high-velocity diffuser is not used, require the discharger to submit data to the permitting agency showing that the most restrictive of the following conditions is met (EPA 1994):

  i. The CMC is met within 10 percent of the distance from the edge of the outfall structure to the edge of the mixing zone.

ii. The CMC is met within a distance of 50 times the discharge length scale in any direction.

iii. The CMC is met within a distance of 5 times the local receiving water depth in any horizontal direction from the discharge outlet.

- A fourth alternative would be for the discharger to provide data showing that a drifting organism would not be exposed to 1-hour average concentrations exceeding the CMC.

For the third and fourth options, EPA (1994) states that the data requirements can be satisfied either through computer modeling or a field study, details of which are discussed in Chapter 4 through Chapter 7 of this document.

The Handbook also lists several factors that might cause a state to deny a mixing zone to a discharger. According to EPA (1994), denial should be considered when a discharge contains bioaccumulative pollutants. As a general rule, the Handbook considers pollutants with a bioaccumulation factor of 100 or more to present a significant bioconcentration potential in the receiving water (EPA 1994). This is one order of magnitude below the bioaccumulation factor used to identify BCCs in the GLI guidance.

Effluents which attract biota provide another justification for mixing zone denial. A review conducted by EPA showed that most pollutants elicited an avoidance or neutral response in fish. However, warm effluents may sometimes counter an avoidance response and attract aquatic organisms to a discharge (EPA 1994).

Finally, the Handbook provides guidance to the states on selection of receiving water critical low flows for effluent dilution analyses. The low flows recommended by EPA (1994) are identical to those promulgated with the National Toxics Rule at 40 CFR 131.36(c)(2) and discussed in Section 2.2.1.

2.2.4 Technical Support Document for Water-Quality-Based Toxics Control. The Technical Support Document for Water-Quality-Based Toxics Control (TSD) was first released by EPA in 1985 and subsequently revised in 1991 (EPA 1991). The intent of this guidance is to help states develop water-quality-based effluent limitations for toxic pollutants in point source discharges. Procedures are presented to derive effluent requirements for individual chemical pollutants along with whole effluent toxicity as determined by aquatic bioassays.

The mixing zone policy guidance provided in the TSD is in many respects identical to that given in the Handbook (EPA 1994) and discussed in Section 2.2.3. Examples include the following:

- EPA (1991) recommends that states have an unambiguous mixing zone policy in their water quality standards regulations and clearly describe their procedures to define mixing zones.
- EPA (1991) reaffirms the concept that acute and chronic mixing zones may apply to the same outfall (see Figure 1-1).
- EPA (1991) includes the same benchmarks as EPA (1994) to determine whether mixing zone size is appropriate.
- EPA (1991) provides the same four options as EPA (1994) to prevent lethality to aquatic organisms passing through a mixing zone.
- EPA (1991) restates the factors cited in EPA (1994) for denial of a mixing zone.

In addition, the TSD advises states that a mixing zone may be denied when necessary to account for "uncertainties" in the protectiveness of water quality criteria or the assimilative capacity of the receiving water. However, no specific criteria are provided by EPA (1991) to define the level of uncertainty that would justify denial of a mixing zone for either of these reasons. Given the ambiguity of EPA's guidance on this point, NPDES permittees should be prepared to vigorously challenge a state regulatory agency decision to deny a mixing zone based on "uncertainty."

Compared to the Handbook (EPA 1994), the TSD offers more extensive policy guidance on the role of human health protection in sizing mixing zones. EPA (1991) states that mixing zones should not result in unacceptable health risks when evaluated using reasonable exposure assumptions. Specifically, mixing zones should not encroach on drinking water intakes or areas often used for fish or shellfish harvesting.

In addition to policy guidance, the TSD offers numerous technical recommendations on mixing zone implementation. Issues covered by EPA (1991) include design of outfalls to maximize initial dilution, use of field tracer studies to evaluate mixing zones, mixing zone models, and critical receiving water conditions for performing mixing zone analyses. Much of this information is presented in later portions of this document and will not be repeated here. Outfall design issues are discussed in Section 3.2 and Section 3.3. The mixing zone models referenced by the TSD are presented in Section 4.2. Chapter 7 describes the use of dye or other tracer studies as alternatives and supplements to models for mixing zone analysis.

The remainder of this section will summarize the EPA (1991) recommendations regarding critical conditions in each of four major waterbody types (streams and rivers, lakes, bays and estuaries, and oceans) for the analysis of effluent mixing and dilution:

- **Streams and Rivers:** For streams and rivers, the TSD recommends that effluent dilution analyses be conducted at the same critical low flows recommended by EPA (1994), promulgated at 40 CFR 131.36(c)(2), and discussed in Section 2.2.1. References are provided by EPA (1991) for the DFLOW model used to estimate the 1B3 and 4B3 low flow values. Equations are given to calculate the harmonic mean flow used to evaluate ambient water quality against human health criteria. EPA (1991) also notes that certain rivers may have low flows regulated by dams or reservoirs that exceed the critical flow recommendations cited above. In these situations, the actual minimum flow maintained in the river should be used for mixing zone analysis.

- **Lakes:** For lakes, EPA (1991) recommends that seasonal variations in water level, wind speed and direction, and solar radiation should be evaluated to determine the critical period for effluent dilution. Since effluent density relative to the ambient water can vary seasonally, no one season or stratification condition can be selected as the most critical dilution condition for all cases. The TSD therefore suggests that all four seasons be analyzed when evaluating effluent mixing in lakes.

- **Bays and Estuaries:** Estimating the nature and extent of effluent dilution in marine systems is complicated by conditions such as tides, river inputs, wind intensity and direction, and ambient stratification. Because of the complex circulation patterns of estuaries, effluent mixing cannot be determined simply by calculating the discharge rate and the rate of receiving water flow (i.e., critical low flow). Tidal frequency and amplitude vary between discharge locations, and tidal influences at any one location have daily and monthly cycles. Therefore, EPA (1991) recommends the following empirical criteria to evaluate the dilution of effluent discharges to bays and estuaries:

i. For receiving waters without density stratification, the critical dilution condition should include a combination of low-water slack at spring tide (large tidal ranges) and critical low flow for any river inputs.

ii. For stratified bays and estuaries, the TSD suggests that site-specific dilution estimates be made at periods of minimum and maximum stratification. Both analyses should be performed at periods of low-water slack tide to determine which condition results in minimum effluent dilution. EPA (1991) states that minimum stratification is generally associated with low river inflows and spring tide conditions, whereas maximum stratification occurs during periods of high river inflows and low tidal ranges (neap tide).

After determining effluent dilution under critical conditions for a bay or estuary, EPA (1991) also recommends checking a non-critical condition (e.g., higher river inflow or lower stratification) which encompasses the period of maximum ambient velocity during a tidal cycle. This will show greater effluent dilution than the critical condition, but it also will result in the maximum extension of the discharge plume within the receiving water. The TSD notes that extension of a plume into critical resource areas such as shellfish beds may be of greater concern than a low-dilution situation in the immediate vicinity of the discharge point.

- **Oceans:** The TSD refers to two other publications (EPA 1982 and EPA 1985a) for details on critical mixing conditions for ocean discharges. EPA (1991) generally requires that mixing zone analyses for ocean discharges include periods of maximum stratification in the receiving water. The TSD also suggests that effluent mixing in oceans be evaluated with key model variables such as discharge flow rate and oceanographic conditions (e.g., spring tide and neap tide currents) set at the 10th percentile value of their respective cumulative frequency distributions. This recommendation is intended to generate model inputs which define a period of minimum effluent dilution. However, EPA (1991) does not address the fact that setting each of several independent model inputs at low individual probability values results in an extremely low joint probability. The strategic importance of this issue is discussed further in Section 6.3.2, along with various approaches NPDES permittees may suggest to state regulatory agencies to obtain more realistic inputs to mixing zone models involving multiple independent variables.

2.2.5 EPA Region VIII Mixing Zones and Dilution Policy. In December 1994, EPA issued a mixing zone and dilution policy intended to help states in Region VIII derive water-quality-based NPDES permits (EPA Region VIII 1994). The states directly affected by this policy and technical guidance are Colorado, Montana, North Dakota, South Dakota, Utah, and Wyoming.

However, to the extent that the Region VIII policy reflects more broad-based EPA concerns on the role of mixing zones in the NPDES permit process, this document is also important to dischargers located in other parts of the United States. This is especially true given the possibility that EPA may require more specific mixing zone policies in state water quality standards when (and if) current regulations at 40 CFR 131.13 are revised.

The basis for the Region VIII mixing zone policy is EPA's belief that it is generally inappropriate for states to allow use of the entire receiving water low flow to calculate available dilution and derive effluent limits. According to EPA, such policies often result in effluent-ambient water mixtures considerably exceeding water quality criteria and extending far downstream of the discharge point. This condition, categorized as "slow" or "incomplete" mixing, is said to threaten existing and designated uses of receiving waters throughout Region VIII (EPA Region VIII 1994). Accordingly, Region VIII believes that proper implementation of mixing zones in the NPDES permit process must go beyond simple dilution calculations and directly control both the size of mixing zones as well as in-zone water quality.

The Region VIII document includes a model state mixing zone policy and a separate implementation procedure. These are provided as examples which would satisfy federal requirements and could be approved by EPA, although Region VIII notes that both the policy and the procedure can be modified by the states. While acknowledging the optional nature of its mixing zone policy, Region VIII clearly indicates that it will be considered in the interim to be the preferred method of making dilution and mixing zone decisions. Implementation of this policy statement and guidance will be given a high priority when Region VIII reviews state water quality standards regulations as well as individual NPDES permit decisions (EPA Region VIII 1994). Note that all states in Region VIII currently have authority to issue and administer NPDES permits (see Figure 2-1).

EPA intends that this policy will result in two basic changes to current dilution and mixing zone determinations in Region VIII. First, the Region expects to reduce the perceived environmental risks posed by mixing zones in general through a recommendation that all point source dischargers comply with acute aquatic life criteria (i.e., the CMC) at the end-of-pipe. Thus, the acute mixing zone, as shown on Figure 1-1 and articulated in guidance such as EPA (1991) and EPA (1994), would be eliminated or severely restricted in the Region VIII states. Second, to address perceptions of unacceptable risk in specific cases, the Region provides an extensive list of reasons for states to further limit or deny mixing zones for individual dischargers.

The Region VIII policy document lists seven specific issues that states must address in their mixing zone policies and implementation procedures prior to EPA approval. These are summarized below (EPA Region VIII 1994):

- **Complete vs. Incomplete Mixing at Critical Conditions:** In reviewing individual NPDES permit decisions, Region VIII will require that states demonstrate complete mixing between the effluent and receiving water before using simple dilution estimates to establish discharge limitations. States must also have a procedure which distinguishes complete from incomplete mixing situations. Simple dilution estimates are only appropriate in cases of complete mixing, which Region VIII assumes to occur if an effluent diffuser covers the entire width of the receiving stream at low flow, when mean daily flow of the discharge exceeds the critical low flow of the receiving water, or as demonstrated by a permittee according to a study plan approved by Region VIII and the state. Otherwise, EPA recommends that the permit writer assume incomplete mixing between effluent and receiving water and delineate a mixing zone as a defined spatial area around the outfall.

- **Size of Mixing Zones:** Region VIII requires that states determine the size of mixing zones on a case-by-case basis, with maximum size restrictions specified by regulation. For streams and rivers, the Region recommends that mixing zones not exceed one-half the cross-sectional area or a length 10 times the stream width at critical low flow, whichever is more limiting. For lakes, mixing zones must not exceed 5 percent of the surface area or 200 feet in radius, whichever is more limiting. As noted below, site-specific factors may justify denial of a mixing zone or downsizing from these maxima.

- **Mixing Zone Models and Field Studies:** Region VIII requires that states specify the models or other methods used to develop water-quality-based effluent limitations which meet the mixing zone size restrictions. The Region's recommended approach is to use one of three progressively more sophisticated approaches:

  i. A <u>default</u> method, in which effluent dilution credits are limited to no more than 10 percent of the critical low flow in streams and rivers. For lakes, a default dilution factor of five is recommended (see Equation 1-1). Region VIII acknowledges that the default method, though easy to implement, is very conservative.

ii. A modeling method, in which a simplified dilution model provided by Region VIII is used to calculate effluent plume width along the length of a river. Average and maximum pollutant concentrations within the mixing zone can also be determined using this model. More sophisticated mixing zone models, such as those discussed in Chapter 4 through Chapter 6 of this document, may also be used at the discretion of the states.

iii. A field study method, such as described in Chapter 7, is considered by Region VIII to be the most reliable means of documenting available effluent dilution within the prescribed mixing zone size restrictions.

EPA notes that states will be given flexibility to follow the Region's recommendations or develop their own technically defensible protocols. At a minimum, states must demonstrate that procedures are in place to ensure that water-quality-based effluent limits will achieve the size and shape requirements specified for mixing zones.

- **In-Zone Water Quality:** EPA's minimum requirement is that water quality within mixing zones not result in lethality to migrating fish, drifting organisms moving through a plume, or sessile organisms that may attempt to reside within a mixing zone. To implement this policy, the Region recommends that the CMC be achieved at the end-of-pipe for specific chemical pollutants, without credit for dilution. Region VIII acknowledges that existing Agency guidance (e.g., EPA 1991 and EPA 1994) does allow for acute mixing zones (see Figure 1-1). Thus, the Region will give the states some flexibility on this point. However, for acute toxicity as measured by whole effluent bioassays, the Region will allow no dilution in the receiving water.

- **Critical Low Flow:** The EPA Region VIII policy states that the duration and frequency of the ambient flow values used for dilution and mixing zone calculations should match the duration and frequency provisions found in state water quality criteria. Therefore, the Region recommends that the critical low flows used to develop effluent limits be the "biologically based" 1B3 and 4B3 values to prevent receiving water exceedances of the CMC and CCC, respectively. On this point, the Region VIII policy is inconsistent with and somewhat less flexible than other EPA regulations and guidance, notably 40 CFR 131.36(c)(2), EPA (1991), EPA (1994), and the GLI implementing regulations at 40 CFR 132. For compliance with health-based water quality criteria, Region VIII recommends that the receiving water harmonic mean flow be used for carcinogens and either the 1B3 or 4B3 low flow be used for non-carcinogens. Again, this is inconsistent with the other EPA guidance cited above. Region VIII also notes that its recommendations regarding critical receiving water flows are open to negotiation with the states, and presumably with NPDES permittees as well.

- **Restriction or Denial of Mixing Zones:** The Region VIII policy clearly states that dischargers are not automatically entitled to a dilution allowance or a mixing zone. This is a discretionary action on the part of the permitting agency. Factors listed by Region VIII for limiting or denying a mixing zone include the following:

  i. Existing bioaccumulation problems in fish or sediment.

  ii. Intrusion of a mixing zone into biologically important areas.

  iii. Whole effluents or individual contaminants with a low ratio of acute to chronic toxicity.

  iv. Potential human exposure to an effluent plume via drinking water or contact recreation.

  v. Attraction of aquatic life to the effluent plume.

  vi. Need to maintain zones of passage for migrating fish.

  vii. Existence of multiple or overlapping mixing zones.

  In addition, the Region VIII policy calls for prohibitions on mixing zones for all discharges to wetlands or in situations where the critical low flow in the receiving water is zero.

- **Adjustment of Mixing Zones:** Region VIII requires that states include a specific provision in their regulations which allows the permitting agency to adjust a dilution allowance or a mixing zone for a specific discharge as better information becomes available. At a minimum, NPDES permits issued within the Region are to include language which allows for dilution and mixing zone decisions to be reviewed upon permit expiration and renewal.

2.3 State Mixing Zone Policy and Guidance

States use a variety of methods to incorporate mixing zones and effluent dilution considerations into NPDES permits. This section reviews mixing zone provisions and related guidance for the following 14 states:

- Alaska
- California
- Florida

- Illinois
- Indiana
- Louisiana
- Minnesota
- New Jersey
- Ohio
- Pennsylvania
- Oklahoma
- Texas
- Utah
- Washington

These states were chosen to cover the major petroleum refining centers of the United States as well as to provide a wide geographic distribution and a variety of receiving water environments.

The intent of this section is not to simply recite regulations which are available elsewhere. Rather, the focus is on the practical application of mixing zones in writing NPDES permits in these various states. Information was gathered primarily through telephone interviews with state regulatory agencies. Nonpromulgated "guidance" to state permit writers has been analyzed to the extent the authors could identify and obtain it.

2.3.1. State-Specific Information. States fall into two categories with regard to the overall process of establishing mixing zones. In the first category, a state sets the dimensions of the mixing zone and calculates dilution factors for the discharger. The state-established dilution factors are then used to calculate NPDES permit effluent limits. The permittee is typically not required to submit any data other than discharge quantity and quality. Receiving water data are either gathered by the state or assumed for the dilution factor calculation. In most cases, a discharger not satisfied with the results of the dilution estimate may conduct a more thorough mixing zone study and submit the results to the state for consideration. It is generally recommended to submit a study plan prior to executing work. States that fit this general description include California, Illinois, Indiana, Louisiana, Minnesota, New Jersey, Oklahoma, Pennsylvania, and Utah.

The second category of states require the discharger to submit a mixing zone study which establishes the dilution factor. These states typically describe the spatial extent of the mixing zone in the NPDES permit. The discharger is able to use whatever data exist to establish the appropriate dilution factor. The burden of gathering any additional information required for the study is on the discharger. Through a special review group, the state will consider the study submitted by the discharger and either accept the results or return comments. States included in this category are Alaska, Florida, Ohio, Texas, and Washington.

Table 2-1 presents summary information on each of the 14 states interviewed for this report, including status of NPDES permitting authority and mixing zone regulations. Table 2-2 lists how states specify the size of mixing zones.

2.3.1.1. Alaska. EPA has not delegated Alaska the authority to administer NPDES permits. Instead, Alaska certifies EPA-derived NPDES permits and can attach stipulations which may include mixing zone requirements. EPA reviews the mixing zone established for each discharger. One factor heavily considered is the flushing and mixing of the receiving water.

Presently, all major NPDES permits in Alaska have mixing zones. State law requires that the mixing zones be as small as practicable, meaning that they are not an arbitrary size, as in some states. Instead, they are determined by performing an analysis to find the smallest mixing zone that allows the discharger to meet ambient water quality criteria as long as no historical maximum effluent concentration is exceeded. A risk analysis is required in addition to a mixing zone dilution analysis. This risk analysis evaluates the human and ecological bioaccumulation factors of the discharge and includes a whole effluent toxicity (WET) evaluation. Starting with the undiluted effluent, serial dilutions are tested to find one that meets the state criterion of one toxicity unit. This value is compared to dilution factors required for other individual pollutants for which there are criteria (such as metals and ammonia). Whichever method results in a more stringent dilution factor is applied to the discharge.

Alaska also considers nondegradation of the receiving water if it appears that the discharge might lessen water quality. To do this, Alaska sometimes requires the discharger to sample upstream to develop baseline water quality data, but this is usually done only for new permits. In general, the applicant is directed to use Alaska Administrative Code (AAC) 70.032 as a checklist for the mixing zone report and risk analysis.

Table 2-1. Mixing Zone Regulations of Selected States

State	Status	Regulatory agency	Mixing zone regulations
Alaska	ND[a]	Department of Environmental Conservation	AAC70.032
California	D[b]	Regional Water Quality Control Boards	
Florida	D	Department of Environmental Protection	FL 62-4.244
Illinois	D	Environmental Protection Agency	35 1AC 302.102
Indiana	D	Department of Environmental Management	327 IAC2 1-4
Louisiana	D	Department of Environmental Quality	LA 33.IX CH. 11, 115.C
Minnesota	D	Pollution Control Agency	7050.210
New Jersey	D	Department of Environmental Protection	7:9B, 1,5,C4
Ohio	D	Environmental Protection Agency	OH CH 3745-1-06
Oklahoma	ND	Department of Environmental Quality	785:45-5-26
Pennsylvania	D	Department of Environmental Resources	25 PA 93.5
Texas	ND	Natural Resources	30 TAC
		Conservation Commission	307.3(50)
Utah	D	Department of Health	UT R317-2-5
Washington	D	Department of Ecology	WAC 173-201A

[a]ND = Not delegated to issue NPDES permits.

[b]D = Delegated to issue NPDES permits.

Table 2-2. Spatial Definitions of Mixing Zones in Selected States

State	Rivers			Lakes	Tidal water bodies	Minimized dimensions?	Other
	Length	Width	Flow	Radius	Radius	(Yes/No)	Time
Alaska	Point of complete mix			<10% surface area	<10% surface area	Yes	
California							
Florida	<800 meters	<3/4 width					
Illinois			<1/4 flow				
Indiana		<1/2 width	<1/2 flow	Prohibited			
Louisiana				<100 feet			
Minnesota		<1/2 width	<1/4 flow	Prohibited		Yes	
New Jersey		<1/4 width		Prohibited	100 meters		
Ohio	<5 times width	<1/2 width (1/5 at mouth)		Prohibited (except Lake Erie)			
Oklahoma	<13 times width		<1/4 flow				
Pennsylvania	None			Prohibited			15 minutes[1] 12 hours[2]
Texas	<300 feet d.s. <100 feet u.s.			<100 feet	<200 feet		
Utah	None			20-50 feet acute 200 feet chronic		Yes	
Washington	<300 ft + depth (d.s.) <100 ft (u.s.)	<1/4 width	<1/4 flow	Prohibited	<300 ft + depth (d.s.) <100 ft (u.s.)		

[1]Acute time.
[2]Chronic time.
u.s. = upstream.
d.s. = downstream.

The Major Facilities and Water Permits Group within the Department of Environmental Conservation reviews the mixing zone studies. Typically, the review is done by a team. Each person reviews the document according to his or her specialty. Sometimes an outside third party will review controversial risk analyses.

The required review time depends on the complexity of the situation and the size of the discharge. In general, 1 month is required for simple conditions and up to several years for a complicated, large discharge. For example, a large wood processing plant has had a mixing zone study pending for several years due to perceived environmental impacts.

The state has no existing policies for either the mixing zone studies or risk analyses. Significant discretion is left to the permit writer, whose main sources of guidance are (in order of precedence) AAC provisions on mixing zones, the TSD (EPA 1991), and the Handbook (EPA 1994). According to state staff, the current lack of a mixing zone policy is a major point of contention. Many dischargers are requesting a policy and more strict guidance for the permit writers. Such a policy is planned, but it is currently on hold with no ultimate deadline.

Reviewers will generally accept any mixing zone model that is widely used, including the EPA-supported CORMIX and PLUMES models discussed in Chapter 4. Under some complicated circumstances, field testing is required to calibrate the model. Detail required in the mixing zone submittal is a function of site-specific complexity. Other conditions affecting the detail in the mixing zone submittal include whether the receiving water is fresh or marine. Not much receiving water data are available from the state. Any established monitoring stations are probably the result of an existing discharge permit.

Sediments and benthic organisms are considered in NPDES permitting by requiring a risk analysis which addresses bioaccumulation. In some cases, this may be the controlling parameter for a mixing zone allowance. Not all permits require a risk analysis, but it is being more frequently required, especially if there is any likelihood of sediment impacts.

Mixing zones are not automatically given to dischargers in Alaska. AAC 70.032 states, "The burden of proof for justifying a mixing zone through demonstrating compliance with the requirements . . . rests with the applicant."

2.3.1.2. California. California has been delegated authority by EPA to administer the NPDES permit program. Permits are issued and enforced by nine Regional Water Quality Control Boards (RWQCBs), each of which reports to the State Water Resources Control Board (SWRCB).

Statewide, California only allows mixing zones and dilution factors for ocean discharges. The SWRCB's Inland Surface Water Plan and Enclosed Bays and Estuaries Plan would have provided consistent policies and procedures for mixing zones and dilution factors for other surface waters of the state. However, both plans were voided by the courts in 1993. Revisions to these rescinded documents are not anticipated for several years. In the interim, water-quality-based effluent limits for dischargers to inland waters, enclosed bays, and estuaries are determined regionally using whatever dilution factors may be provided in the nine separate Basin Plans adopted by the various RWQCBs.

For example, the Basin Plan for San Francisco Bay (San Francisco RWQCB 1995) allows permittees with discharges to deep water an arbitrary 10:1 dilution factor for both acute and chronic water-quality-based effluent limits. Background water quality is also taken into consideration and may limit the dilution credit. As a general rule, shallow water discharges must meet water quality criteria in the effluent pipe.

For ocean discharges, the California Ocean Plan (SWRCB 1990) allows the RWQCBs to allow dilution credits based on models identified and approved by SWRCB staff. In practice, the request to calculate a dilution factor usually comes from an RWQCB at the time of NPDES permit renewal. Dilution estimates are made by SWRCB staff using the PLUMES model and input data provided by the permittee. The selected dilution factor will correspond to the lowest average near field dilution within any single month of the year. Therefore, the mixing zone is bounded by the point at which the plume either surfaces or far field processes dominate mixing. Dilution provided by the ambient ocean currents cannot be considered in sizing a mixing zone.

Ocean dischargers are required to characterize the outfall and the area of the mixing zone in order to provide input to PLUMES. This involves surveying the discharge location to determine its depth with respect to the mean lower low water tidal elevation and sampling the receiving water at several depths to determine its density profile. There is no guidance in the Ocean Plan for performing this receiving water survey. Procedures are usually prescribed by letter from the

SWRCB. Other information required of the discharger includes average and peak wastewater flow rates. Background water quality data are usually not requested from the discharger; instead, typical background concentrations provided in the Ocean Plan are used.

Once the dilution factor is finalized, it is used to calculate revised NPDES permit limits. The discharger may submit an independent estimate of available dilution for consideration by the RWQCB, but the state will generally rely on its own modeling analysis. The dilution factor used in the permit may be further reduced from the PLUMES model output after consideration of background water quality.

2.3.1.3. Florida. The Florida Department of Environmental Protection (DEP) is delegated NPDES permitting authority and has the responsibility of establishing all mixing zones. This delegation is recent (May 1995), and the division of duties between DEP headquarters in Tallahassee and the district offices is still being worked out. In the past, the district offices had considerable autonomy in administering and writing state discharge permits. A condition of the NPDES permitting delegation was that DEP regulations be applied uniformly. To that end, a new DEP permit writer's manual is being developed. This manual will contain recommended procedures to establish mixing zone conditions. The following discussion summarizes historical mixing zone practices in Florida.

Mixing zone requests are evaluated based on the ability of the applicant to provide DEP with reasonable assurance that conditions outlined in Rule 62-4.244 are met. The rule is supplemented with written policies to establish flow conditions for determination of available dilution. For new discharges, the state usually negotiates a technology-based permit through the first round or until the effluent is better characterized. A water-quality-based permit can be negotiated after discharge data have been collected. Most dischargers in Florida now have water-quality-based permits.

Typically, only dischargers greater than 1 million gallons per day (mgd) are required to perform mixing zone studies. First, the discharger must prepare a study plan and submit it to DEP for review. The applicant will be required to collect the data for the study. Upon request of the applicant, DEP will provide examples of previous mixing zone studies that are comparable to the situation under consideration. Generally, the applicant and DEP meet to discuss data requirements. Under certain conditions defined by the rule, DEP may conduct the data collection and mixing zone evaluation for small domestic waste discharges.

Within DEP, the Division of Water Facilities is responsible for review of mixing zone studies. In most cases, this review is accomplished as a group effort involving the permit writer in the district office and staff in the Point Source Evaluation Section located in Tallahassee. Individuals conducting the review are selected based on the particular issues under consideration and can be expanded to include staff outside those identified above. Such additional staff might include biologists, chemists, quality control and quality assurance experts, or other engineering support as needed.

Review times for mixing zone studies vary. Simple desktop calculations could be acceptable if the applicant can demonstrate compliance with DEP rules. Under such conditions, the review could be completed by the permit writer within hours. In more complex situations involving multiple parameters, dischargers, or complex hydrodynamic conditions, DEP could require that a formal plan of study be developed and implemented using more sophisticated computer modeling techniques. Such complex studies could take months to review.

DEP accepts a variety of mixing zone models. The model selected for a particular case is controlled by site-specific issues and complexity. For instance, if a multi-dimensional model is being used to establish water-quality-based effluent limits, it might also be used for determining near field dilution characteristics for any mixing zones requested. Models typically used include CORMIX and PLUMES. Proprietary models, even if based on other approved models, require peer review and documentation prior to state acceptance. Florida prefers to see a model recommendation in the mixing zone study plan submittal.

Receiving water characteristics play an important role in determining the degree of information required to establish mixing zones. If circumstances warrant, DEP can require the applicant to provide reasonable assurances that the discharge is not affecting benthic organisms, sediments, or otherwise contributing to violations of state surface water quality criteria. For all industrial and most domestic waste dischargers, the burden of providing reasonable assurance is on the applicant. This evidence is based on existing data, data collected by the discharger, or state-approved assumptions regarding pollutant fate and transport.

For water quality surveys, the state always requires dissolved oxygen and metals data. Data for other contaminants such as organics are required if the effluent from an upstream discharger contains such contaminants. All of Florida's ambient water quality monitoring data are available through STORET. The applicant may also request copies of all compliance monitoring data.

The initial flow used for dilution modeling in streams and rivers is 7Q10. If the receiving stream has no data, the state will accept any method to estimate 7Q10 that is endorsed by the United States Geological Survey (USGS). For tidally influenced bodies, the discharger must collect 2 weeks of velocity data over a neap tide cycle. The lowest 10th percentile velocity is used in the dilution model. For lakes, an estimate on residence time is used to calculate a velocity.

DEP has established by rule and policy the use of worst case flow conditions for calculating dilution in receiving waters (such as 7Q10 or the harmonic mean flow for steady state streams). Other coefficients used in mixing zone modeling are those provided in EPA guidance documents or derived from the "best fit" during calibration and verification of the model against actual field conditions.

2.3.1.4. Illinois. In Illinois, a discharger submits a mixing zone report only if a reasonable potential analysis, as described by EPA (1991), determines that some effluent dilution is necessary because toxic contaminants present in the discharge have the potential for violating water quality criteria. If the results of the analysis indicate that a mixing zone is required, the Illinois Environmental Protection Agency (IEPA) estimates baseline dilution, usually assuming a 3:1 dilution ratio. If the discharge does not achieve sufficient dilution according to this calculation, the discharger is required to submit a mixing zone report. Of the 200 or so mixing zones in Illinois, only about ten mixing zone reports have been required.

The results of the reasonable potential analysis are also used to determine the maximum size of the mixing zone. The applicant can use site-specific data instead of the standard assumptions provided by EPA (1991). Although state regulations allow a maximum mixing zone in terms of percent of the receiving water area and flow, dischargers are only allowed a mixing zone of sufficient size to achieve water quality criteria at the mixing zone boundary.

Another potential requirement while negotiating a water-quality-based permit in Illinois is a chlorine dissipation study to determine more accurately the actual dilution of chlorine at the mixing zone boundary. Such a study would appear to help the discharger, but it also allows the state to make the mixing zone smaller based on field data. A chlorination study is only required if the downstream receiving water is swimmable, for example, the Mississippi River or Lake Michigan.

The IEPA Water Pollution Control Division (Planning Standards Section) reviews proposed mixing zones and makes recommendations to permit writers. Two internal IEPA guidance documents (IEPA 1991 and IEPA 1993) are available to help permit writers on the subject of mixing zones. Illinois staff are only now beginning to become acquainted with more complex mixing zone models such as CORMIX and PLUMES.

Illinois permitting staff take about 2 weeks to determine whether a mixing zone is needed. Review of a mixing zone study takes about 2 months. Illinois typically requires field work to determine model input such as water body cross-section and stream velocities. Rarely are dye studies required. For dischargers planning a mixing zone study, it is recommended to first submit a study plan for IEPA review.

2.3.1.5. Indiana. The future of the NPDES permitting process in Indiana with respect to mixing zones is presently undefined due to the GLI. Current Indiana regulations allow mixing zones but do not describe them in detail. Although Indiana is an NPDES-delegated state, EPA Region V reviews permits for major industrial and municipal dischargers.

Indiana Department of Environmental Management staff estimate dilution for the discharger. No guidance document exists at this time, but one will be developed after GLI implementing regulations are adopted. Dilution estimates are made with a complete mix, mass balance approach using 50 percent of the 7Q10. CORMIX is used to simulate high-rate diffusers. No dye studies have been performed. A zone of initial dilution is allowed if the acute aquatic life protection value is not exceeded. If the discharge does not appear to meet mixing requirements for water quality criteria with the existing outfall, the state will attempt to size and recommend a new diffuser configuration.

Indiana presently provides data for dilution estimates. Upstream conditions are taken into account and most receiving streams have some data available. Indiana may begin to have dischargers sample upstream when there is a known problem meeting water quality criteria for metals.

2.3.1.6. Louisiana. Louisiana was recently (August 1996) delegated authority to issue NPDES permits. The Louisiana Department of Environmental Quality (LDEQ) administers all NPDES permits in the state. The permit writer estimates dilution assuming complete mixing between the effluent and the receiving stream. Any further modeling of special conditions, such as for static water bodies, is done in a LDEQ modeling group. Mixing zone studies submitted by dischargers are reviewed by this special modeling group.

In Louisiana, all dischargers begin with a technology-based permit. When a water-quality-based permit is in development, the state will compare effluent characteristics to water quality criteria. This process follows the Louisiana Implementation Plan (LDEQ 1995). The initial estimate is based on a complete-mix dilution calculation using a percentage of the 7Q10, which can range from 3.3 percent to 100 percent depending on the receiving water conditions and whether acute or chronic conditions are being analyzed. After calculating dilution, the resulting ambient concentration is compared to water quality criteria following the guidelines of the Implementation Plan.

Typically, water quality criteria are applied at the end of pipe in stagnant receiving waters (i.e., zero dilution). Due to the topographical relief in Louisiana, there are many stagnant water bodies, and these situations arise often in permits.

A discharger may elect to use a model to better define available dilution. Louisiana only allows the jet momentum equation (see Section 4.2.1 and EPA 1991) and CORMIX for dilution calculations in stagnant water bodies. The jet momentum equation can only be used in a stagnant body if the discharge centerline velocity is greater than 0.5 ft/s, the jet diameter is less than the receiving water depth, the discharge is neither strongly positively nor negatively buoyant, and there is no boundary interaction.

2.3.1.7. Minnesota. Minnesota performs a preliminary dilution estimate using a complete mix approach. Regulations require using 25 percent of the 7Q10. State staff perform a reasonable potential analysis (per EPA 1991) using the maximum measured effluent concentration and calculate a maximum ambient concentration with the dilution estimate. A discharger is allowed to perform its own mixing zone study if not satisfied with the state's preliminary results.

Critical conditions considered when estimating dilution include 7Q10 river flow and peak wet weather flow for discharge. Minnesota Pollution Control Agency (PCA) staff recognize the contradiction in using a drought condition river flow with a rainfall-induced treatment plant discharge. Minnesota may adopt the average dry weather discharge design flow in the future to eliminate this contradiction. Plant discharge is probably the most easily negotiable item input to the dilution estimate. Stream flow, 7Q10, is set by USGS estimates. Unlike many states, Minnesota uses 100 percent of the 7Q10 instead of the harmonic mean flow for evaluating dilution with respect to human health criteria. The harmonic mean flow may be used to evaluate compliance with human health criteria in the future.

The PCA Standards Unit reviews mixing zones. The time needed to estimate dilution is typically very short. Gathering background information takes the most time. Typically, the state gathers the data used for the dilution estimate. Minnesota has some STORET stations and any additional data are gathered by the state. Field studies to estimate dilution are done in some situations. In the future, they will be done more often to investigate potential bioaccumulation problems.

Mixing zones are not allowed in lakes. For intermittent streams, water quality criteria must be met at the discharge without dilution credits.

2.3.1.8. New Jersey. New Jersey recently (February 1997) implemented new water quality standards regulations. The prior regulations had very little information on mixing zones. Despite internal guidance documents, permit writers used inconsistent procedures to establish mixing zones, resulting in numerous challenges to NPDES permit limits. New Jersey has now adopted EPA (1991) guidance for evaluating mixing zones. The new water quality standards regulations are quite detailed and will serve as the guidance for writing future NPDES permits. A new guidance manual is in development which will supplement the revised regulations.

A different process is followed in the development of mixing zones for existing and new dischargers. Some treatment plant expansions may be viewed as new discharges if significant flow increases result.

Existing dischargers going from a technology-based to a water-quality-based NPDES permit may elect to take default values for acute (10:1) and chronic (20:1) dilution factors. Alternatively, the discharger may perform a complete-mix dilution estimate using 1Q10 for acute and 7Q10 for chronic critical design flows. Typically, a 1-month review time is required for a complete mix dilution estimate. If these results are also not acceptable, the discharger can perform an aquatic organism exposure study. None of these has been done yet, and the Department of Environmental Protection (DEP) is not sure what the requirements will be for these studies.

New dischargers will be required to do instream studies for background water quality and flow (if necessary). Simple calculations (detailed in the new regulations) will be used to develop water-quality-based limits. In lieu of calculations, a mixing zone study can be done to show better dilution.

New Jersey has settled on CORMIX for estimating dilution in complex situations. There is some PLUMES modeling done, but it has the perception of being outdated.

Regulations allow DEP to reduce dilution when mixing zones overlap. Presently, New Jersey is just reviewing one discharger at a time. As the new water quality standards regulations are implemented, it will be more appropriate to look at overlapping zones. At that time, dye studies may become necessary.

Mixing zone studies are not submitted very often, but are expected to increase with the new regulations. For tidally influenced and ocean discharges, the mixing zone size is limited to a 100-meter radius for aquatic life criteria and 200-meter radius for human health criteria. Average tide conditions are used for chronic discharge dilution estimates and neap conditions are used for acute. River mixing zones are limited to 25 percent of the stream width. Estuaries are reviewed to see if it is more appropriate to analyze them as a river or tidal water body.

The burden of supplying data for the dilution estimate is placed on the dischargers. However, DEP will accept published values from previous studies. DEP uses EPA (1991) guidance in determining data requirements. Dischargers collecting data for the mixing zone study need to submit a monitoring plan which is reviewed by DEP. Some data are available from the state, but mostly for larger water bodies. The new water quality standards regulations have details on how this monitoring plan should be structured.

2.3.1.9. Ohio. Ohio Environmental Protection Agency (OEPA) review of mixing zones is done by the Water Quality Unit of the Monitoring and Assessment Section in the Division of Surface Water. Mixing zone studies are either requested by OEPA in a revised permit or initiated by the discharger if initial estimates of dilution are not favorable.

Study review takes several months. Mixing zone studies are rarely accepted after the first submittal. Typically, OEPA has comments on the report and requests more analysis or data. Available agency guidance consists of an internal procedures manual, a draft field/dye study guidance policy, and state water quality standards regulations. Recent legislation requires that more specifics be supplied through regulation than presently exist in policy. These changes and revisions to the policy and guidelines will not be performed until Ohio determines what is necessary to implement the GLI.

There are two mixing zones available to a discharger in Ohio corresponding to the two-number aquatic life water quality criteria. The mixing zone boundary marks the point at which acute and chronic water quality criteria, also known as outside mixing zone maximum (OMZM) criteria, must be met. The area of initial mixing (AIM) is an additional mixing zone allowed if the discharger does not wish to comply with inside mixing zone maximum (IMZM) criteria at end of pipe. The IMZM concentration is equal to two times the acute water quality criterion. OEPA will only grant an AIM if the discharge exhibits turbulent diffusion after exiting the outfall. The criteria for this determination are from EPA (1991) and usually the mechanism for achieving such a discharge is a high-energy diffuser.

Methods of determining the mixing zone and AIM sizes are different. The size of the AIM is determined on a case-by-case basis but generally is defined at the transition point from near field to far field mixing processes (see Section 4.1.1), which is typically determined by computer modeling. The mixing zone size is determined with the criteria listed in the Ohio Administrative Code, Chapter 3745-1-06.

The method for calculating mixing zone acute and chronic dilution factors is also different from that used to calculate the AIM dilution factor. The mixing zone dilution factors are calculated using a complete mix, mass balance approach. Receiving water flows used are percentages of 7Q10 for acute criteria and 30Q10 for chronic criteria. Hydrodynamic computer models, such as CORMIX and PLUMES, are used to estimate dilution at the edge of the AIM. The human health criteria dilution factor is calculated by a complete-mix, mass balance approach using the harmonic mean flow. If the discharge is to the Ohio River, a special set of criteria is used due to the influence of dams on river flow. The IMZM concentration is applied at end of pipe, acute dilution is calculated using 1 percent of 7Q10, and chronic dilution is calculated 10 percent of 7Q10. For all of the above dilution calculations, either the mean discharge flow is used (based on historical data) or another flow is specified by the permit writer to represent future average flow conditions.

Field studies are rare in Ohio and, when done, OEPA requires subsequent modeling to simulate critical discharge conditions. A draft procedure for performing field dye studies is available from OEPA. Only one Ohio discharger has reportedly attempted to determine chronic dilution with a dye study.

OEPA will make available any previously recorded data for input to a mixing zone study. Additional data must be collected by the discharger. If no site-specific background water quality data are available, OEPA has a stream statistics report that provides standard background data categorized by basin and upstream land use characteristics. The discharger should submit a study plan prior to beginning the mixing zone study. For river discharges, a common requirement is to sample stream velocity and survey the cross section to determine the appropriate dimensions at critical flow conditions.

2.3.1.10. Oklahoma. Responsibility for water quality issues in Oklahoma is split between two agencies. The Water Resources Board develops water quality criteria and writes guidance documents. The Department of Environmental Quality (DEQ) writes discharge permits, which are issued jointly by DEQ and EPA. Oklahoma has not been delegated NPDES permitting authority.

DEQ performs the dilution estimates used to evaluate permit limits. Mixing zone studies are not performed. A set of equations developed by the Water Resources Board is used to calculate dilution. A guidance document is also available for permit writers estimating dilution.

Input data for calculating dilution estimates are typically the responsibility of the state. Water quality data are required for the calculations, but are usually provided in the permit. Few data are available from the state as Oklahoma has no established sampling stations. A small number of USGS flow stations exist. Another possible source of instream data is an upstream discharger.

2.3.1.11. Pennsylvania. The Pennsylvania Department of Environmental Resources (PDER) determines dilution for a discharger using the jet momentum equation (EPA 1991). The field office permitting section makes the initial estimate of the mixing zone and the dilution factor. A PDER headquarters office group answers questions for the field offices. The discharger can submit a separate mixing study if not satisfied with PDER's results. Review time for independent submittals depends on the completeness of the report and how much it departs from the state's findings.

Pennsylvania staff prefer the jet momentum equation to estimate dilution but will accept CORMIX, although they believe it is generally less conservative. PDER is experimenting with the tidal version of CORMIX in analyzing discharges to the Delaware River.

Unlike most states, Pennsylvania uses the criteria compliance travel time procedure rather than distance or flow to describe the mixing zone. The travel time mixing zone concept is described by EPA (1991). For acute criteria compliance, 15 minutes of travel time at 7Q10 design flow conditions dictates the mixing zone. The chronic boundary is set for 12 hours of travel time at 7Q10. For human health criteria, 12 hours of travel time is used with the harmonic mean flow for carcinogenic compounds or with 7Q10 for noncarcinogens.

The actual flow available for mixing is the 7Q10 times a partial mixing factor. The partial mix factor is calculated as:

$$(\text{Maximum criteria compliance time} \div \text{Time to complete mix})^{1/2}$$

The instream concentration must meet the water quality criteria at the point of complete mix or by the criteria compliance time, whichever is less.

Pennsylvania believes that dye studies must be repeated several times to obtain conclusive results. The study must be able to relate dilution obtained under field conditions to the actual design condition used for discharge permitting, i.e., 7Q10.

2.3.1.12. Texas. Texas has not been delegated NPDES permitting authority. EPA reviews the Texas mixing zone implementation plan and issues NPDES permits. However, decisions on mixing zones in specific permits are made by the Texas Natural Resources Conservation Commission (TNRCC). Publication RG-194 (TNRCC 1995) is the main source of policy and guidance for the review of mixing zone studies.

The discharger submits the mixing zone study following TNRCC guidelines. Texas will only allow CORMIX applications in rivers and narrow tidal rivers. There is no preference shown toward dye studies over desktop modeling studies, except with discharges less than 10 mgd. The state requires a field study plan be submitted for review prior to beginning the work.

The parameters for the study are rigidly defined by TNRCC. For streams and rivers, 7-day average low flow with a return frequency of 2 years (7Q2) is used for stream flow if it is greater than 0.1 cubic feet per second (cfs). For lakes, the mixing zone is held to a 100-foot radius. For bays and estuaries greater than 400 feet wide, the mixing zone is in a 200-foot radius from the discharge. The jet momentum equation (EPA 1991) is used to estimate dilution for discharges greater than 10 mgd, and for smaller discharges dilution is assumed to be 8 percent. For narrow tidal rivers less than 400 feet wide, the mixing zone is half the width or 100 feet if little data are available on the river. The minimum assumed dilution for this condition is 8 percent. For human health criteria analysis, the harmonic mean flow is used for rivers, lakes have a 200-foot radius mixing zone with 8 percent minimum dilution, and tidal rivers have a 400-foot radius mixing zone with 4 percent minimum dilution. For all the above cases, the zone of initial dilution for compliance with acute aquatic life criteria can be no more than 25 percent of the total mixing zone.

Texas provides default data for input to the mixing zone study. The permittee is also allowed to submit site-specific data. Background contaminant concentrations are not taken into consideration unless there is a known problem. Under these circumstances, data are gathered jointly by TNRCC and EPA. If 7Q2 has not been calculated for the receiving stream, several years of flow data are required to develop it.

2.3.1.13. Utah. Utah has NPDES permitting authority and the Department of Health estimates dilution for the discharger. No dischargers have ever submitted a mixing zone modeling study in this state. There exist no guidelines for dilution estimation in Utah. However, the discharger is allowed to comment on how these estimates are made by the state. Reportedly, only one dye study has ever been performed for the purpose of estimating dilution.

If there is no overlapping mixing zone, effluent dilution is estimated by assuming complete mixing with the receiving stream. The entire 7Q10 is used for chronic dilution, and 10 percent of the 7Q10 is used for acute. If there are multiple discharges to the stream, Utah uses an EPA

Region VIII spreadsheet model which performs a mass balance for each stream segment. For lake discharges, the mixing zone is defined with a 200-foot radius for chronic and a 20-foot radius for acute water quality criteria compliance. The acute boundary distance is negotiable with the state.

The burden of supplying data for dilution estimates is on the state. Typical data requirements are background water quality and flow or a USGS-developed 7Q10. Effluent concentration data are also important, as any constituents with historical concentrations greater than the water quality criteria are automatically included in the permit for monitoring purposes.

2.3.1.14. Washington. In Washington, the state may make an initial estimate of dilution at the acute and chronic mixing zone boundaries. However, the Washington Department of Ecology (WDOE) typically requires the discharger to submit a mixing zone study demonstrating the dilution at these locations. The EPA PLUMES model is preferred unless the discharge is to a stream with known boundary interaction (either shoreline, surface, or bottom). Review of the mixing zone report can take several months with WDOE submitting comments back to the discharger. The review is done at WDOE headquarters in the Environmental Investigations and Laboratory Section.

For purposes of effluent dilution estimation, receiving waters are reviewed as either fresh, estuarine, or ocean waters. Typically, more detail is required in the mixing zone study if the discharge is to estuarine or ocean waters. If the fresh water body supports anadromous fish, such as salmon, additional constraints are placed on the calculation of effluent limits for ammonia.

Dye studies may be performed instead of desktop modeling studies and, in some cases, are preferred. WDOE is preparing guidance on whether to do a slug or continuous test depending on the discharge conditions. Before performing a dye study, the discharger is encouraged to submit a study plan to WDOE for review.

The burden of supplying data for the dilution estimate is typically on the discharger. Such data include effluent concentration and flow, background water quality, ambient density, and ambient current magnitude and direction. The 7Q10 design flow is used for modeling river discharges. For tidally influenced water bodies, the state requires the discharger to determine a velocity frequency distribution. Acute dilution is evaluated with the 10 percent low velocity, and chronic dilution is measured with the 50 percent velocity. The state may also require the discharger to test the 90 percent velocity to determine if it is the critical condition for acute dilution. Density measurements in the discharge are typically required for summer time, when ambient density stratification is strongest.

The WDOE Permit Writer's Manual (WDOE 1994) provides detailed directions on how to structure the mixing zone report. A recent EPA review may result in changes to WDOE's mixing zone policy and manual and could result in more specific requirements on the amount of data required for developing velocity statistics for estuarine and ocean discharges. Instead of conducting field velocity measurements, the discharger could elect to do a velocity sensitivity analysis with the PLUMES model to determine critical conditions.

2.4 Emerging Issues

Each interviewed state was asked to identify emerging issues that would shape how mixing zones are used to regulate wastewater discharges in the future. In addition to aquatic life and human health water quality criteria, some states will consider bioaccumulation, sediment criteria, and wildlife criteria. For some discharges, these new criteria may change the dilution factor which controls permit requirements or diffuser design. Bioaccumulation criteria may require risk assessments of the discharge which would rely on results of the mixing zone study.

Many states have regulations that discuss overlapping mixing zones. Most prohibit such overlap, resulting in a comprehensive mixing zone for all dischargers within a given area. At issue is how to model and allocate dilution to each discharger in these situations. More sophisticated states recognize that the allocation cannot be done simply based on flow apportionment. However, most states have not settled on a policy for handling overlapping mixing zones.

CHAPTER 3

MIXING ZONE PHYSICS AND OUTFALL DIFFUSER DESIGN

This chapter presents an introduction to mixing zone physics, the elements of diffuser design, and outfall design criteria. Several key points are identified. The degree of effluent mixing achieved in practice is a function of many parameters related to ambient conditions, the discharge itself, and the outfall configuration. Hence, understanding the physics of mixing is important to properly design a diffuser system. Finally, appropriate construction materials and techniques are the key to a successful diffuser installation.

3.1 Mixing Zone Physics

The physics of effluent mixing and dilution involve the principles of conservation of mass, momentum, and energy. Several key questions can be asked to determine how the discharge will interact with the receiving water:

- What is the effluent discharge rate compared to the receiving water flow? (conservation of mass)
- What is the velocity of the effluent discharge compared to that of the receiving water? (conservation of momentum)
- What angle (if any) exists between the discharge direction and the receiving water flow? (conservation of momentum)
- What is the density difference between the discharge and the receiving water? (conservation of energy)

The respective mass, momentum, and energy of both the discharge and the receiving water determine how the effluent will mix. Changes in either effluent or receiving waters can result in drastically different mixing conditions. The following section explains some of these different discharge circumstances.

3.1.1. Jets and Plumes. The energy and momentum of the discharge determine whether it behaves as a jet or a plume. In essence, discharges behaving as jets overpower receiving water velocity and any buoyancy differences between the two fluids. As the jet leaves its discharge conduit, its cross sectional area does not change through the Zone of Flow

Establishment (ZFE) as shown on Figure 3-1. The velocity and effluent flow concentration are nearly uniform across the cross section in the ZFE. As the high-energy jet entrains the receiving fluid, dilution occurs, and the jet cross-sectional area begins to "grow." At this point, the effluent velocity and concentration are normally described with a Gaussian (or bell-shaped) distribution.

In contrast, plumes are dominated by buoyancy and receiving water current forces. Plumes can also experience high rates of dilution depending on the turbulence caused by velocity differences between the effluent and the receiving water. Figure 3-1 illustrates the difference between jets and plumes.

All jets eventually evolve into plumes. However, some plumes do not start as jets. The mathematical criterion typically used to define a discharge as either "jet-like" or "plume-like" is calculated from the following expression (Fischer *et al.* 1979):

$$\Psi = \left[\frac{b_2\,(g\,Q)^{2/3}\;Z^{4/3}}{A\;u_o^2}\right]\left[\frac{\rho_a\;-\;\rho_o}{\rho_o}\right]^{2/3} \tag{3-1}$$

where:

Ψ	=	dimensionless distance along discharge axis
b_2	=	dimensionless experimental coefficient = 0.35
g	=	gravitational constant [LT^{-2}]
ρ_o	=	discharge density [ML^{-3}]
ρ_a	=	ambient density [ML^{-3}]
Q	=	discharge rate [L^3T^{-1}]
Z	=	distance along discharge trajectory [L]
A	=	area of discharge cross-section [L^2]
u_o	=	discharge initial velocity [LT]

A value of Ψ much less than 1 indicates "jet-like" behavior, and a value much greater than one indicates "plume-like" behavior. A value near 1 indicates a transitional flow that exhibits properties of both classifications. Figure 3-2 illustrates the transition of jets to plumes and the behavior of both discharge types under different ambient conditions.

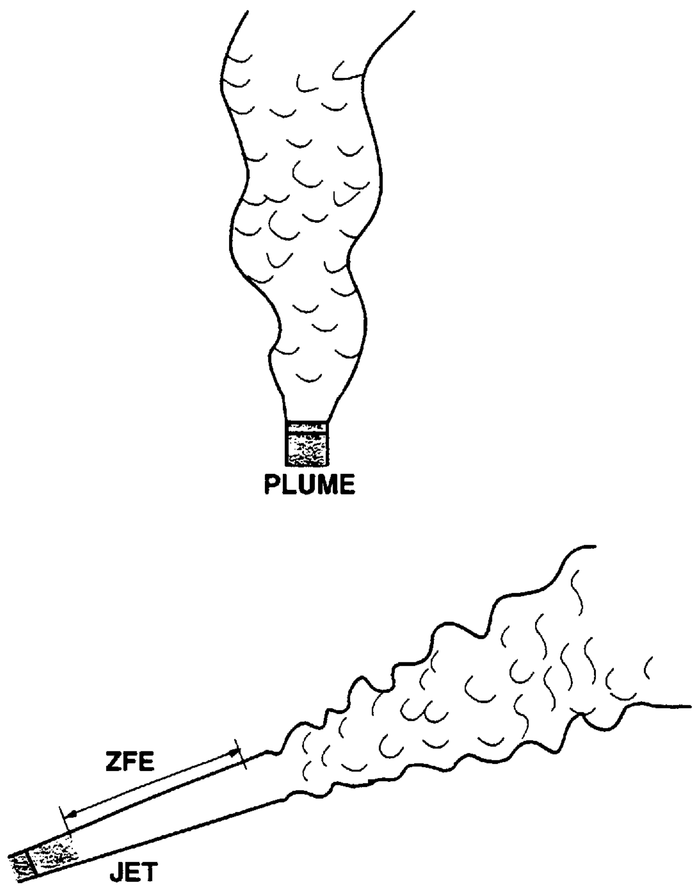


Figure 3-1. Illustrations of Plumes and Jets

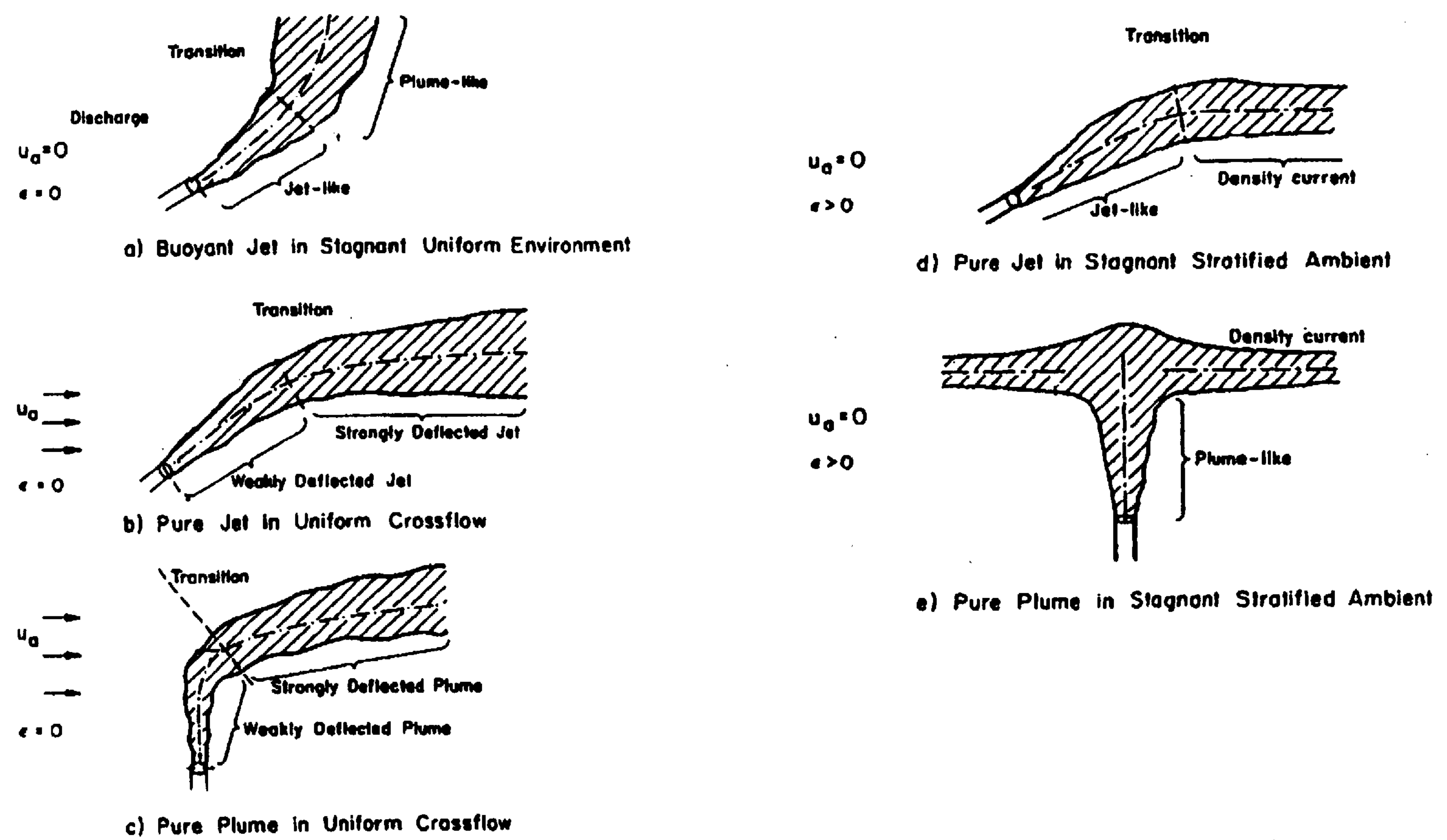


Figure 3-2. Examples of Effects of Ambient Conditions on Discharge

3.1.2. Near Field and Far Field Mixing Processes. Traditionally, the mixing of effluents and receiving waters is analyzed in terms of "near field" and "far field" processes. These are discussed in more detail in Section 4.1.1. In the near field region, factors such as discharge velocity and buoyancy dominate effluent mixing. Once the discharge reaches a point of neutral buoyancy, either trapping below the surface or impacting the surface or bottom, mixing is controlled by ambient current and direction as well as local turbulence. This condition marks the beginning of the far field region, and effluent dilution to this point is called "initial dilution." An additional phenomenon known as buoyant spreading, or density current effect, occurs at the onset of the far field as the lighter effluent plume attempts to spread itself out in a layer of neutral buoyancy while entraining the heavier, ambient fluid. Figure 3-3 shows the demarcation between near field and far field regions for a buoyant discharge.

3.1.3. Discharge Buoyancy and Ambient Stratification. The buoyancy of a discharge is caused by the difference in effluent and ambient densities. This density difference is mainly due to dissolved solids, such as salt in saltwater, or suspended solids, such as sediment in fresh water.

Buoyancy is one of the major forces mixing an effluent with the receiving water. A fluid discharged into another fluid of dissimilar density will rise or sink until becoming neutrally buoyant. Positively buoyant discharges will rise regardless of discharge hydraulics until reaching the surface or entraining sufficient ambient water to equal the density of the receiving body. Negatively buoyant discharges sink and attach to the bottom. Such conditions are caused by discharging heavy brine solutions or by discharging to cold waters at or near freezing. This latter case is due to the properties of water as it freezes. Fresh water has its maximum density at approximately 4 degrees Celsius (°C). Warm effluent discharged to ambient water colder than 4°C will mix and attach to the bottom unless turbulent hydraulics cause complete mixing.

Ambient density can be described in one of three general stratification categories. The density stratification profile (a plot of density versus depth) can be uniform, constant gradient, or uniform with a sharp density increase at a specific depth. The last condition is known as a pycnocline (or thermocline), which can be caused by temperature effects, subsurface currents, or tidal effects in estuaries known as salt wedges.

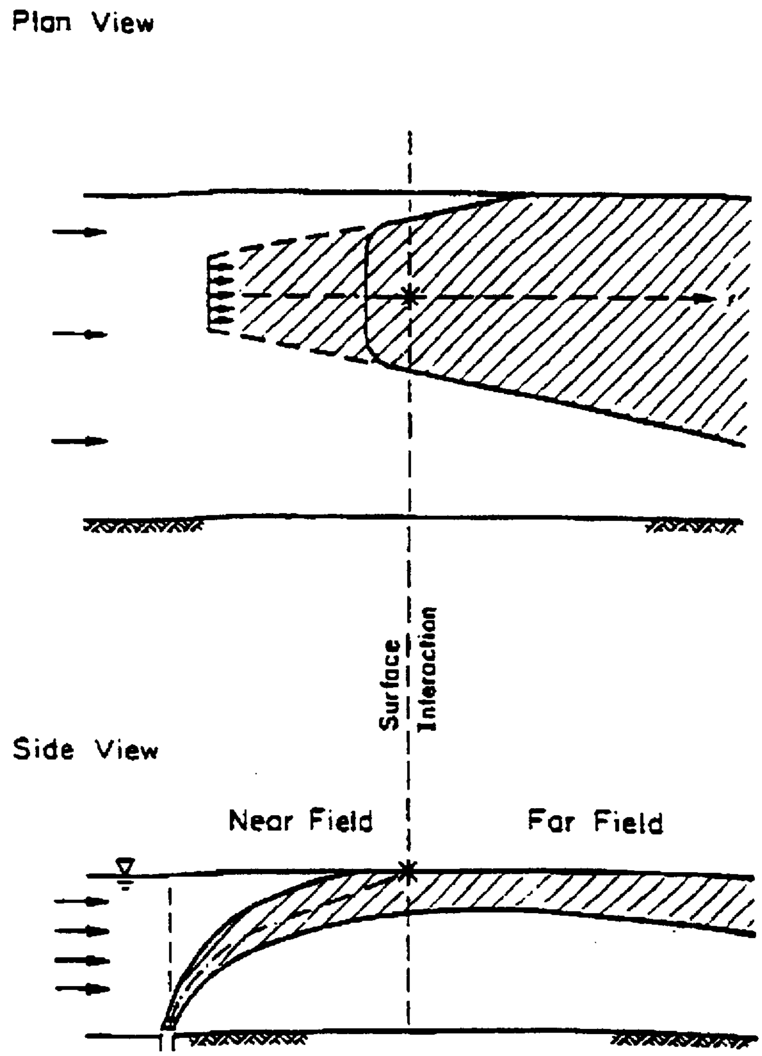


Figure 3-3. Illustration of Transition from Near to Far Field for Buoyant Discharges

3.1.4. Lateral and Vertical Mixing. The mixing of effluent with a receiving water occurs in both the lateral and vertical directions away from the point of discharge. In shallow free flowing rivers, turbulence along the channel bottom and in the water column promotes rapid and uniform vertical mixing. Lateral mixing in rivers occurs over relatively longer distances and is dependent on factors such as current speed, channel morphology, and the presence or absence of bottom roughness and rapids.

In tidal systems, vertical mixing may be limited by water column stratification, as discussed in Section 3.1.3. For example, a positively bouyant plume may rise to the surface of the receiving water or it may become trapped subsurface, and it may alternate between rising to the surface or remaining subsurface depending on tidal currents and vertical density stratification. Once neutral bouyancy is achieved, subsequent lateral and vertical dilution will be driven by ambient currents and turbulence, including effects of current interactions with the bottom of the water body as well as wind-driven currents and turbulence at the surface.

3.1.5. Current Interactions. The direction and magnitude of the ambient current can have a dramatic effect on effluent mixing. Typically, these parameters have a greater influence in the far field region, although they may also impact near field processes if strong relative to discharge momentum. Like density, velocity can also be stratified in a water body. This situation is particularly true in small rivers where the drag effect of shorelines and the bottom can cause significant differences in the velocity profile both with depth and across the stream. Tidal effects have also been found to cause reversing currents, which can occur near the bottom or across the entire water depth. For example, in an estuary an outward velocity may occur in a fresh water layer at the surface while an inward velocity in an underlying salt wedge occurs along the bottom. Discharge into the saline bottom layer may result in effluent being trapped near the bottom and actually carried upstream.

3.1.6. Tidal Effects on Mixing. Tidal cycles can have significant effects on far field mixing processes. Re-entrainment of previously discharged effluent can cause accumulation of pollutants in the discharge zone. This commonly occurs in bays with extremely long detention, or flushing, times. Effluent cannot be entirely swept away during a single tidal cycle, and some is perpetually left behind. Such effects illustrate the importance of physical scale models in some situations to provide a truer picture of the far field mixing process than mathematical models.

3.2 Elements of Diffuser Design

An outfall is any device used to discharge wastewater to a receiving water. In the past, outfalls consisted of large-diameter pipes which discharged to the receiving water surface, typically at the shoreline. Study of hydrodynamic mixing has brought about many improvements in the introduction of effluent into the environment. One such improvement is the practice of submerging discharges to make use of the hydrodynamic forces that dilute effluent quickly. Early examples of such discharges were open-ended pipes. Another improvement, the high-energy diffuser, is described in this section.

3.2.1. Components of a Typical Diffuser. The typical outfall system designed today consists of an outfall pipe, a diffuser pipe, and smaller diameter discharge ports. The term "outfall pipe" is typically used to refer to the pipe extending from the wastewater treatment plant to the first port. The diffuser pipe is the large diameter pipe that begins with the first port and ends with the manhole at the last diffuser. An end manhole is recommended to provide access to the pipeline interior for inspection or repair. The components of a typical outfall diffuser system are illustrated on Figure 3-4.

Effluent can be conveyed from the diffuser pipe to the receiving water in several ways. Some systems may be as simple as slots or ports cut into the side or top of the pipe. Another method involves burying the diffuser pipe and extending smaller-diameter pipes, or risers, above the bed of the receiving water. Nozzles are typically attached to the ends of the risers and can be fabricated with bends to direct the discharge in nearly any direction. The diameter of the nozzle may or may not be the same as the riser. Figure 3-5 and Figure 3-6 provide examples of engineering details for a buried multi-port-diffuser with extended risers and nozzles.

Another method of dispersing flow is a radiator diffuser, such as that used to discharge the City of Boston effluent. Diffuser pipes extend to the underwell of a conical structure installed on the bottom of the water body. The structure distributes flow to many nozzles that extend from it.

Diffusers have been supported from piers such as loading wharves and from dedicated pile structures, particularly over soft bottoms. In rivers, diffusers have also been buried, with the effluent diffusing upward through the river bottom and then mixing into the receiving water.

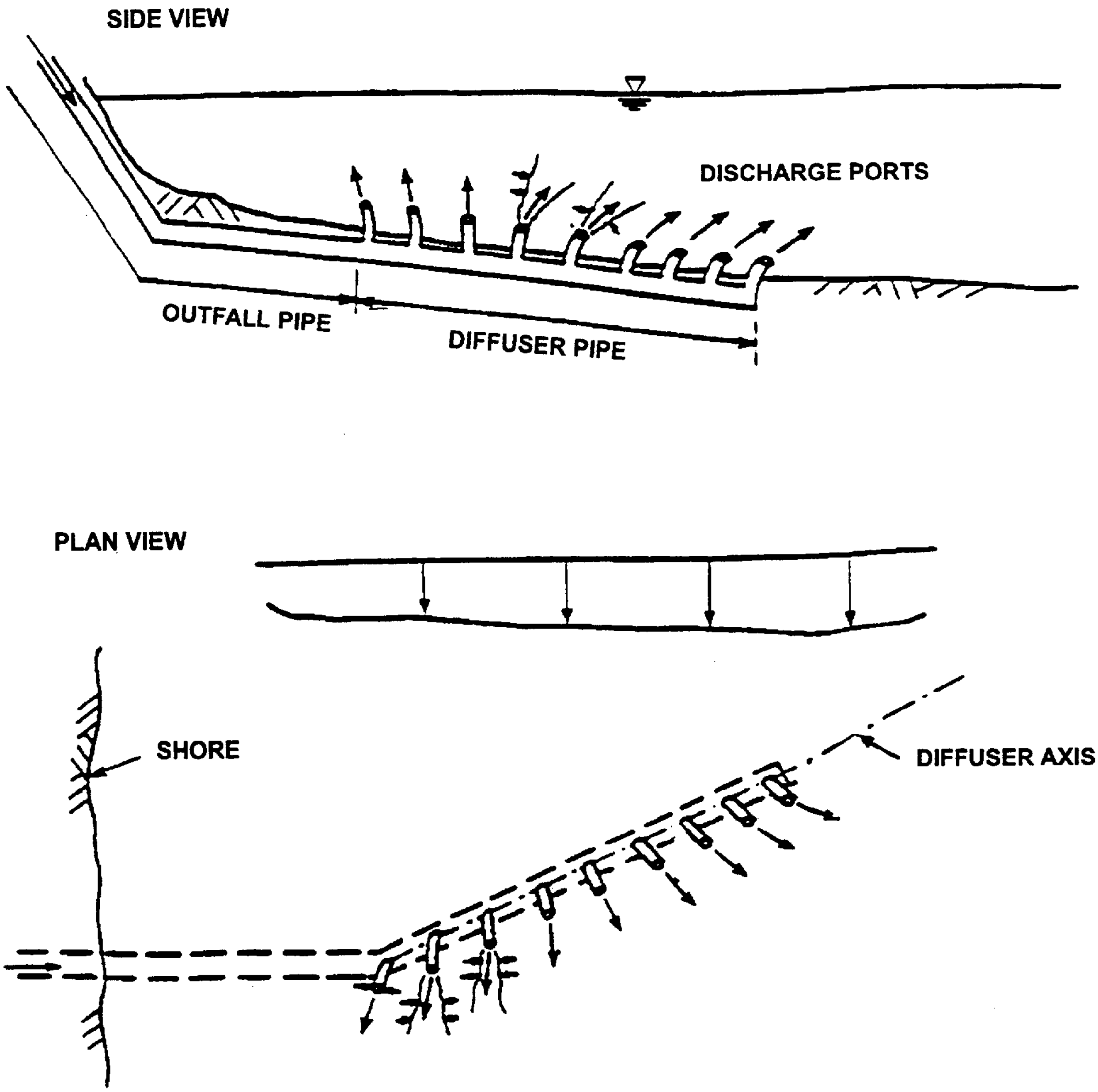


Figure 3-4. Components of a Typical Outfall Diffuser System

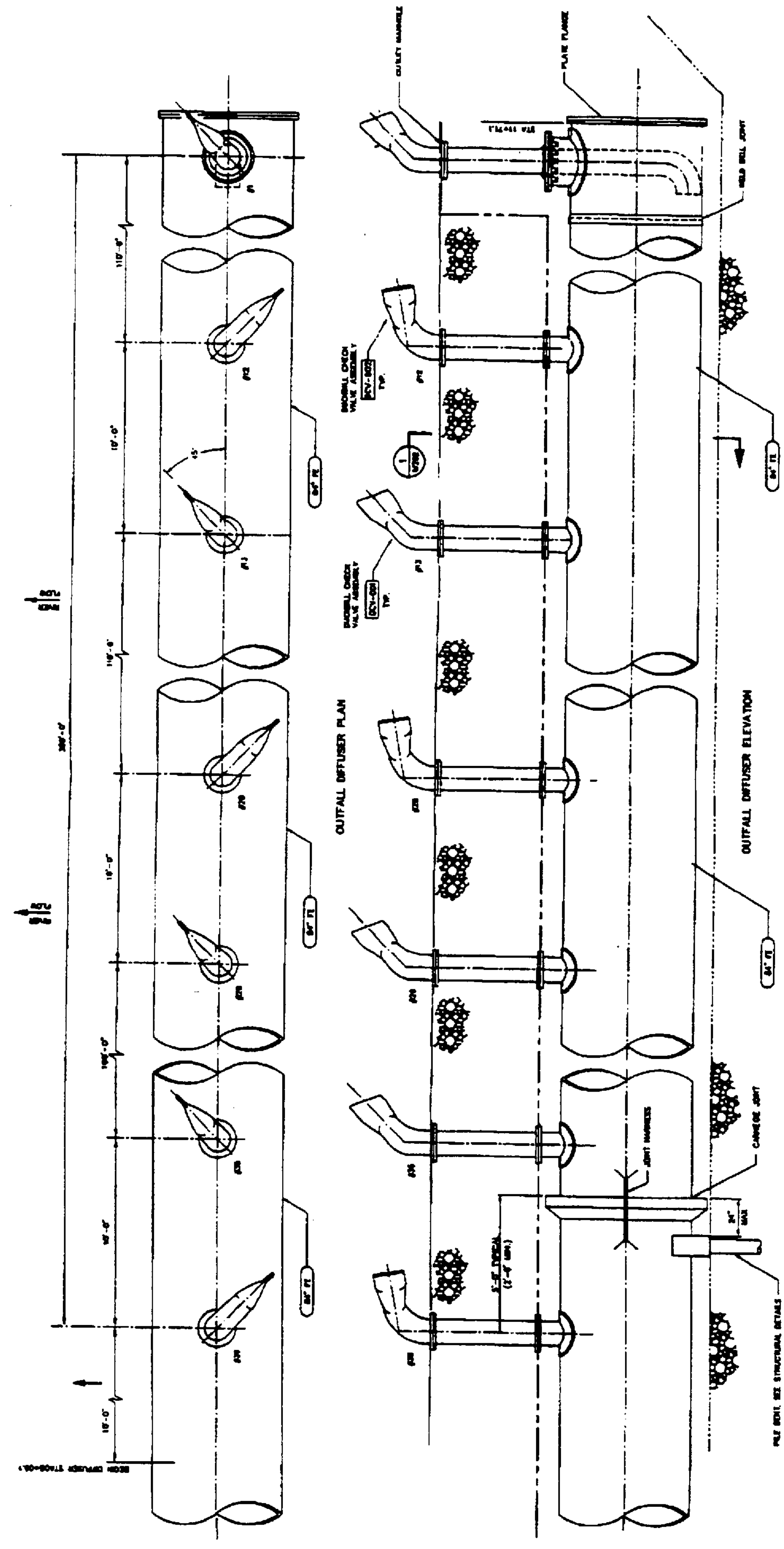


Figure 3-5. Example of Buried Multi-Port Diffuser with Extended Risers and Nozzles

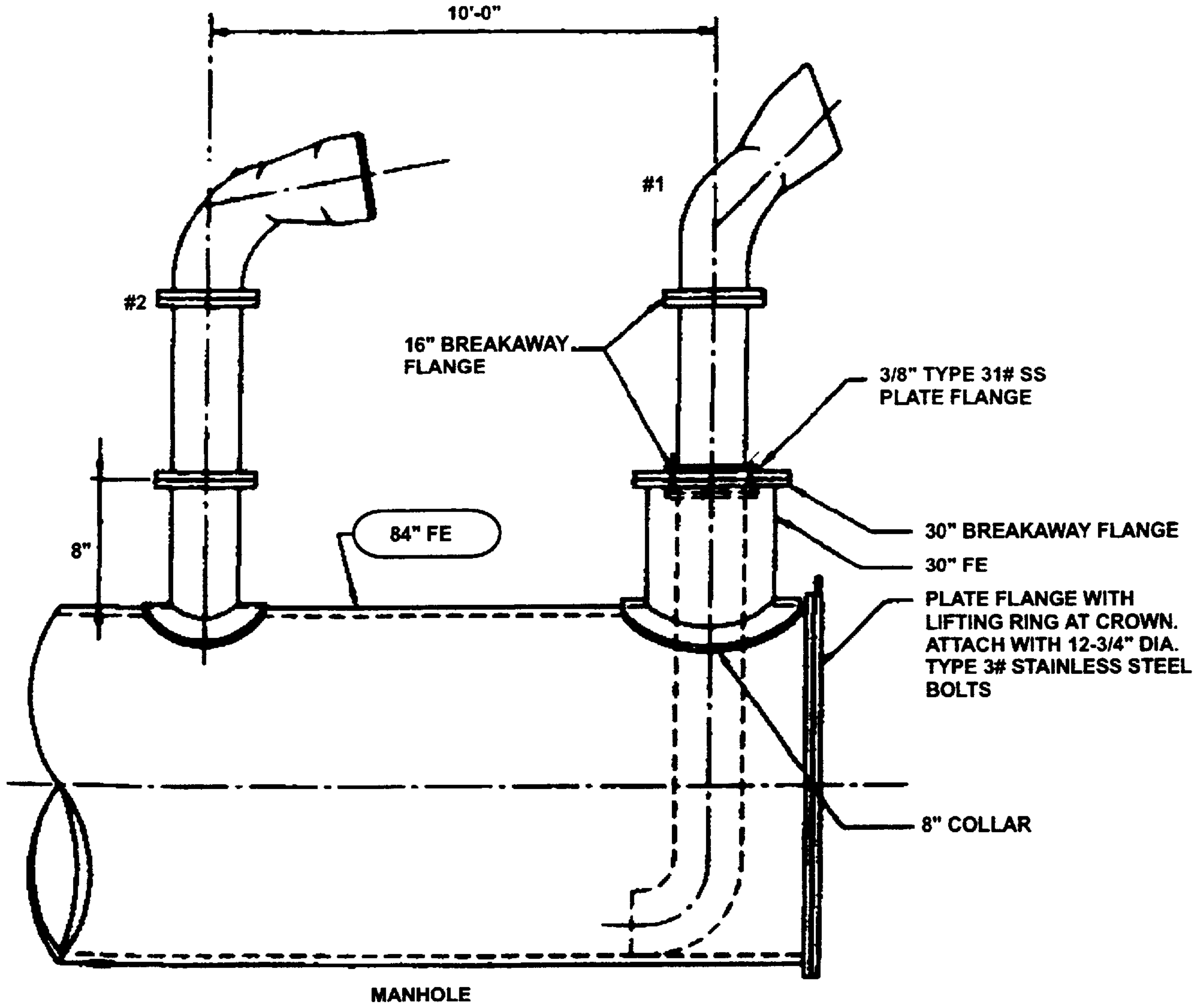


Figure 3-6. Example of Multi-Port Diffuser Engineering Details

3.2.2. Diffuser Hydraulics. Fischer *et al.* (1979) provide a thorough explanation of the hydraulic issues to be considered in ocean outfall design. Most of these concepts also apply to diffuser designs for fresh water discharges. Highlights of this reference and additional information are provided below.

Energy losses in outfall systems occur in all components. First, the outfall pipe which extends from the last treatment process (or effluent pumping station) to the diffuser system causes headloss due to friction in pipes, bends, and fittings. Second, friction in the diffuser pipe causes additional headloss. Friction from the risers, if present, is added to the diffuser pipe headloss. Most significant is the exit loss at the port or nozzle. The typical head deduction for exit loss is equal to the velocity squared and then divided by two times the acceleration due to gravity, or $u_o^2/2g$. Finally, additional energy is needed to overcome a pressure differential if the receiving water density is greater than effluent density:

$$h_{pd} = \left(\frac{\rho_a - \rho_o}{\rho_o} \right) h \qquad (3\text{-}2)$$

where:

h_{pd}	=	pressure head difference between discharge and receiving water
h	=	water depth

The available head must be considered when selecting the diameters of outfall pipe, diffuser pipe, and the port-riser-nozzle system. In some cases, the limiting factor may be the elevation difference between the receiving water surface at the highest expected tidal level and the water level in the critical process tank at the treatment plant. In other cases, the outfall system components must be analyzed to develop a system headloss relationship for an effluent pumping system. In either case, selecting pipe diameters that create too much headloss can result in overflows at the plant or pumps running outside of optimal efficiency ranges.

Each port of a multiport diffuser discharges a fraction of the total flow which is proportional to the available head and the port cross-sectional area. As flow is discharged from each port, less head is available at the next port. If the diffuser pipe is a constant diameter, the velocity in the pipe will decrease in the downstream direction, corresponding to the cumulative flow discharged from upstream ports. This is based on the continuity equation:

$$Flow = Velocity \times Area \qquad (3\text{-}3)$$

Rearranging terms, the velocity is equal to flow divided by the area. As flow is discharged from each successive port, pipe velocity decreases and there is less headloss per length of pipe. This lower velocity, while saving energy head, can result in sediment deposition in the pipeline either from the effluent or from receiving water solids which have intruded into the diffuser during low discharge conditions. These conditions can lead to a loss in cross sectional area and degradation of pipe material. In some cases, marine organisms have taken up residence within the diffuser, contributing to blockage problems. A design feature to counteract this situation is to install a reduced diameter diffuser pipe at a point where velocity drops below 2 feet per second during peak flow conditions, a standard value for self-cleansing conditions. Another solution is to use one-way check valves on each diffuser port.

3.2.3. Flow Distribution. When possible, it is advisable to design a diffuser with a flow distribution scheme that produces equal velocities through all ports. By doing this, each port or riser will be adequately flushed and dilution will occur more uniformly along the diffuser. The mathematical models used to evaluate multi-port diffusers divide the total flow evenly among all ports, and each port must have the same opening area. The result is that all ports or nozzles have equivalent exit velocities. Distributing flow for equivalent velocity across all exits can be done in one of two ways:

- Designing the diffuser pipe with a decreasing diameter in the downstream direction.
- Designing ports, risers, and nozzles with increasing diameter in the downstream direction. This approach is important when the diffuser is laid on a slope and there may be density differential along the diffuser.

The correct configuration of the system to achieve this goal can only be found by trial and error.

3.2.4. Configuration. The size, spacing, number, horizontal and vertical orientation, and shape of the ports, risers, and nozzles will dictate the effectiveness of initial mixing. Port size must be designed with the headloss considerations described above. Also, when discharging to marine or brackish waters, the size should be selected such that sufficient exit velocities are achieved during the low design flow condition. A test of this is the densimetric Froude number, calculated as:

$$F_d = \frac{u_o}{(g_o\ d)^{1/2}} \tag{3-4}$$

where:

F_d	=	densimetric Froude number
g_o	=	$\frac{(\rho_a - \rho_o)g}{\rho_o}$
d	=	discharge port diameter

A densimetric Froude number less than one indicates that the port will experience seawater intrusion. In some cases this can result in seawater permanently occupying portions of the diffuser pipe and further preventing complete flushing. To protect against this, the designer should specify port sizes which cause densimetric Froude numbers much greater than one under minimum flow conditions. A safe criterion is $F_d \geq 2$ (Brooks 1988). Another rule-of-thumb for the port diameter is to select a size such that the sum of nozzle cross-sectional areas is less than one-third to two-thirds of the diffuser pipe cross-sectional area. This recommendation also dictates the number of ports. Again, a trial-and-error analysis of alternative sizes is required to determine the best configuration.

The spacing between ports will also have a significant impact on initial dilution. For buoyant discharges, research has shown that the dilution of a multi-port diffuser in unstratified waters increases in proportion to the length raised to the 2/3 power, as indicated in Equation 3-5 (Fischer *et al.* 1979):

$$S_m = 0.38\, g_o^{1/3}\ Q^{-2/3}\ L^{2/3}\ H \tag{3-5}$$

where:

S_m	=	minimum dilution factor
Q	=	design discharge rate
L	=	total diffuser length
H	=	diffuser depth

For stratified waters, the dilution increase is proportional to length raised to the 1/3 power. Equation 3-5 also shows that dilution tends to decrease as flow through the diffuser increases.

Diffuser configuration and orientation must be selected with both site bathymetry (the underwater topography) and current direction in mind. It is generally recommended to direct diffuser nozzles perpendicular to the diffuser centerline and in the direction of the strongest current. For rivers, this means in the downstream direction. For oceans, bays, and estuaries, direction can only be determined with site specific velocity data gathered over a full lunar cycle (neap to spring tide).

3.2.5. Construction. The two main construction considerations are materials and outfall location. Materials must be selected based on both the characteristics of the effluent and the receiving water as well as the risks associated with geotechnical conditions and physical exposure. Installations subject to salt water must be made of corrosion-resistant materials. Acceptable pipe materials include polyvinyl chloride (PVC), fiberglass, and high density polyethylene (HDPE). Use of PVC pipe should be considered carefully as attack by marine organisms has been reported. Metallic pipe such as welded steel and ductile iron also give long service life with proper lining and coating and possibly cathodic protection. Reinforced concrete pipe and concrete cylinder pipe have also performed well.

Metal fittings must be made of marine-grade stainless steel, i.e., AVESTA 254 or Allegheny Ludlum 6XN, monel, 70/30 copper nickel alloy, or high silicon bronze. Finally, materials resistant to plant growth or subject only to attachment by soft plants are recommended. This will make replacement of risers and nozzles less complicated.

Durability is also an important factor in selecting construction materials. Due to the nature of the outfall placement, it may be subject to significant floating debris such as logs and sediment loads as well as ship traffic. For one particular installation in the State of Washington, there was considerable concern over floating river debris during spring floods. This was remedied by installing a screen on the upstream side of the diffuser section. Break-away bolts attached risers to the diffuser pipe flanges to provide a sacrificial structural member if a log should strike the risers. Finally, metal chains tethered risers to the diffuser pipe so they would not be lost if the riser broke away. This systematic approach to protecting the diffuser section increased the reliability of the outfall.

Outfall design must also recognize risks from wave and current action. In exposed locations, ballast rock must be provided to protect the outfall and diffuser.

In general, the outfall should be placed as deeply as possible, given cost constraints. However, local bathymetry has a significant impact on outfall siting. It is difficult to ensure uniform distribution of flow between ports if the diffuser is installed on a steep slope. The critical slope for construction is largely a function of the local soils. It is recommended that the design engineer consult with an experienced marine geotechnical engineer on local information prior to selecting a site. In some locations, seismic conditions must also be taken into account.

Factors such as the distance from shore, depth, and soil conditions will dictate siting and construction methods. Underwater pipeline construction methods depend on the pipe material selected but include:

- Cut-and-cover trench construction
- Coffer dam construction (shallow water only)
- Microtunneling and directional drilling (soils and distance permitting)

Successful outfall construction has also included floating outfalls into place and pulling or launching the pipeline from the shoreline. The former technique is often applied for HDPE pipe, the latter for welded steel and ductile iron.

3.3 Outfall Design Criteria

The following criteria must be considered when designing an outfall:

- Required effluent dilution
- Receiving water depth
- Receiving water body type
- Discharge rate

- Cost
- Risk

The actual dilution factors achieved by the outfall placement and configuration will determine compliance with effluent limits. The designer must determine whether the outfall will achieve the desired dilution with either computer modeling or a field study, as discussed in Chapter 4 through Chapter 7.

Receiving water depth influences the calculation of effluent dilution factors, system hydraulic performance, and construction techniques. Minimum depth is of importance in estimating dilution, as it most often represents the critical discharge condition. Maximum depth is a constraint for hydraulic modeling. Joint risk probabilities can be assessed by calculating the treatment plant water surface elevation required to push the peak wet weather design flow through the outfall during a maximum water depth condition. The expected water level during construction should be estimated with a survey prior to construction and a review of tide tables, if in a marine water body, or historical flow records, if in a river. As noted previously, the depth of water can impact construction techniques, cost, and schedule.

The proposed receiving water body can influence outfall design for a number of reasons. Salt water bodies generally have densities greater than the discharge, causing the plume to be buoyant. In many cases the ambient density will be stratified, allowing the discharge to reach a point of neutral buoyancy and trap beneath the water surface. Such a condition is favorable for dispersing effluent. Estuaries can include fresh water rivers that are influenced by tides. One result is a salt wedge which encroaches upstream in the river. Such a condition can have an impact on dilution which the designer must consider when evaluating the critical condition.

Knowledge of the discharge rate is necessary for estimating dilution and evaluating outfall system hydraulics. Peak flow conditions must be evaluated to ensure that sufficient head exists to discharge effluent at the design high water level without adversely impacting treatment plant hydraulics. Minimum flow should be used to evaluate the individual port discharges for potential salt water intrusion as indicated by the densimetric Froude number calculation.

Cost influences outfall configuration, location, and construction methods. Underwater construction is expensive, increasing at a geometric rate with depth. Construction techniques vary significantly in cost. However, in some situations, a particular method may provide less risk during construction and may be chosen despite added cost. Construction materials can vary significantly in cost. For instance, marine-grade stainless steel used for fittings exposed to salt water is several times more expensive than standard stainless steel.

The outfall system can be at risk in a number of contexts. Risk of infrastructure damage can come from causes including storms, currents, shipping, seismic failures, debris, sediment, and plant growth. There can be risk of violating water quality criteria if an insufficient factor of safety is designed into the system to attain the required dilution. Selection of a nonconservative friction factor can create a risk of hydraulic overloads at the treatment plant. Careful consideration of these risks, along with the other design issues discussed in this chapter, is an important element in a successful outfall system installation.

CHAPTER 4

MODEL SURVEY

This chapter provides an introduction to the use of computer models to predict effluent discharge mixing characteristics in a receiving water. It is divided into the following subsections:

- **Model Characteristics:** Discusses the mixing conditions described by models.
- **Available Models:** Identifies and describes available mixing zone models and presents model capabilities in a simple tabular format.
- **Model Applicability:** Discusses the range of discharge and ambient conditions for which each model is appropriate.
- **Example Applications:** Provides case histories of model applications and illustrates the decisionmaking process used in model selection.

4.1 Model Characteristics

Effluent and receiving water conditions combine to define the criteria for mixing zone model selection. For purposes of this discussion, mixing zone models can be characterized with respect to:

- Stages of Mixing
- Spatial Dimensions
- Temporal Resolution
- Deterministic vs. Probabilistic Models
- Model Complexity

4.1.1. Stages of Mixing. Mixing zones are defined as areas where water quality criteria may be exceeded while an effluent undergoes initial mixing with the receiving water. Relatively close to the discharge point, significant water quality gradients are observed between those areas which have mixed with the wastewater and those which have not. These gradients can occur across the width of the receiving water (lateral gradients) or over depth (vertical gradients). Complete mixing occurs as the lateral and vertical water quality gradients become small.

The types of water quality analyses described in this document focus on two distinct stages of mixing. The first is referred to as discharge-induced mixing. It is controlled by the characteristics of the effluent and is most important near the discharge location. Models used to assess discharge-induced mixing are termed near field models. The second stage of mixing, termed ambient-induced mixing, occurs farther from the discharge as the turbulence of the receiving water becomes an important consideration. Mixing models used to assess ambient mixing are termed far field models. The following describes each stage of the mixing process as it relates to mixing zone modeling.

- **Near Field (Discharge-Induced) Mixing:** The first stage of mixing that occurs as a wastewater is discharged to the environment is caused by the properties of the discharge itself. Discharge-induced mixing is caused by two influences: jets and plumes. Jets are caused by the initial discharge velocity (i.e., momentum), as the difference in velocity between the discharge and the ambient environment creates shear stress and tends to entrain receiving water and cause dilution. Plumes are caused by effluents whose density is different from the receiving water. Freshwater effluents discharged to marine environments are often less dense than the ambient water and tend to rise upon discharge. This movement also serves to create shear stress and entrain ambient water, causing dilution. Brine effluents are typically denser than the receiving water (termed negatively buoyant) and tend to sink after discharge. This sinking action will cause dilution in the same manner as a positively buoyant discharge. Oftentimes, a discharge will contain both buoyancy and momentum. This situation is termed a buoyant jet, and the two types of mixing work in concert to dilute the effluent. Figure 4-1 shows a buoyant jet, and indicates the areas where each phase of mixing is most important.

- **Far Field (Ambient-Induced) Mixing:** As the distance from the outfall increases, mixing caused by ambient turbulence in the receiving water becomes increasingly important. The point where ambient-induced mixing dominates discharge-induced mixing is a function of receiving water turbulence and effluent buoyancy and momentum. This point is not easily defined without the use of a model that considers both types of mixing. In general, ambient turbulence will become important more quickly in systems with high velocity differences (both direction and speed) between the receiving stream and the discharge.

Near field models are often used in mixing zone evaluations because the spatial limitations of many regulatory mixing zones (especially for acute toxicity) are such that discharge-induced mixing is the primary source of available dilution. Near field models underpredict dilution in cases where the regulatory mixing zone extends beyond the distance

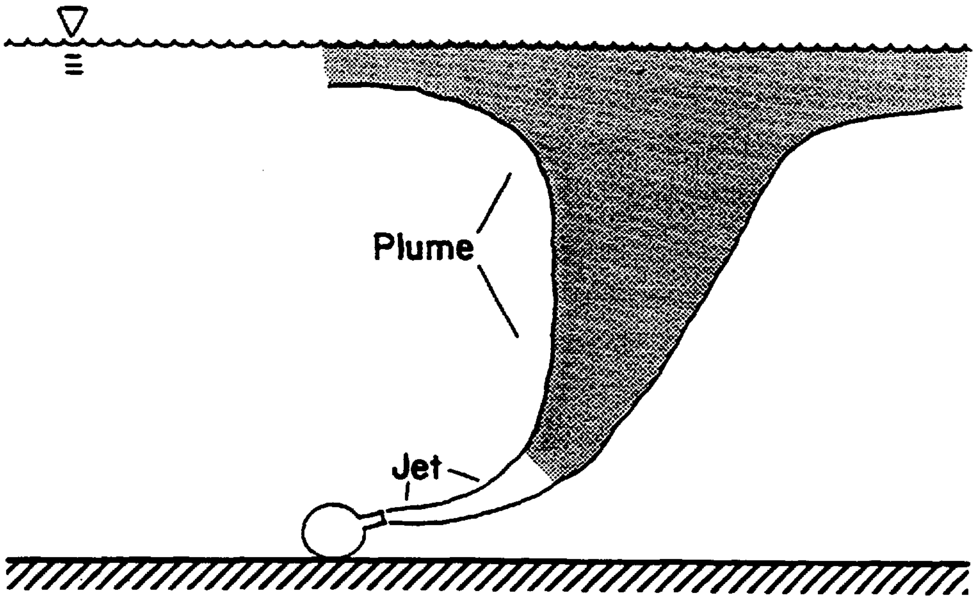


Figure 4-1. A Buoyant Jet Discharge

controlled by discharge-induced mixing. In these situations, NPDES permits based strictly on near field mixing predictions will be overly conservative. Any permit that is based upon a near field model should be reviewed to ensure that ambient-induced mixing is not also important. controlled by discharge-induced mixing. In these situations, NPDES permits based strictly on near field mixing predictions will be overly conservative. Any permit that is based upon a near field model should be reviewed to ensure that ambient-induced mixing is not also important. More accurate permit limits will require a methodology that considers the additional dilution that occurs outside the near field zone.

Ambient mixing in riverine systems is typically dominated by upstream flow. Well-accepted procedures exist for defining ambient-induced dilution in rivers. Ambient mixing in marine and estuarine systems can be caused by many factors. These include tidal currents, Coriolis effects, freshwater inflow, and wind-driven currents. Characterization of these mixing processes can be extremely difficult and is often outside the scope of a typical mixing zone assessment. Exposure assessments requiring consideration of ambient-induced mixing in marine and estuarine areas should be conducted (or reviewed) by specialists with expertise in this area.

4.1.2. Spatial Dimensions. Mixing zone models are available which consider water quality changes over zero, one, two, or three dimensions in space. A guiding principle of water quality analysis is to use the simplest model available that describes the important features of the system under study. Limiting the number of spatial dimensions is one simplification often used by water quality modelers. The following discussion describes model spatial dimensionality and discusses where each type can—and cannot—be appropriately used.

Zero-dimensional models assume complete and instantaneous mixing to predict a uniform pollutant concentration for a defined volume of the receiving water. These models do not consider pollutant concentration gradients in any direction. As such, they are restricted to systems that can be considered completely mixed in all dimensions over the area of concern. They are typically applied only when there is a regulatory mandate for their use. The only acceptable application of a zero-dimensional mixing zone model is to describe pollutant concentrations at the point of complete effluent mixing. In these cases, the regulatory definition of the mixing zone has no physical meaning and consists of a theoretical cross-sectional slice across some portion of the receiving water. The spatial resolution of the zero-dimensional approach is too coarse for any application where the mixing zone has true physical dimensions.

One-dimensional models consider changes in pollutant concentration over a single dimension in space, typically the axis of the discharge jet or plume. The discharge axis may be linear in the case of a true jet discharge or curvilinear in the case of a buoyant jet. One-dimensional models only predict dilution at the centerline of the discharge plume, where dilution is at a minimum. This provides a worst-case estimate of available dilution at any given distance away from the outfall.

One-dimensional near field models are designed for cases where the regulatory definition of the mixing zone is such that water quality standards must be met within a specific *distance* from the discharge outlet. They are less suited for cases where the allowable mixing zone is defined in terms of area. One-dimensional near field models are best used for single port discharge situations. Multi-port diffusers are more appropriately addressed using a two- or three-dimensional model.

Two-dimensional models consider the change in pollutant concentrations over a defined area. Categories of two-dimensional mixing zone models, corresponding to the dimensions under consideration, are lateral/longitudinal or axial/radial. Two-dimensional models are more complex than the models discussed previously. Their application will require a detailed understanding of the nature of the discharge and/or receiving water.

The lateral/longitudinal models are used for predicting the extent of a mixing zone over the length and width of a river. These can be considered an extension of the linear one-dimensional model discussed previously, with predictions extending downstream from the point of discharge. This type of model is recommended when considering mixing zones that are defined in terms of the fraction of receiving water surface area where concentrations can exceed criteria.

The axial/radial two-dimensional model can be considered an extension of the curvilinear one-dimensional model. The additional dimension considered by this model extends radially away from the centerline of the plume. This type of model is recommended when considering mixing zones with multi-port diffusers, as concentration gradients must be considered both parallel to outlet orientation (as the distance from the outlet increases) as well as perpendicular to outlet orientation (as effluent from adjacent ports merges).

Three-dimensional models provide the most detailed assessment of receiving water pollutant distribution with respect to a discharge point. They also have the most extensive model input requirements and are the most difficult to apply. As a result, three-dimensional models are not typically used to derive NPDES permit limit derivation. When needed, they should be applied by a specialist trained in their use.

4.1.3. Temporal Resolution. Water quality models are also categorized in terms of how they consider changes in pollution concentration over time. Typically, models are divided into two categories:

- Steady state
- Time variable

Steady state models predict receiving water concentrations in response to model inputs (e.g., effluent flows, concentrations) which remain constant over time. Time variable models, as the name implies, predict how concentrations in the environment change over time. Marine and estuarine systems add another temporal concern, relating to whether model predictions represent average conditions over a tidal cycle (tidally averaged model) or changes in conditions within a tidal cycle (real time model).

Steady state models predict a single concentration profile in response to constant effluent and environmental conditions. The primary assumption inherent to steady state models is that model inputs will remain constant, and that water quality conditions have fully responded to these constant inputs. Just as the modeler's desire is to use the fewest number of spatial dimensions possible to adequately describe the system, it is also useful to factor out the complexity of temporal changes if possible.

Steady state models can be appropriately used if inputs change slowly over time and/or if receiving water concentrations respond quickly to changes in environmental conditions. The inputs to near field mixing zone models depend primarily on discharge characteristics which can be realistically assumed to remain constant over the time scales of concern for the analysis of near field mixing. Also, the response time of the waterbody to changes in inputs is relatively fast. Consequently, steady state models are generally appropriate for use in assessing near field mixing zone issues. Essentially all near field mixing zone assessments rely on steady state models.

However, it should be noted that there are situations in which highly variable effluent conditions, coupled with relatively slow responses in the receiving water, invalidate the steady-state assumption. A time variable or probabilistic model should be considered in these instances.

Far field dilution models rely on characteristics of the receiving water which can vary more significantly over time than do discharge characteristics. Due to the complexity introduced by consideration of time variability, the most common modeling assumption is that receiving water characteristics remain relatively constant. This allows use of a steady state model.

Steady state modeling of estuarine systems is complicated by tides which cause both the direction and magnitude of flow to vary substantially over the course of a day. Near field mixing predictions in estuaries are primarily dependent on discharge characteristics and can be appropriately assessed using a steady state model. Far field dilution is driven by tidal flows and cannot be treated truly as steady state. For many cases, this problem can be solved by examining the average conditions which occur over an entire tidal cycle, called tidal averaging. Under other uniform environmental conditions, water quality from tidal cycle to tidal cycle remains fairly constant. Consequently, tidal average conditions can be represented using a steady state model. As such, tidally averaged steady state conditions are typically used to assess mixing in estuarine areas.

Time variable models can predict changes in concentrations both within and between tidal cycles. The potential advantage of these types of models is that they allow assessment of variations in effluent dilution over the course of a tidal cycle. This allows prediction of critical minimum dilution during the period of slack tides. Time variable models are not discussed in this document as they are generally not used for mixing zone assessment due to their great complexity.

4.1.4. Deterministic vs. Probabilistic Models. Mixing zone models are generally used under specified design conditions to compare predicted water quality against regulatory criteria.

EPA water quality criteria guidance specifies that the duration and frequency with which criteria are violated are important considerations in addition to the magnitude of pollutant concentrations in the receiving water. There are two methods available for considering the frequency and duration of criteria violations, deterministic modeling for critical environmental conditions and probabilistic modeling.

A deterministic model predicts a single environmental response to a single set of model inputs. The intent of deterministic modeling is to select model input values for environmental conditions which will be protective of the duration and frequency considerations inherent to water quality criteria. These analyses are based on the assumption that permit limits derived to be protective at some "critical" set of environmental conditions will be protective for other environmental conditions as well. The most common example is river dilution modeling where the 7Q10 low flow is frequently used to characterize ambient dilution. One potential drawback to deterministic models is the difficulty in selecting values for critical environmental conditions that are appropriately protective. When available dilution is based upon several factors, deterministic models can result in overly stringent NPDES discharge limits due to the assumption of the concurrence of numerous independent rare events.

Probabilistic models predict the entire distribution of water quality conditions that can occur in response to the expected range of environmental and loading conditions. They are best suited for explicitly addressing the expected frequency of water quality criteria violations in the receiving environment. Probabilistic model application, however, requires far more effort than deterministic modeling and a complete discussion is beyond the scope of this document.

The overwhelming number of NPDES permits will be based upon a deterministic modeling approach. Care should be taken to ensure that appropriate critical conditions are used to prevent against unnecessarily restrictive permit limits. If doubt exists as to the appropriateness of critical inputs, probabilistic modeling should be considered as an alternative.

4.1.5. Model Complexity. As discussed in Section 4.2, a number of modeling frameworks are available which consider the characteristics described above over a wide range of complexity. Simple desktop calculations describe zero- and some one-dimensional modeling problems for steady state and deterministic conditions. More detailed computer models are required to address multi-dimensional, time-variable, or probabilistic situations. Some judgment will be involved in defining which processes are important for each situation. Proposed NPDES permit limits should be reviewed to ensure that neither an overly simplistic modeling approach (i.e., one that ignores important processes) nor an overly complex one (one that contains poorly understood processes) has been used. Guidance on model selection is provided in Section 4.3.

4.2 Available Models

Modeling tools available and commonly used for mixing zone analyses include:

- Simple dilution equations
- DYNTOX
- CORMIX
- UM-PLUMES
- RSB
- UDKHDEN
- PDS
- PDSM

These are the primary public-domain mixing zone models in current use. At the time this document was prepared, EPA was only supporting CORMIX, UM-PLUMES and RSB, which include applications previously covered by other EPA models. The structure, applicability, assumptions, complexity, output, and computer requirements of each model are described below, summarized in Table 4-1, and provided on a model-specific basis in Appendix A. Appendix C provides sample output for the models PDS, UM-PLUMES, CORMIX, and UDKHDEN.

Additional mixing zone models exist that will not be discussed here. These include obsolete EPA models, proprietary software, and laboratory experimental models. Several older models, including UPLUME, UMERGE, UOUTPLM, ULINE, and MOBEN, were formerly distributed and supported by EPA. However, the UM-PLUMES and RSB models have largely replaced these models. A proprietary model, "OOC" was developed for the Offshore Operators

Table 4-1. Summary of Mixing Zone Model Capabilities

	Jet momentum equation	River initial mix equation	Ambient dilution equation	DYNTOX	CORMIX	UM-PLUMES	RSB	PDS	PDSM	UDKHDEN
Discharge	Submerged	Either	Either	Either	Either	Submerged	Submerged	Surface	Surface	Submerged
Receiving water	Any	Shallow	Shallow	Shallow	Any	Any	Deep	Deep	Deep	Any
No. of ports	Single	Single	Any	Single	Any	Any	Multiple	Single	Single	Multiple
Dimensions	One	Zero	One	Zero	Three	Three	Three	Three	Three	Three
Complexity	Low	Low	Low	Moderate	Moderate	Moderate	Moderate	High	High	High

Committee (Brandsma 1995). This model simulates the three dimensional behavior of offshore effluent plumes discharged from a single port outfall. Lastly, several researchers have developed their own unique mixing zone models that have not been applied to "real world" situations and are currently not available for widespread use in developing NPDES permits.

The models described in this section predict effluent mixing in different ways, but they can be discussed on a common basis through the term "dilution factor." For practical purposes, the dilution factor describes how many times an effluent is diluted by background water. For any given mixture of effluent and background water, the dilution factor, S, can be defined as:

$$S = \frac{100}{\%\ of\ total\ volume\ consisting\ of\ effluent} \qquad (4\text{-}1)$$

Undiluted effluent within the discharge pipe will have a dilution factor of one. A parcel of water containing 25 percent effluent and 75 percent background water will have a dilution factor of four. The dilution factor will vary over distance, increasing as the distance from the outfall increases.

For purposes of predicting compliance with water quality criteria, receiving water concentrations can be determined at any location as a function of the dilution factor and effluent concentration. For receiving waters with a "clean" (i.e., zero concentration) background, concentrations in the mixing zone can be calculated as:

$$C_{mix} = C_{eff} / S \qquad (4\text{-}2)$$

where:

C_{mix} = pollutant concentration in mixing zone

C_{eff} = effluent concentration

For sites with non-zero background, pollutant concentrations in the mixing zone can be calculated as:

$$C_{mix} = C_{eff} / S + (1 - 1/S) C_{back} \qquad (4\text{-}3)$$

where:

C_{back} = background pollutant concentration

Some of the models described here only provide estimates of the dilution factor, S. Others directly predict concentrations in the mixing zone as a function of dilution and background concentrations. To allow for consistency of discussion, all model descriptions in this section are provided in terms of a dilution factor.

4.2.1. Desktop Calculations. The simplest approach for predicting pollutant concentrations at the edge of a mixing zone consists of a single equation that can be solved using a handheld calculator. Three types of desktop equations are commonly used for mixing zone assessment:

- **Jet Momentum Equation:** The first desktop equation considers dilution caused by discharge momentum only. It is most appropriately applied to cases where the effluent is neutrally buoyant in the ambient water, such as freshwater outfalls. Effluents discharged into estuarine and coastal waters are usually positively buoyant and rarely neutrally buoyant. The equation, as taken from EPA (1991), is:

$$S = 0.3(x / d) \tag{4-4}$$

  where:

  S = average dilution factor (dimensionless)
  x = distance from outlet to edge of mixing zone
  d = diameter of outlet

  Equation 4-4 provides a minimum estimate of mixing zone dilution, as it assumes that ambient-induced mixing is zero. Ambient-induced mixing will dominate jet-induced mixing as the distance from the outfall increases. Consequently, this equation is most appropriate for predicting dilution very close to the outfall. Predictions become increasingly conservative as distance from the outlet to the edge of the mixing zone increases, and ambient-induced mixing becomes more important.

- **River Initial Mix Model:** The second desktop equation has been widely used for mixing zone assessments in rivers. It consists of a simple zero-dimensional model which predicts initial mix concentrations in the direct vicinity of a river outfall (EPA 1985b). The model equation can be written as:

$$S = \frac{aQ_{up} + Q_w}{Q_w} \qquad (4\text{-}5)$$

where:

a	=	fraction of upstream river flow (or cross-section) available for dilution
Q_{up}	=	upstream river flow
Q_w	=	wastewater discharge flow

As discussed in Section 4.1.2, this equation is only appropriate for a situation in which mixing between the effluent is complete and nearly instantaneous. In actual practice, this desktop equation will overpredict dilution (i.e., underpredict concentration) near the discharge and underpredict dilution at the far end of the mixing zone. Therefore, this model is often considered protective. It is incapable of predicting the downstream extent of mixing, however, and can result in long downstream plumes that exceed water quality criteria.

- **River Ambient Dilution Model:** A more rigorous tool is available for predicting maximum instream concentrations downstream of a discharge as well as attenuation due to ambient dilution. This desktop equation (EPA 1991) is:

$$S = \frac{Q_{up}(\pi D_y X / u)^{1/2}}{Q_w W} \qquad (4\text{-}6)$$

where:

D_y	=	lateral dispersion coefficient
X	=	distance downstream from outlet
u	=	instream velocity
W	=	stream width

The lateral dispersion coefficient can be determined from dye tracer studies, or estimated via the equation:

$$D_y = 0.6d(gds)^{1/2} \pm 50\% \qquad (4\text{-}7)$$

where:

d	=	water depth
g	=	acceleration due to gravity
s	=	channel slope

4.2.2. DYNTOX. DYNTOX (EPA 1995) performs probabilistic simulations using the river initial mix model described by Equation 4-5. DYNTOX requires as input a description of the variability in upstream flow and effluent flow (as well as upstream and effluent concentration) and will automatically predict the variability in mixing zone dilution. DYNTOX also provides calculations of downstream fate and can consider multiple overlapping discharges in the completely mixed areas of the river. While not designed as a "mixing zone" model, DYNTOX is included here because it is the only tool readily available to provide probabilistic mixing zone assessments.

4.2.3. CORMIX. EPA has supported development of an expert system for the analysis of submerged discharges, entitled CORMIX. CORMIX has been released in several forms. The original model, CORMIX1 (Doneker and Jirka 1990), was designed for submerged single port discharges. This model was followed by CORMIX2 (Akar and Jirka 1991) which was designed for submerged multi-port discharges. The model CORMIX3 (Jones and Jirka 1991) was designed specifically for surface discharges. The most recent version of CORMIX, CORMIX Version 2 (NCASI 1992), incorporates all prior versions of CORMIX and can handle surface and submerged, as well as single or multiport, discharges.

CORMIX consists of a large number of mixing zone model equations for both near field and far field conditions. It contains an analytical scheme that classifies any given discharge/environmental situation into one of several categories with distinct hydrodynamic features. Based upon the site-specific conditions provided by the model user, the "expert system" in CORMIX automatically chooses and applies the mixing zone model equation appropriate for the system under study.

Application of CORMIX requires an explicit description of the characteristics of the discharge and receiving water. CORMIX then provides information regarding the dilution and geometric configuration of the plume in the ambient water. CORMIX also explicitly considers regulatory mixing zone dimensions and requirements.

4.2.4. UM-PLUMES. The EPA-supported UM-PLUMES model replaces the old UMERGE model, providing essentially equivalent results but possessing considerably more capabilities. UM is the actual model; PLUMES is the user interface portion. UM-PLUMES is a three-dimensional model that considers a positively buoyant plume issuing at an arbitrary angle into a stagnant environment. It can be applied to shallow and deep receiving waters for submerged multiple port discharges. UM-PLUMES allows for specification of ambient current velocities at various depths in the water column and provides calculations of average dilutions within the plume at various depths.

4.2.5. RSB. The RSB model, also managed by the PLUMES interface, considers submerged multiple port discharges to deep receiving waters. RSB largely replaces and updates the old ULINE model. RSB is based on experimental studies on multiport diffusers in stratified currents.

4.2.6. UDKHDEN. UDKHDEN is a three-dimensional model that can be used for either single or multiple port diffusers. The model applies to submerged discharges in either shallow or deep water. Ambient inputs allow variation in density and/or current as a function of depth. The user can enter either temperature and salinity, or density of effluent and receiving water, to account for plume buoyancy.

4.2.7. PDS. PDS is a three-dimensional steady state model designed to consider single port surface discharges. Specifically, PDS is designed for deep receiving streams and moderate ambient current. It assumes that the plume is positively buoyant and makes no contact with the bottom or the shoreline.

4.2.8. PDSM. PDSM is a modified version of PDS, designed to predict the dilution of three-dimensional surface plumes that re-attach to the near shore but not to the bottom. It is therefore intended for deep receiving streams. PDSM is otherwise essentially the same as the PDS model, except that it is designed to account for situations with higher ambient velocities where the plume is expected to attach to the shoreline.

4.3 Model Applicability

This section discusses the range of discharge and ambient conditions for which each of the above mixing zone models is appropriate, along with typical errors in model application. Table 4-2 summarizes the applicability of each of the various models for the following discharge situations:

- Shallow river (acute toxicity)
- Shallow river (chronic toxicity)
- Deep river (acute toxicity)
- Deep river (chronic toxicity)
- Tidal estuaries
- Open water

Table 4-2. Applicability of Selected Mixing Zone Models

Model	Shallow river (acute)	Shallow river (chronic)	Deep river (acute)	Deep river (chronic)	Tidal estuary	Open water
Jet Momentum Equation	Y		Y			
River Initial Mix	Y	Y				
Ambient Dilution		Y				
DYNTOX	Y	Y				
CORMIX	Y	Y	Y	Y	Y[a]	Y
UM-PLUMES						Y
RSB						Y
PDS			Y	Y		
PDSM			Y	Y		
UDKHDEN	Y	Y	Y	Y		Y

[a] When used in conjunction with DRBC pre- and post-processor.

4.3.1. Shallow River (Acute Toxicity). A shallow river is defined for purposes of this discussion as one where vertical mixing is essentially instantaneous, i.e., the effluent is completely mixed from top to bottom in the immediate vicinity of the discharge. It is also generally assumed that the allowable mixing zone for acute toxicity will be small in spatial extent and that near field mixing will be the only source of dilution. Assessment techniques that are potentially applicable for this situation are the jet momentum equation, the initial mix equation, DYNTOX, CORMIX, and UDKHDEN.

The jet momentum equation will provide a quick screening-level estimate of dilution in the immediate vicinity of the discharge. The range of applicability for this model is on the order of two to three times the ambient water depth. At greater distances, this method will underpredict dilution.

The river initial mix equation should be used if the regulatory mixing zone is defined by an initially well-mixed area over a fixed cross-section of the receiving stream,. This equation is typically applied in a deterministic manner. EPA guidance suggests use of the once in ten year, one day average low flow (1Q10) as the background stream flow for the initial mix equation. The primary limitation of this technique occurs when critical environmental conditions must be selected for multiple parameters (e.g., upstream flow, upstream pollutant concentration). In these cases, appropriate critical values for all parameters cannot be easily defined, and many permits are based upon overly stringent input values. Use of the DYNTOX probabilistic model should be considered in such situations.

Another option for acute toxicity assessment in shallow rivers is CORMIX. Substantially more effort will be required to apply CORMIX than for desktop equations, although this effort may be worthwhile if both near and far field assessments are necessary. If there is uncertainty whether the regulatory mixing zone extends into the area where far field mixing is important, application of CORMIX will address these concerns. UDKHDEN can also be applied, but it requires even more detailed input information and is more difficult to use than some of the other models.

4.3.2. Shallow River (Chronic Toxicity). Chronic toxicity assessment generally requires use of a far field modeling approach, as the regulatory mixing zone will extend to areas where ambient-induced mixing is important. Far field assessment techniques that are potentially applicable are the initial mix equation, DYNTOX, ambient far field dilution equation, CORMIX, and UDKHDEN. The initial mix equation will be as applicable for chronic toxicity as for acute toxicity. The primary difference is that EPA guidance recommends use of the 7Q10 as an upstream dilution flow. The same caveats discussed above regarding selection of multiple critical condition inputs and probabilistic modeling apply equally to chronic toxicity assessment.

The ambient dilution equation is applicable to define the downstream extent of a mixing zone. The primary caveat regarding this approach regards selection of the lateral dispersion coefficient, D_y. Predicted dilution can be sensitive to changes in this parameter, which can only be crudely estimated in the absence of a field dispersion study.

CORMIX is also an option for chronic toxicity assessment in shallow rivers. Although it generally requires more effort than the methods described above, it is applicable for a wide range of conditions. The most significant disadvantage to CORMIX is that it provides no capability to adjust dispersion coefficients. The model user must accept all input values selected by the expert system. UDKHDEN can also be applied for chronic toxicity in shallow rivers, but it requires even more detailed information than the other models.

4.3.3. Deep River (Acute and Chronic Toxicity). If vertical water quality gradients are expected to be important, mixing zones can be assessed with the jet momentum equation (acute only), PDS, PDSM, UDKHDEN, and CORMIX. The jet momentum equation is as appropriate in deep water for acute mixing as it is for shallow water, with the same caveats. PDS and PDSM are both applicable for this situation. The primary distinction between these models is that PDS assumes that the plume makes no contact with the bottom or shoreline, while PDSM allows shoreline interactions. Both models require site-specific inputs for lateral and vertical dispersion coefficients, which cannot be easily determined by the inexperienced model user. UDKHDEN can also be applied, but requires even more detailed input information. Finally, CORMIX is applicable for this situation, with the same limitations as described above.

4.3.4. Tidal Estuaries. Estuaries present a difficult situation to model, as ambient currents are constantly changing in response to tidal actions. A second complicating factor is that background concentrations can be affected by the discharge, due to tidal-induced reversals in the direction of flow. A review of mixing zone models for estuarine systems (LTI and Wright 1991) has indicated that the only available method to rigorously assess tidally influenced mixing is full-scale application of a time-variable hydrodynamic model. The costs associated with such a modeling effort can be hundreds of thousands of dollars.

The Delaware River Basin Commission (DRBC) has recently sponsored the development of pre- and post-processing software for the CORMIX model to help assess estuarine mixing zones (LTI 1995). This software will perform multiple CORMIX simulations corresponding to various points in the tidal cycle, and then combine the results to provide an estimate of tidally averaged dilution.

4.3.5. Open Water. Models applicable for submerged discharges to open water situations such as lakes or oceans are CORMIX, UM, RSB, and UDKHDEN. The first three are equally applicable and generally produce comparable results for the near field stage of mixing. These models have shown a tendency to diverge in the transition between near and far field processes, and can provide widely different results for similar input values. It is often a good idea to apply more than one model concurrently to define the uncertainty in predicted dilution. UDKHDEN can also be applied in these situations, but its application is much more complex than the previous models.

4.4 Example Applications

Three examples are provided to illustrate the actual use of some of the mixing zone models described above. The intent is to demonstrate how "real world" information is factored into the decisionmaking process of model selection and application. The case studies presented are:

- Potomac River Chronic Ammonia Mixing Zone
- Gunston Cove Acute Toxicity Analysis
- Gulf of Mexico Produced Water Analysis

4.4.1. Potomac River Chronic Ammonia Mixing Zone. The District of Columbia (District) operates a municipal wastewater treatment plant that discharges to the Potomac River. Draft permit limits for ammonia were proposed that were based upon a mixing zone assessment for chronic toxicity. Permitting procedures were such that the mixing zone was defined to assume complete initial mixing over 25 percent of the river cross-section. This corresponds to the river initial mix model described by Equation 4-5. Allowable ammonia effluent concentrations at the edge of the mixing zone depended upon several factors. These included the dilution factor as well as receiving water pH, temperature, and upstream ammonia concentration. Temperature and pH were a concern because they control the percentage of ammonia that will exist in a toxic form. The draft permit used a deterministic initial dilution approach specifying critical input values for each model input. The input values selected consisted of 7Q10 upstream flow, 90th percentile summer temperature, 90th percentile summer pH, and mean upstream ammonia concentration. Calculations for the draft NPDES permit indicated the need for stringent effluent ammonia limits to meet water quality criteria at the edge of the mixing zone.

The District was concerned about the suitability of assuming that a once in ten year low flow value occurred in conjunction with 90th percentile values for pH and temperature. A predecessor to the DYNTOX model was used to simulate mixing zone concentrations over the entire range of expected environmental conditions (Freedman *et al.* 1988). Historical data were collected and reviewed for upstream flow, temperature, pH, and ammonia concentration. These inputs were characterized as statistical frequency distributions and a probabilistic dilution analysis was conducted. Results of this probabilistic analysis indicated that NPDES permit limits, much less restrictive than those originally proposed, were sufficient to meet water quality objectives.

This example demonstrates a case where performance of probabilistic modeling by a permittee resulted in less restrictive NPDES permit limits than those originally proposed by the regulatory agency. Probabilistic modeling will not necessarily result in more lenient limits than a deterministic approach, but should be considered whenever there is a concern that the critical environmental inputs used in permit development are more conservative than necessary.

4.4.2. Gunston Cove Acute Toxicity. Fairfax County, Virginia, operates a municipal wastewater treatment plant that discharges to a small stream, Pohick Creek. Initial mix dilution calculations conducted as part of a planned treatment plant expansion showed that a dilution factor of less than 1.1 would be available after effluent flows were increased. Based upon a review of existing effluent concentrations, it was determined that a dilution factor of at least 5 was required to meet water quality criteria. The feasibility of relocating the discharge outlet to Gunston Cove (an embayment of the Potomac Estuary) was investigated in an attempt to achieve greater dilution (LTI 1992). Mixing zone modeling was required by the State of Virginia to define the size of the acute mixing zone that would be created in the vicinity of the proposed outfall. Existing effluent concentrations were known, but site-specific discharge studies could not be conducted because the outfall had not yet been moved. Characteristics of a proposed multiport diffuser were provided by the treatment plant designer.

The CORMIX model was selected because its expert system automatically selects all model coefficients without requiring site-specific field data. The model was provided inputs describing the depth and ambient velocity of the receiving water, along with a complete description of the proposed multiport diffuser. CORMIX model results indicated that a dilution factor of 9.5 was achieved immediately (i.e., at the first model output prediction), indicating that acute criteria would not be exceeded in the ambient environment and that no acute mixing zone was required. While this mixing zone modeling analysis was accepted by the State, the final decision was to keep the outfall in its present location, as the costs of relocation were greater than those associated with adding additional treatment processes to reduce effluent concentrations at the existing discharge location.

4.4.3. Gulf of Mexico Produced Water. EPA Region VI was responsible for preparing a general NPDES permit for produced water discharges to the Gulf of Mexico. In developing this general permit, numerous mixing zone model simulations were conducted to define the dilution available 100 meters from the point of discharge as a function of discharge rate, pipe diameter, and height of the discharge point above the sea floor. These results were to be used to define NPDES permit limits for hundreds of produced water discharges. The EPA consultant performing the mixing zone modeling selected CORMIX, as it provided all necessary model capabilities for this application. CORMIX model results were provided to EPA and used as input to a draft general NPDES permit. These modeling results were reviewed by technical experts for the Offshore Operators Committee, who concluded that CORMIX provided overly stringent effluent limits. Alternative modeling of the same sites using the UM-PLUMES model resulted in much different dilution predictions.

LTI was subsequently contracted to review the results of both models and recommend an appropriate approach for defining general NPDES permit limits. The analysis (LTI and Wright 1992) found that the two models produced essentially identical results when predicting both near and far field dilution. However, in the transition zone between these two regions, the results from the two models differed by more than a factor of ten. Dilution factors predicted by CORMIX were on the order of 100, while those predicted by UM-PLUMES were on the order of 1000. Dr. Steven Wright, hydrodynamic modeling expert at the University of Michigan, examined the nature of this discrepancy and concluded that CORMIX underpredicted the dilution that occurred in this transition zone and UM-PLUMES overpredicted dilution. While the "truth" lay somewhere between the two models, too little is known to precisely describe the behavior of plumes in this region of mixing. Dr. Wright developed a method for correcting CORMIX results that provided a best estimate of the dilution that would occur in the transition between discharge-induced and ambient-induced mixing.

This example demonstrates that two alternative mixing zone models can give widely varying results, even though both may be applicable to a given situation. It is often a good idea to apply more than one model to gain an understanding of model prediction uncertainty. Finally, this example demonstrates the large uncertainty that can occur when modeling buoyant plumes if the distance to the edge of the regulatory mixing zone occurs beyond the near field mixing zone.

CHAPTER 5

MODEL AVAILABILITY

5.1 Model Sources

Several EPA offices provide access and support for the mixing zone models identified in the previous chapter. Table 5-1 presents sources and contacts for each model.

5.1.1. Desktop Calculations. EPA (1991) provides a brief description of each of the equations along with references to the original literature.

5.1.2. DYNTOX. DYNTOX is distributed by EPA's Office of Science and Technology in Washington, DC. It is available on diskette only, with documentation included. While EPA distributes and approves use of this model, no technical assistance is provided.

5.1.3. CORMIX. EPA's Center for Exposure Assessment Modeling (CEAM) in Athens, Georgia, provides access and support for numerous water quality models, including the CORMIX and PLUMES mixing zone models. Software is provided on diskette, or it can be downloaded from the Internet or the EPA Bulletin Board System (BBS).

5.1.4. UM-PLUMES/RSB. CEAM also distributes the UM-PLUMES and RSB models. Software is provided on diskette, or it can be downloaded from the Internet or the BBS. UM-PLUMES and RSB are also available from and supported by EPA's Environmental Research Laboratory in Newport, Oregon.

5.1.5. UDKHDEN. UDKHDEN was formerly supported and distributed by EPA. However, since the introduction of the UM-PLUMES and RSB models, EPA has ceased supporting UDKHDEN and the other "U" series models, including ULINE, UMERGE, UPLUME, etc. The model is therefore no longer available from EPA.

5.1.6. PDS. PDS was formerly distributed by EPA for the analysis of three-dimensional surface plumes. It is no longer available from EPA.

5.1.7. PDSM. PDSM is very similar to PDS and was likewise once supported by EPA. However, support for PDSM has also ceased, and the model is no longer available.

Table 5-1. Mixing Zone Model Access Information

Model	*Source Agency*	*Contact*	*Documentation*	*Costs*	*Electronic access*
Desktop Calculations	NTIS 5285 Port Royal Rd. Springfield, VA 22161	National Technical Information Service (NTIS) (703) 487-4650	*Technical Support Document for Water Quality-based Toxics Control* EPA/505/2-90-001	N/A	N/A
DYNTOX	EPA Office of Science & Technology 401 M. Street SW Washington, DC	Brian Ibrahime Goodwin (202) 260-1308	Included on diskette	None	None
CORMIX	EPA Center for Exposure Assessment Modeling 960 College Station Road Athens, GA 30605-2700 ceam@athens.ath.epa.gov	David Disney (706) 546-3590	Included on diskette	None	Internet: ftp.epa.gov World Wide Web: ftp://ftp.epa.gov/epa_ceam/wwwhtml/ceamhome.htm Bulletin Board System
PLUMES (UM & RSB)	EPA Environmental Research Laboratory-Narragansett Newport, OR 97365-5260	Walter Frick (503) 867-4029	Included on diskette	None	Internet: ftp.epa.gov World Wide Web: ftp://ftp.epa.gov/epa_ceam/wwwhtml/ceamhome.htm Bulletin Board System
UDKHDEN	formerly distributed by EPA Environmental Research Laboratory - Narragansett, Newport, OR 97365	None	*Initial Mixing Characteristics of Municipal Ocean Discharges*, 1985. EPA 600/3-85/073	N/A	None
PDS	formerly distributed by EPA Monitoring and Data Support Division, Office of Water Regulations and Standards	None	Appendix F to EPA 1984 *Technical Guidance Manual for the Regulations Promulgated Pursuant to section 301(g) of the Clean Water Act of 1977*	N/A	None
PDSM	formerly distributed by EPA Monitoring and Data Support Division, Office of Water Regulations and Standards	None	Appendix F to EPA 1984 Technical Guidance Manual	N/A	None

5.2 Model Access

Table 5-1 presents ordering information, available documentation, associated costs, and electronic access for each model identified in Section 4.2. The EPA models supplied by CEAM include documentation on the diskette. Additional information regarding electronic access is provided in Appendix B.

It is important to register as a model user whenever given the possibility to do so. Models are often updated, and users registered with the supporting agency typically receive notification whenever newer versions become available.

5.3 Model Support

Model support can be divided into endorsement and application assistance. The mixing zone models listed in Table 5-1 are supported (i.e., endorsed) by EPA. All were developed under EPA supervision and/or recommended in EPA guidance manuals.

The level of application assistance provided for these models varies widely. The current EPA models, CORMIX, UM-PLUMES, and RSB, have the highest level of support. Application assistance is available by telephone or electronic mail from the EPA laboratories listed in Table 5-1.

In contrast, technical assistance is no longer available from EPA for the models UDKHDEN, PDS, and PDSM. Some guidance on the applicability and use of these models is available in EPA (1985b) and Kannberg and Davis (1976). Application assistance is also available through many environmental consulting firms as well as through the authors of the models.

While EPA distributes DYNTOX, no technical support is formally provided by the Agency. Questions regarding model application are typically referred to LTI, the authors of DYNTOX, where they are answered informally. The simple dilution equations (EPA 1991) also receive no specific technical assistance from EPA. The best sources of information on the use of these equations are the original literature references. These include EPA (1985b) for the initial mix equation, Holley and Jirka (1986) for the jet momentum equation, and Fischer *et al.* (1979) for the ambient dilution equation.

CHAPTER 6

MODEL USE STRATEGY

As noted in previous chapters, a wide variety of mixing zone modeling options are available for developing and negotiating NPDES permit limits. Selection of a model for a given discharge should be guided by consideration of regulatory requirements, discharge outfall characteristics, and ambient conditions

Regulatory requirements for mixing zones vary across the United States, as described in Chapter 2. Some states allow both acute and chronic toxicity mixing zones, so a modeling approach which considers both near field and far field mixing conditions may be required. In general, a basic understanding of the applicable mixing zone regulations will help eliminate consideration of unnecessarily complex modeling approaches. It should also be noted that many states provide a great degree of flexibility in mixing zone model selection and will allow the use of any modeling approach that can be technically justified.

A concept that must be emphasized for a user developing a modeling strategy is that the least complex approach that can accomplish project goals (i.e., environmentally protective and cost-effective NPDES permit limits) is generally best. There is a trade-off between cost and accuracy. Simple models tend to err on the side of overprotective limits, while more complex models bring additional costs related to data collection and consultant support. Each discharger must make a site-specific determination whether the costs involved in selecting a more rigorous modeling technique are likely to be recouped via a less restrictive discharge permit.

The following sections of this chapter present guidance on conducting a mixing zone evaluation using a modeling approach. This includes defining model data needs, model calibration requirements (if any), and model projection or forecasting requirements.

6.1 Model Data Requirements

Water quality models are mathematical abstractions of reality that provide a means to evaluate the effects of effluent discharges on a receiving water under both monitored (e.g., calibration) and unmonitored (e.g., forecast) hydrologic and environmental conditions. As such, models are simply processing tools which require specific information (or data) as input.

Simple models, such as the desktop calculations discussed in Section 4.2.1, require only limited site-specific data. However, the predictions from these calculations may be overly conservative or contain a high degree of uncertainty. Models with greater complexity can reduce uncertainty and better represent actual conditions, but they also require increasing amounts of accurate descriptive information regarding the specific characteristics of a site. This translates to higher data acquisition costs and a requirement for greater modeling expertise. As discussed in Chapter 4, care should be taken to ensure that neither an overly simplistic nor overly complex model is used.

The following subsections present the input data requirements for identifying and applying mixing zone models. These data generally fall into two categories, discharge characteristics and ambient conditions.

6.1.1 Discharge Characteristics. A description of discharge characteristics is required for appropriate selection and application of a mixing zone model. These include outfall configuration, effluent physical characteristics, and effluent chemical characteristics. The design of the outfall structure and the momentum and buoyancy of the effluent being discharged are significant factors which affect effluent mixing with ambient waters. The chemical characteristics of the effluent determine dilution levels required to meet water quality criteria at the edge of a mixing zone.

<u>6.1.1.1. Outfall Configuration</u>. Outfall designs may be classified as either surface or submerged discharges. Submerged outfalls are additionally classified as either single port or multiple port (i.e., diffuser) discharges. The advantages of various outfall designs for enhancing mixing between effluent and receiving waters were presented in Chapter 3. In general, a highly engineered submerged diffuser will provide optimum mixing. However, the increased cost associated with the design and implementation of such a diffuser may not always be offset by concurrent reductions in treatment costs.

Outfall design characteristics relevant to mixing zone modeling include the following:

Surface Discharge Outfalls:

- Distance from outlet to shoreline

- Outlet channel width and depth (or area) of flow for rectangular channels

- Outlet channel diameter and depth (or area) of flow for circular pipe channels
- Outlet orientation (i.e., angle) relative to direction of ambient flow

Submerged Discharge Outfalls:

- Distance from outlet to shoreline
- Outlet port diameter (or area), including effective contraction due to aging
- Outlet port height above the bottom sediment
- Outlet orientation (i.e., angle) relative to direction of ambient flow
- Outlet orientation (i.e., angle) relative to horizontal

For Multiport Diffusers Only:

- Number of outlet ports
- Outlet orientation (i.e., angle) relative to diffuser arm orientation
- Port arrangement (i.e., unidirectional, vertical, alternating, staged)
- Total length of diffuser arm

Descriptions of complex submerged multiport diffusers, such as those with two or more diffuser arms, must be either simplified for mixing zone models or evaluated in piecemeal fashion. These outfall design situations require greater expertise than is possible to convey within this guidance manual.

The CORMIX model user guide (NCASI 1992) provides definition sketches and data templates for each of the outfall configurations mentioned above. These templates can be modified to allow inclusion of ambient tidal conditions. Detailed information on the specific outfall configurations simulated by CORMIX is provided in the documentation for each of the CORMIX sub-models: CORMIX1 for submerged single port discharges (Doneker and Jirka 1990), CORMIX2 for submerged multi-port discharges (Akar and Jirka 1991), and CORMIX3 for surface discharges (Jones and Jirka 1991).

6.1.1.2. Effluent Physical Characteristics. Nearly all effluent discharges of concern to the users of this manual will undergo some degree of near field (discharge-induced) mixing, due to both initial momentum (i.e., exit velocity) and initial density differences between the effluent and the receiving water. The flow rate and density of an effluent directly affect these initial flux characteristics of the discharge. These additional factors, along with the outfall design configuration discussed above, control mixing characteristics of the effluent in the near field.

Effluent flow rate, temperature and salinity measurements are typically available from monitoring reports for existing discharges. Effluent density can be calculated from temperature and salinity data. Fischer *et al.* (1979) provide lookup tables and nomographs for estimating density from these two parameters. Some models, including CORMIX, allow the user to specify density either directly or in terms of temperature and salinity.

If a probabilistic mixing zone model analysis is being considered, then available effluent monitoring records should be analyzed to statistically characterize (e.g., mean, standard deviation) the effluent flow rate and density.

6.1.1.3. Effluent Chemical Characteristics. Effluent chemical concentrations must be determined if a mixing zone assessment is being conducted to calculate water-quality-based NPDES permit limits. These data are available from discharge monitoring reports for chemicals regulated under existing permits. Effluent data must be collected to identify other chemical parameters which may require a mixing zone evaluation. Facility operations and design reports should provide sufficient information to identify chemicals which must be evaluated for newly proposed discharges.

Effluent monitoring records must also be analyzed to statistically characterize the variability of effluent chemical levels if a probabilistic modeling approach is to be used.

6.1.2 Ambient Conditions. The term "ambient conditions" refers to the physical and chemical characteristics of the water body to which the outfall discharges its effluent (i.e., the receiving water). All mixing zone models require a minimum level of information describing these ambient conditions, if only to define the extent of the mixing zone in relation to the dimensions of the receiving water. These characteristics include:

- Water body type
- Bathymetry (i.e., water body depths and widths)
- Hydraulics (flow rate and/or velocity profile)
- Density structure (vertical profile)
- Ambient (background) water quality conditions

Application of EPA's simple initial dilution calculation (see Equation 4-4) requires no ambient information. However, this calculation may provide overly conservative estimates of near field dilution since the effects of ambient conditions are ignored. The precision to which each of the ambient characteristics must be defined depends on the specific model that will be applied. On the other hand, this information is also needed initially for model selection, so it is important to assemble and review all readily available data describing ambient conditions.

6.1.2.1. Water Body Type. The mixing zone models discussed in Chapter 4 are classified according to their applicability to specific types of receiving waters. These include shallow rivers (vertically well mixed), deep rivers (possible stratification), tidal estuaries (and tidal rivers), and open waters (lakes, embayments, coastal ocean).

Some models, such as CORMIX, account for shoreline boundary effects on the far field mixing of an effluent plume. The width of bounded water bodies, such as rivers and estuaries, should be characterized when regulatory mixing zone dimensions are large enough that significant interaction could occur between an effluent plume and either or both shorelines.

6.1.2.2. Bathymetry. Various sources of information are available describing receiving water bathymetry, a minimal knowledge of which is required for all but the simplest mixing zone models. Depending on the type and size of the receiving water body, bathymetric information may be available from government sources including the National Oceanographic and Atmospheric Administration (NOAA), USGS, Federal Emergency Management Agency (FEMA), and the United States Army Corps of Engineers (ACOE). Local governments and libraries may also be able to provide information from previous studies of the receiving water, including Environmental Impact Statement (EIS) reports that may have been prepared for nearby facilities. Table 6-1 provides a list of potential sources of bathymetric information for different types of receiving waters. Alternatively, a field reconnaissance survey may be necessary to identify receiving water geometry when existing sources of information are incomplete, as may be the case for smaller water bodies.

Table 6-1. Sources of Bathymetric Information

Water Body Type	Source
Rivers and other flowing inland waters	USGS quadrangle maps ACOE channel depth maps or pool sheets FEMA flood insurance study maps
Lakes and Reservoirs	NOAA navigation charts Commercial fishing depth charts Tennessee Valley Authority
Estuaries	NOAA navigation charts
Coastal Ocean	NOAA navigation charts

Once bathymetric data have been gathered and reviewed, the following characteristics of the receiving water should be identified:

- Distance of the outfall from the shore
- Depth of water at the outfall location
- Average depth of the water body
- Slope of the bottom geometry in the direction of the outfall discharge
- Width of the water body (if appropriate, as discussed under water body types)

NOAA tidal height tables provide the supplemental information needed to characterize geometry in estuarine and coastal waters as a function of the tidal cycle.

This site-specific information is important not only for application of a mixing zone model, but also for selection of the modeling approach. Specific mixing zone models are appropriate for different types of water bodies and outfall configurations. Developing a description of the water body geometry in relation to the outfall location is a necessary step in evaluating possible models for application.

6.1.2.3. Hydraulics. Characterization of receiving water hydraulics for a mixing zone assessment is typically based upon existing information such as USGS flow records and/or NOAA tidal current tables. These data may be obtained directly from the relevant government agency, from local libraries, or through commercial vendors.

All but the most complex mixing zone models assume a simple steady-state characterization of receiving water hydraulics, including no variation in current speed throughout the depth of the water column. Hydraulic input may either be specified in terms of an average flow rate or an average velocity, depending on the specific mixing zone model.

6.1.2.4. Density Structure. Buoyancy depends on the relative difference in density between the effluent and ambient water. As discussed in Chapter 4, the relative buoyancy of effluent discharging from an outfall structure has a significant effect on the rate of mixing that occurs as an effluent plume rises or sinks through the water column during the initial stages of discharge-induced (i.e., near field) mixing.

The density structure (or vertical profile) of the receiving water can be readily determined from temperature and salinity data. Sources for this information include:

- USGS water quality records
- EIS studies
- Mixing zone studies for adjacent discharges
- NOAA atlases which classify salinity zones in estuarine and coastal waters

Receiving waters that may be significantly stratified should be characterized by measured vertical density profiles. Highly stratified waters may significantly impede mixing over distances relevant to regulatory mixing zones. Data from previous nearby studies may also be available for characterizing vertical profiles.

6.1.2.5 Ambient Water Quality Conditions. The final ambient characteristics that must be identified for a mixing zone evaluation are the background or upstream water quality conditions for all chemicals under consideration for a water-quality-based NPDES permit. Significant background concentrations require greater effluent dilution to meet water quality criteria outside a mixing zone. Dischargers whose permit limits are based upon the assumption of non-zero background concentrations should review how background concentrations were defined. Consider collecting additional information if the existing data are uncertain (or non-existent) and use of a lower background concentration would result in a significantly different permit limit.

Data sources for background water quality conditions include USGS water quality records, the EPA STORET database, or NOAA. State and local agencies may also have access to information from historical studies conducted by third parties (e.g., university researchers, private consultants, etc.) at or near the site being evaluated.

6.2 Model Calibration Requirements

Model calibration compares predictions to observed data to demonstrate that the model accurately describes the system under study. Adjustments to specific input parameters may be made during calibration to improve the accuracy of the prediction. Many times, calibration is not required when applying a mixing zone model to develop NPDES permit limits. However, some state water quality standards or mixing zone policies may require a demonstration of model validity. This demonstration may encompass the following:

- Justification of model selection and inputs: Demonstrating that the selected model and its inputs are appropriate.

- Sensitivity of model predictions: Displaying the variability of model results in response to changed inputs.

- Calibration of model simulations to field data: Adjusting model inputs so that predicted results are consistent with an observed data set.

- Verification of model results against additional field data sets: Demonstrating that model results are consistent with an additional independent data set(s).

The necessary level of demonstration may be initially difficult to determine since requirements for model validation are typically not specified in state water quality regulations. Instead, mixing zone assessments are generally handled on a case by case basis guided by either a mixing zone policy or the expectation that EPA technical guidance will be followed.

6.2.1. Justification of Model Selection and Inputs. At a minimum, the model selected for a mixing zone evaluation must be justified based on its capabilities to simulate conditions for the site under consideration. Documentation of site-specific ambient and discharge conditions integrated with a review of model capabilities (see Chapter 4) generally provides adequate justification for selection of a specific mixing zone model. Documentation of previous applications of the selected model under similar conditions may also help to support model choice. Use of the EPA-supported models described in this document, although not required, will also lend credibility to the model selection process.

Model parameters which are not site-specific should be supported by references to relevant technical literature and to similar studies, if possible. These may include dispersion and other coefficients which affect the rate of mixing and entrainment of ambient water with an effluent plume.

6.2.2. Sensitivity of Model Predictions. A second level of model validation involves sensitivity analyses to evaluate the uncertainty in predictions resulting from input parameters not developed from site-specific sources. A sensitivity analysis typically consists of performing two additional model simulations for each parameter to be evaluated. The first of these simulations will set the parameter of interest to the lowest end of its expected range, with the second simulation using the highest expected value. The range of model results between these two simulations defines the sensitivity of predictions to the uncertainty in any given model input. Professional judgment is often required to define the expected range for a given model input, although a range corresponding to +/- 50 percent of the default parameter value is commonly used.

Two factors will determine the uncertainty range that results from sensitivity analysis. These are the uncertainty in the model parameter of concern and the importance of that parameter in *model* predictions. Model output uncertainty is greatest when both of these factors are large, and is small if either of the factors is small. For example, upstream flow is very important in determining available dilution for a discharge to a river (i.e., the second factor is large), but can be measured very accurately (i.e., first factor is small). In these cases, overall uncertainty caused by upstream flow is small. The dispersion coefficient in open water discharge situations is one example of a parameter that is both highly uncertain and has a significant impact on model predictions.

6.2.3. Calibration of Model Simulation Results to Field Data. Mixing zone model calibration consists of the adjustment of model inputs to achieve a satisfactory comparison between predictions and actual field data. In general application, mixing zone models predict effluent dilution within ambient waters as a function of distance from the outfall. A conservative (e.g., non-reactive) tracer provides the best means for evaluating a mixing zone model calibration. Methods for assessing model performance using water quality field survey data and dye surveys are presented in Chapter 7.

6.2.4. Verification of Model Results with Additional Field Data Sets. In some instances, model results must be compared to additional data set(s) beyond the one used for calibration to further verify predictive capability. This process is called model verification. Although the costs required to collect additional data and perform model verification are high, the reliability—and ultimately, regulatory acceptability—of predictions from a verified model are also high.

6.3 Model Projection Requirements

Model projection analyses have traditionally taken either of two forms:

- Predict the amount of dilution available at a specific location and use this information to define allowable effluent concentrations.
- Predict the size of the mixing zone (i.e., area where water quality criteria are exceeded) that will occur with existing effluent concentrations and demonstrate to regulatory authorities that this size is acceptably small.

The first form is the most common, and will be used here as the basis of discussion for selecting critical model input conditions. All guidance for selecting critical conditions provided in this section is equally applicable to both approaches.

6.3.1. Use of Environmental Design Conditions for Model Projections. The use of a statistically derived critical design condition in a model is the most common approach to defining necessary controls to protect water quality at the edge of the mixing zone. In the simplistic case of a constant discharge, the frequency of water quality exceedance can be directly controlled by selecting a critical design condition with an appropriately small frequency of occurrence. Consider the basic dilution equation:

$$C_{mix} = C_{eff} / S \qquad (6\text{-}1)$$

where:

C_{mix} = Concentration at the edge of the mixing zone

C_{eff} = Effluent concentration

S = Available dilution

This equation is rearranged for permitting purposes to calculate the maximum allowable continuous load ($C_{eff,allow}$) that will result in mixing zone concentrations which achieve the water quality standard (C_{WQS}) for some critical design dilution (S_{DESIGN}).

$$C_{eff,allow} = C_{WQS} + S_{DESIGN} \qquad (6\text{-}2)$$

If C_{eff} remains constant in Equation 6-1, the variability of the mixing zone concentration is determined strictly from the variability in dilution. The percent of time that the concentration will exceed water quality standards can be directly controlled by using an appropriate critical dilution in Equation 6-2. For example, the use of a once in ten year low dilution for specifying $C_{eff,allow}$ - the most common practice in defining critical dilution in rivers - will restrict exceedances of the criterion to once in ten years.

The approach is somewhat less straightforward for most real world cases where the load is variable (yet still continuous) over time. If $C_{eff,allow}$ in Equation 6-2 is used to define the allowable *average* loading rate, use of a once in 10-year design dilution can result in a frequency of exceedance much more often than once in 10 years, because the actual loading may often exceed the average value. To account for this fact, permitting guidance in the TSD (EPA 1991) recommends that $C_{eff,allow}$ calculated from Equation 6-2 represent the 95th or 99th percentile allowable load, with the allowable average loading much less than this value. Depending upon effluent variability, allowable average concentrations are typically 50 to 70 percent less than the value calculated from Equation 6-2. This approach does not provide an exact estimate of the loading rate required to achieve the desired frequency of violation, but it is often a reasonable approximation.

6.3.2 Selection of Design Condition Inputs. Application of the design condition approach requires selecting a design dilution (S_{DESIGN}) with an acceptable frequency of occurrence to be used in Equation 6-2. This is accomplished by performing a dilution model simulation using input values that represent some seldom-achieved environmental condition. Selection of model inputs is straightforward when a single environmental parameter controls available dilution. The 7Q10 low flow is mandated in many state regulations for use with the simple initial dilution model. Selection of design condition inputs becomes much more problematic as the number of model inputs increases. For example, the joint probability of occurrence of three independent once in ten year events is once in *one thousand* years. Unfortunately, no easy method exists for selecting multiple design condition inputs. Some options include use of data for a single condition only, using an extreme value for a critical parameter only, a critical period approach, and probabilistic analysis.

The first option occurs when data are available describing only a single set of environmental conditions. This may occur for marine discharges, where it is difficult to gather multiple observations on ambient stratification. This option is best suited for screening purposes only, since it provides no information on the frequency with which water quality criteria will be violated.

The second option is applicable in those cases where a single environmental parameter is most responsible for determining available dilution, even though inputs on many parameters may be required by the model. In these cases, a critical value (e.g., once in 10 years) may be selected for this parameter, with more typical values selected for the less important parameters. This is consistent with the approach taken by the state of Nebraska for calculating ammonia permit limits, where a once in 10-year stream dilution flow is used in conjunction with 50th and 75th percentile values for pH and temperature.

The third option, the critical period approach, consists of reviewing the record of environmental conditions at the discharge site to identify a historical period that provided very low assimilative capacity. The conditions that occurred during this period are then used as input to the dilution model. This approach is somewhat qualitative in that the frequency of occurrence of the critical period cannot be rigorously defined. However, it does provide inputs with some reasonable likelihood of occurrence, as opposed to arbitrarily selecting critical values for all inputs.

The final, and most rigorous, option is probabilistic analysis. With this approach, the variability in all environmental inputs is characterized, and the resulting probability of occurrence of different dilution values is directly obtained. Another advantage of probabilistic analysis is that it can directly consider the variation in effluent quality, and does not require the simplistic calculation of allowable long term average effluent values discussed previously. Unfortunately, the only widely available probabilistic modeling tool for mixing zones is DYNTOX, which is applicable only for initial mix calculation in rivers. Probabilistic analysis can also be conducted using more rigorous models by performing repeated model simulations and modifying model input values to reflect their variability. This is a very powerful tool to demonstrate when critical conditions selected by the regulatory agency are overly protective, but the effort involved is beyond the scope of this document.

6.4 Model Selection Strategy

Several mixing zone models have been identified and discussed in Chapter 4 and Chapter 5. The following strategy is suggested for selecting a mixing zone model that is appropriate to a specific outfall and receiving water configuration.

- Conduct a preliminary evaluation of the three primary factors which affect mixing zone model selection, including regulatory requirements, discharge outfall characteristics, and ambient conditions. This information should first be summarized in a general narrative fashion. For example, an existing outfall may be described as a surface discharge, or as a submerged single or multiport diffuser. The receiving water can also be characterized in relatively general terms, such as a deep river or stratified estuary.

- The preliminary site-specific information can then be used to select potentially appropriate mixing zone models from Table 4-1 and Table 4-2. This will likely limit the scope of model selection to only one or two choices.

- The detailed development of the mixing zone model input data requirements, discussed previously in this chapter, can then be used to finalize the model selection.

- The process of model validation can then be used to justify the mixing zone model selection and its application. It is not uncommon for technical problems to arise during the validation process as the selected model is developed and initial simulations are conducted. Mixing zone model output should be carefully examined. Unrealistic dilution predictions may indicate that the model cannot appropriately simulate the specific ambient and discharge configuration. In these situations, an alternative, yet equally valid, model may provide realistic predictions of effluent dilution within the receiving water.

Some sites may be too complex for any of the mixing zone models discussed in this document. In these cases, the discharge and receiving water characteristics may need to be simplified for model application, or more complex models may be required. Technical guidance for these situations is beyond the scope of this document and consultation with hydraulic modeling and outfall design experts is recommended.

CHAPTER 7

DYE STUDIES AND OTHER ALTERNATIVES

Dye tracer studies may be used as supplements or alternatives to mixing zone modeling. The objective of a tracer study is to quantitatively characterize an effluent plume as it actually disperses in the receiving water. Study results can be used to map the horizontal and vertical boundaries and dilution of the plume in the near and far field, quantify dispersion coefficients or other site-specific model input parameters, measure minimum (worst case) and average dilution at the edge of a defined mixing zone, and calculate the rate of dilution with distance from the discharge point.

Dye study results are frequently used to calibrate and fine tune a mixing zone model or to verify model predictions. Once the credibility of a model has been established, greater confidence can be placed in its predictions regarding proposed changes in effluent characteristics, the design and location of a new diffuser, or the effect of seasonal flow and variability in ambient stratification.

In complicated flow regimes, tracer tests may be repeated on multiple days at different tidal phases, wind conditions, or discharge rates. Tests may be repeated at different times of the year to evaluate the effects of seasonal changes in density stratification, or the effects of high river runoff compared to minimum river flow. Tracer tests are frequently targeted for the expected worst-case or critical conditions, such as at low river flows and slack current speeds.

7.1 Dye Study Rationale

The primary rationales for conducting dye studies are:

- To provide data for model selection, development, and calibration.
- To demonstrate compliance with mixing zone regulations and water quality criteria.

Both rationales may be driven by regulatory requirements. For example, a regulatory agency may require calibration of a dilution model before accepting it to establish a mixing zone. Or the agency may require a post-construction demonstration of mixing zone dilutions and dimensions originally developed based on modeling.

Other related factors may also justify a tracer study. In some cases, model results may be inaccurate or overly conservative. The same may apply to generic mixing zone guidelines used by a regulator. A discharger may therefore want to justify a larger mixing zone or greater dilution credit based on actual field measurements. However, the discharger in such a situation should carefully evaluate the trade-off between costs associated with a tracer study versus the capital expenditures to upgrade treatment or modify an outfall if model results or generic dilution guidelines were to be taken at face value.

7.2 Field Study Execution

A plume characterization study that provides useful results requires a substantial effort in planning, logistics, equipment, and field execution. A similar effort is needed to process, present, interpret, and report the field results in a meaningful manner.

The best strategy for a particular test depends on a number of factors, including the hydrographic and flow conditions at the time of testing. Any available data should be reviewed during the planning stages. This may include information on historical discharge and receiving water flows, receiving water quality, currents and tides, and weather. Testing options should be developed and evaluated based on available resources and the data required to meet regulatory and/or modeling needs.

The field study approach also depends on the type of discharge, the receiving water, and the primary purpose of the study. Is it to define only the near field mixing zone, or both near field and far field? Is the discharge to a free-flowing river, tidally influenced river, estuary, bay, or coastal waters? In general, the level of effort increases with the complexity and variability of receiving water conditions. Greater variability equates to more planning, longer tests, more equipment and field staff, more tracers, and greater costs. Tables 7-1, 7-2, and 7-3 list some of the factors to consider and possible approaches for conducting tracer tests in different types of receiving waters.

7.2.1. Tracer Selection. A tracer is usually added to the wastewater discharge specifically for the field dilution study. However, in some cases, a specific property of the effluent may serve as the tracer without the need to add anything. In the case of a thermal discharge study, a conservative tracer may or may not be used. Since temperature is not conservative (heat is transferred through conduction and evaporation as well as dilution), a conservative tracer would be used to quantify the dilution aspect.

There is no single ideal tracer for all applications and conditions. Some of the characteristics of an ideal tracer include:

- Nontoxic
- Inexpensive
- Measurable to parts per billion or lower
- Easily measured in the field with portable instrumentation
- Conservative and stable for many days
- Not present or nonvarying in the receiving water

Typical tracers include fluorescent dyes (Rhodamine WT, Fluorescein), conductive salts (potassium chloride, sodium chloride), and lithium. In some cases, the electrical conductivity of the discharge is distinctive enough to serve as a tracer without adding additional salts. Although radioactive isotopes were once used for effluent tracing in receiving waters, they are no longer used.

Rhodamine WT fluorescent dye, the most commonly used tracer, is sold as a liquid solution. The dye is highly water soluble, stable in sunlight, has low sorptive tendency, and is easily measured to part per billion levels in the field. It has been approved as a tracer in drinking water supplies. On the down side, it is destroyed by oxidants such as chlorine, and can become expensive for long dye injections. Rhodamine WT concentrations are measured with a field fluorometer.

Table 7-1. Free-Flowing River Mixing Characteristics and Tracer Study Approach

Physical characteristics	Uni-directional flow Current speed and water level vary little in the short term Flow confined within well-defined channel boundaries Typically shallow Little or no density stratification Fresh water Base river flows, current speeds, and water depths vary seasonally
Mixing characteristics	Bottom friction promotes rapid vertical mixing Rate of dilution drops significantly after vertical mixing complete Plume will eventually surface although it may be some distance downstream depending on current velocity Lateral dispersion highly dependent on channel morphology and presence or absence of rapids
Field study approach	Single day test scheduled during lowest seasonal flows Identify distance and dilution at point of complete vertical mixing Track plume to complete mixing across river width May be appropriate to use natural conductivity difference as plume tracer
Ancillary measurements	River flow, temperature, conductivity, velocity Effluent flow, temperature, conductivity Wind speed and direction, air temperature

Table 7-2. Tidally Influenced River Mixing Characteristics and Tracer Study Approach

Physical characteristics	Possible bi-directional current flow Current speed and water level vary with tidal stage Flow confined within well-defined channel boundaries Relatively shallow water depths Possible density stratification, varying with tide Fresh water with possible brackish layer Base river flows, current speeds, and water depths vary seasonally Density stratification may vary seasonally
Mixing characteristics	Rate of mixing may change significantly depending on tidal influence on current speeds and water depth Plume may surface over diffuser at slack water, or surface downcurrent, depending on velocity Water column stratification may affect vertical plume distribution Lateral dispersion affected by channel morphology and current speed and direction Wind effects on surface currents may be significant, particularly during slack water periods Plume re-entrainment may occur if flow direction reverses Concentrated plume may form at slack water, and may retain its identity downstream
Field study approach	Multi-day and seasonal tests Extra effort to ensure that timing of study occurs under optimal conditions May be appropriate to track plume downstream to complete mixing Concentrate measurement effort in the near field at slack water Look for plume re-entrainment at tide reversal Identify and track concentrated plume formed at slack water Characterize near field and far field dilution under free-flowing conditions Measure background water quality and density profiles out of plume influence
Ancillary measurements	River flow, water depth change, temperature, conductivity Effluent flow, temperature, conductivity Wind speed and direction, air temperature Current velocity over time

Table 7-3. Bay and Estuary Mixing Characteristics and Tracer Study Approach

Physical characteristics	Multi-directional flow possibilities Current speed and water level vary with tidal stage Larger area does not distinctively confine the plume as in a river, and the plume will be distributed unevenly in a continuously varying manner; however, some predominate distribution trends are expected Water may be deep, and depths vary significantly Density stratification very likely Predominantly sea water, possible freshwater surface lens if near river discharge Density stratification will vary seasonally, particularly in estuarine environments
Mixing characteristics	Initial mixing driven by jet mixing and buoyancy, augmented by advective flow from ambient currents Rate of mixing will change significantly depending on tidal currents Water column stratification will affect vertical plume distribution A buoyant plume may rise to the surface or become trapped subsurface, and it may alternate between rising to the surface and remaining subsurface depending on tidal currents and vertical density stratification Subsequent dilution and dispersion are driven by advection and turbulent diffusion both horizontally and vertically Wind effects on surface currents may be significant Plume re-entrainment may occur if flow direction reverses over the outfall Concentrated plume may form at slack water, and may retain its identity downcurrent
Field study approach	Multi-day and seasonal tests Strategy, logistics, and coordination effort increased to identify and measure optimal conditions May be appropriate to track plume downstream to limits of tracer detection, or to an arbitrary distance Concentrate measurement effort in the near field at slack water Look for plume re-entrainment at tide reversal Identify and track concentrated plume formed at slack water Characterize near field and far field dilution under slack and full running current conditions Measure background water quality and density profiles out of plume influence
Ancillary measurements	Effluent flow, temperature, conductivity Wind speed and direction, air temperature Current speed and direction Receiving water quality and density profiles

7.2.2. Field Measurement Using Dyes. Although the field measurement details provided below are written around the use of Rhodamine WT, many of the same concepts apply to other tracers as well. The following paragraphs step through each major element of a typical outfall dye study and discuss some of the available equipment and options.

The ideal plume tracking methodology provides field scientists with real-time feedback on the location and movement of the wastewater plume. This information can be used in turn to guide subsequent measurements so that effort will be targeted where it will provide the most useful information to characterize the plume. Ideally, the field instrumentation should allow rapid data collection with high spatial resolution, both vertically and laterally, in order to delineate and quantify plume dilution.

7.2.2.1. Dye Injection Considerations. Dye is expensive, so the injection duration and final effluent concentrations impact the project cost directly. Rhodamine WT is sold as a nominal 20 percent active solution. The exact concentration is not critical since dye measurement and dilution calculations are based on relative values, not absolute concentrations.

An important function of the dye injection system is to maintain a constant dye concentration in the effluent even as the effluent flow changes. During dye injection, injection rate and effluent flow data should be recorded at regular, frequent intervals. A variable rate constant displacement pump may be used.

Ideally, the injection point will be at a location that will rapidly mix the dye with the effluent flow. Good sites would be upstream of pumps, mixers, weirs, or sharp turns in a channel or pipeline. Avoid slow-moving channels and tanks or basins as the injection location.

Rhodamine WT is destroyed by chlorine. The effect may or may not be significant, depending on the chlorine residual concentration in the effluent and the contact time. Whenever possible, eliminate or reduce residual chlorine concentrations during dye testing. If some effluent chlorination is unavoidable, special tests may be warranted to determine if the dye will be degraded significantly in the effluent.

7.2.2.2. Effluent Dye Sampling and Monitoring. It is important to have a continuous record of the actual dye concentration in the effluent, particularly when the discharge flow may vary significantly. This may be accomplished by taking frequent grab samples for later dye analysis, either manually or using an automatic discrete sampler, or using a fluorometer outfitted with a flow-through cuvette system and data logger. If available, continuous monitoring by a flow-through fluorometer will provide immediate feedback regarding the actual dye concentration as well as its stability.

Effluent flow should be recorded during dye testing. It may be appropriate to monitor temperature and conductivity or other parameters as well.

Effluent Sample Location--Complete dye mixing should be achieved at the selected effluent sampling location. A general rule-of-thumb is that complete mixing can be expected 100 pipe diameters downstream of the injection point along a straight section of pipe. This distance can be reduced dramatically if conditions exist to cause turbulent mixing.

Effluent Sample Size and Preparation--For grab samples, 250 to 500 mL of sample are recommended, stored in borosilicate glass bottles. It is very likely that grab samples will require dilution before measurement in a fluorometer. This is because the actual effluent dye concentration may be above the linear range; that is, the fluorometer output will vary in a nonlinear fashion with increasing dye concentrations due to the quenching effect. This is remedied by diluting samples to within the linear concentration range before measuring.

If continuous flow-through dye monitoring is used, periodic grab samples are still needed. This is important for several reasons:

- Since the effluent may include suspended solids, the flow-through measurements will be affected by blocking of the fluorometer light path. Post-test measurement of the grab samples will provide a correction factor to account for this effect.

- Since the expected effluent dye concentrations will be above the linear range of fluorescence, a polynomial curve fit may be used to correct measured dye concentrations to actual concentrations. Verification of this curve fit will be important.

Undiluted wastewater samples typically require filtering or centrifuging before analysis in the fluorometer. In some cases, gravity settling of solids in the sample bottle will be sufficient, and clear sample may be decanted directly into the fluorometer cuvettes.

All background samples, standards, and effluent samples should be placed in a water bath as a group for at least 20 minutes before measurement in the fluorometer. Since dye fluorescence is temperature dependent, it is critical that all standards and samples are measured at the same temperature.

Dye Concentration Analyses--The fluorometer to be used for the analysis of effluent samples may be initially calibrated using dye standards produced in distilled or deionized (DI) water. Additional dilution standards may be prepared with background effluent samples spiked with the feed dye to known concentrations.

While measuring a sample, fluorescence will drift as the sample temperature changes in the fluorometer sample compartment, so it is important to read the concentration as soon as the value stabilizes.

7.2.2.3. Receiving Water Measurements. The following paragraphs discuss positioning systems, dye measurement, water quality profiles, and current measurement.

Positioning--Some means to measure position coordinates at receiving water sampling stations is essential. An X, Y, and Z (depth) coordinate is required for every data point. Increasingly, the Global Positioning System (GPS) is used for this purpose. GPS data can be recorded by hand or electronically, at fixed locations or dynamically. There are two important considerations: (1) the GPS data must be differentially corrected, either in real time or during post-processing; and (2) sufficient digits must be recorded to achieve the desired spatial resolution.

Without differential correction, any single coordinate can be in random error by 25 to 100 meters. To resolve positions down to 12 meters, the latitude and longitude degrees must be recorded to 4 digits to the right of the decimal point. One meter resolution requires at least 5 digits. Many handheld GPS units do not provide this resolution.

While performing a dye test, the GPS positions of key reference locations such as navigation markers, landmarks, structures, and established monitoring stations can be recorded for correlation with local charts and maps. Also, key shoreline features can be measured directly to aid in the production of working base maps for data presentation.

Alternative methods of positioning include the use of the LORAN system and standard surveying equipment. Less sophisticated means such as triangulation between known points, or simply using fixed reference markers (existing or specifically installed), may be used in some situations. In the recent past, electronic range-range equipment was commonly used, such as the Motorola Miniranger or Del Norte Trisponder systems. These have been largely superseded by GPS.

Dye Measurements--Receiving water dye measurements can be made from a boat using a flow-through fluorometer and pumping system. *In situ* fluorometers exist, but are expensive and not generally available. In most cases, grab sampling for later analysis is time consuming and simply does not provide enough data points to adequately characterize an effluent plume.

A typical flow-through system includes a fluorometer fitted with a continuous flow-through cuvette, and a 2-inch submersible pump. Sensors for pressure (depth), temperature, conductivity, and other parameters may be deployed along with the submersible pump. Dye and other water property data can be displayed in real time aboard the boat and recorded electronically during transects and profiles. During data processing, the pump-through time delay must be accounted for while processing dye measurements.

Since fluorescence is highly temperature dependent, measured dye concentrations must be compensated for the difference between the receiving water temperature and the fluorometer calibration temperature. The fluorometer may be calibrated using dye standards produced from the feed dye diluted with DI water or background samples of the receiving water.

Water Quality Profiles--In addition to dye measurements, temperature, conductivity, and possibly dissolved oxygen and pH should be measured with depth in the receiving water at background locations and within the plume. These data not only document conditions during the test, but can also be used for input to mixing zone modeling programs.

Current and Water Level Measurements--Receiving water current speeds are one of the primary factors driving far field dispersion. Some means of documenting current speeds during plume monitoring is important for interpreting dilution results and providing input to mathematical models. Water level measurements are useful for documenting tidal conditions and verifying tidal predictions.

Several options are available for measuring current speed. These include releasing current drogues during plume tracking, mooring a current meter array at one or more locations for the study duration, profiling periodically from aboard an anchored boat with a current meter, and running transects with an acoustic doppler current profiler. The least expensive option, current drogues, may also be used to help guide the field effort by providing a visual indicator of the speed and direction of the dyed plume, particularly if the plume remains submerged. Drogues may be deployed at the depth of the plume as determined by the dye profiling system in the field.

Wind Monitoring--In some situations, a temporary automated wind monitoring system on shore may be appropriate. Wind effects on receiving water circulation are significant and important, and a continuous record is valuable to help interpret study results. At a minimum, wind speed and direction should be recorded manually during the test at regular intervals.

7.2.2.4. Data Processing and Reporting. In post-study data processing, sampling positions may be merged with water quality and dye data based on time correlation. A base map may be created for the study area from available maps and field-collected position data. Two-dimensional plots may be produced showing dye concentrations versus distance along transects, and of concentration versus depth in vertical profiles. The locations of each transect and profile can be plotted on corresponding maps.

The plume can be depicted in vertical cross-sections, horizontal planes, and possibly as a three-dimensional representation. One useful plot is peak dye concentration versus distance from the center of the diffuser to illustrate minimum effluent dilution away from the outfall. Effluent water quality, dye concentrations, and flow data can be presented in time-series plots and summarized in tables.

7.2.3. Other Types of Tracer Studies. As noted in Section 7.2.1, effluent dilution testing can also be performed using conductivity measurements and thermal mapping. Many of the field execution concepts described above for dye testing apply equally to these types of studies.

7.2.3.1. Dilution Testing Using Conductivity Measurements. Under certain conditions, high-resolution conductivity measurements can be used to identify and track a wastewater plume in the receiving water and calculate dilution. This technique is particularly suited for rivers or in well-mixed coastal waters.

There are several advantages to using the natural conductivity difference between the effluent and receiving water as the tracer. No dye needs to be added to the effluent and, since nothing is added, there is no need to wait for the tracer to achieve equilibrium concentrations over the area under study. Measurements can be taken *in situ* with highly portable, self-contained data logging instrumentation. When conditions allow, these advantages can result in better data at a lower cost. However, this technique does require sufficient natural conductivity differences between the effluent and receiving water, and the results can be compromised if background values vary excessively with time, the receiving water is stratified, and if there are other discharges or surface water inputs in the area.

For a dilution test of a river discharge, continuous temperature and conductivity measurement and recording instrumentation can be installed in the effluent and in the river upstream of the discharge to document temporal water quality variations. Portable instrumentation would be used along with positioning equipment to record temperature and conductivity in detail downstream of the discharge along lateral transects and vertical profiles. In this application, accurate absolute conductivity values are not as critical as relative accuracy. To ensure relative accuracy between instrumentation systems and demonstrate the conductivity/dilution relationship, conductivity dilution standards can be produced in the field using the effluent and river water.

7.2.3.2. Thermal Plume Mapping. Thermal dispersion studies can be approached in several different ways. A boat or several boats with positioning and temperature logging instruments can be used to gather transect and vertical profile data in the receiving water. In deeper waters, a multi-sensor array can be towed along transects for simultaneous temperature measurements at many depths. Temperature monitoring systems can be established in the thermal discharge for continuous measurements before and during the test.

For more complete surface temperature mapping, aerial thermal imaging can be performed using a multispectral scanner mounted on a small aircraft. Ground truth surface temperature measurements are needed to calibrate and verify aerial thermal images. Typically, both boat and aerial imaging measurements are used in conjunction with each other and, at times, a conservative tracer is added to the discharge.

7.2.4. Field Testing Costs. Typical dilution field measurement programs cost between $20,000 and $75,000 per sampling mobilization. A large multi-disciplinary study conducted over multiple seasons can cost several hundred thousand dollars. Obviously, the study cost depends on the complexity and scale of the testing. Nevertheless, because these costs can be significant, dischargers should clearly define the expected benefits of a tracer study and weigh these against the likely expense of field testing and alternatives such as modeling.

7.3 Example Applications

The following case histories briefly describe two field studies of effluent mixing. The first used Rhodamine WT as the tracer for a petroleum refinery wastewater discharge in

Northern California. The second example illustrates the use of conductivity measurements as a means to quantitatively trace an effluent plume from a municipal wastewater treatment plant discharge to a small river.

7.3.1. Dye Tracer Studies and Initial Dilution Modeling for a Petroleum Refinery. Dye tracer studies were performed at a Northern California refinery to support development of alternate discharge limits (Camp Dresser & McKee, Inc. 1989). The outfall is located in Suisun Bay, a region where the saline waters of San Francisco Bay mix with fresh water from the Sacramento and San Joaquin Rivers. To support the development of alternative discharge limits, the California Regional Water Quality Control Board, San Francisco Bay Region required a determination of initial dilution at the boundary of a pre-defined mixing zone under worst case conditions.

The overall study consisted of four primary tasks:

- Data search and review
- Field program
- Comparison of dilution simulation models and modeling runs
- Minimum dilution simulations

The field program consisted of four dye surveys conducted under neap tide conditions and low river flows. Dye was injected into the effluent at a constant rate. Receiving water dye concentrations were then measured along a transect downstream from the diffuser at various depths. Vertical profiles of salinity, temperature, and current speed and direction were collected before and after each dye transect.

Dilution calculations and plume configurations measured during the field effort were then compared with results predicted by several EPA mixing zone models. Based on the field results, the model UOUTPLM was selected to best characterize the outfall discharge to Suisun Bay. Field-collected receiving water density and current data were used as model inputs for the initial validation. The model was then run using historical data to identify worst case and typical conditions for effluent dilution.

7.3.2. Municipal Discharge Plume Tracing Using Conductivity. A municipality in Nebraska opted to perform a field study in the Elkhorn River to evaluate effluent dilution within a regulatory mixing zone and the impacts of alternative effluent limits for ammonia (Brown and Caldwell 1996). The Nebraska Department of Environmental Control (NDEC) allowed this discharger to conduct site-specific special studies and provide information to modify the conservative assumptions and coefficients used in standard mixing zone models.

After it was determined that the natural conductivity difference between the receiving water and effluent could be used to resolve at least a 100:1 dilution in the receiving water, the NDEC agreed to the use of conductivity as a plume tracer. Temperature and conductivity data were monitored and recorded using portable data logging instrumentation installed in the effluent and upstream of the discharge in the Elkhorn River. These data were collected 24 hours before and during the plume tracking. A third data logging unit was carried aboard a small boat for in-river transects and vertical profiles. Calibration of all three units was performed by reading the conductivity of serial effluent dilutions in river water.

Positioning was accomplished using a differential GPS mounted on the boat used for sampling. Over 5,000 data points with geographical coordinates were collected in about 6 hours on the river, extending from just above the discharge to about 1.5 miles downstream.

The conductivity data were processed to calculate minimum dilution, percent effluent, and percent mixing with distance downstream of the discharge. The distance downstream to complete vertical mixing was also shown. A means to estimate the effect of lower river flow was devised and the results are now being used by the municipality to present a case to the NDEC for less stringent discharge limits for ammonia. The total cost of this field study was approximately $25,000.

CHAPTER 8

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APPENDIX A

SUMMARY DESCRIPTIONS OF MIXING ZONE MODELS

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SUMMARY DESCRIPTIONS OF MIXING ZONE MODELS

Model: Jet Momentum Equation (Equation 4-4)

Source: Technical Support Document for Water Quality-based Toxics Control (EPA 1991).

Model Structure: Single, one-dimensional equation.

Complexity: Low

Applicability: Neutrally buoyant discharges (primarily fresh water); most appropriate for dilution near the outfall.

User-friendly? Simple to apply

Computational Requirements: Handheld calculator

Data Requirements: Low (diameter of outfall and distance from discharge)

Output: Dilution at a given distance from the outfall.

Comments: Rapid, simple screening tool. Minimum dilution estimate. Will be conservative as distance from outlet increases. Assumes ambient-induced mixing is unimportant.

Model: River Initial Mix Model (Equation 4-5)

Source: Water Quality Assessment: A Screening Procedure for Toxic and Conventional Pollutants in Surface and Ground Water (EPA 1985b).

Model Structure: Single zero-dimensional equation predicting concentration at point of mix in a river.

Complexity: Low

Applicability: Restricted to situations where regulatory definition of the mixing zone requires this approach.

User-friendly? Simple to apply

Computational Requirements: Handheld calculator

Data Requirements: Low (upstream flow, effluent flow, fraction of cross-section available for dilution)

Output: Dilution at point of mix.

Comments: Most commonly applied river mixing zone tool, yet applicable only to a specific set of conditions. Assumes complete and rapid mixing over a fixed cross-section of the stream.

Model: River Ambient Dilution Model (Equation 4-6)

Source: Technical Support Document for Water Quality-based Toxics Control (EPA 1991).

Model Structure: Single one-dimensional equation.

Complexity: Low

Applicability: Vertically well mixed free-flowing streams.

User-friendly? Simple to apply

Computational Requirements: Handheld calculator

Data Requirements: Low (lateral dispersion coefficient, instream velocity, stream width)

Output: Dilution at a given distance from the outfall.

Comments: Rapid, simple screening tool. Provides estimate of minimum dilution--may be conservative. Only considers ambient-induced mixing.

Model: DYNTOX

Source: U.S. EPA Office of Science & Technology, Washington, DC.

Model Structure: Probabilistic river wasteload allocation model.

Complexity: Moderate

Applicability: Probabilistic assessment of mixing zones in shallow rivers, surface or submerged single port discharges.

User-friendly? Yes

Computational Requirements: 80486 (or greater) processor, 640k memory, 200k disk space

Data Requirements: Requires description of variability in upstream and effluent flows and concentrations.

Output: Graphic and tabular display of frequency distribution of pollutant concentrations in the mixing zone.

Comments: Not specifically designed as a "mixing zone" model, but the only model available to provide probabilistic assessments.

Model: CORMIX

Source: U.S. EPA Center for Exposure Assessment Modeling, Athens, GA.

Model Structure: Expert system that automatically selects from a set of near field and far field models.

Complexity: Moderate to high

Applicability: Submerged or surface discharge, single and multiple ports, shallow or deep receiving water.

User-friendly? Moderately

Computational Requirements: 80486 (or greater) processor, 640k memory, 5 MB disk space.

Data Requirements: Requires a complete description of discharge and ambient receiving water. Automatically selects all model coefficients.

Output: Tabular description of dilution along centerline of plume.

Comments: Can be applied to the widest range of conditions of any mixing zone model. Assumes that expert system is capable of selecting appropriate model for system under study.

Model: UM-PLUMES

Source: U.S. EPA Office of Research and Development, Environmental Research Laboratory-Narragansett, Newport, Oregon

Model Structure: Buoyant jet model, coupled with estimate of far field dilution.

Complexity: Moderate

Applicability: Submerged discharge, multiple ports, shallow or deep receiving water, positively buoyant plume.

User-friendly? Moderately. Fairly detailed input file, but the UM-PLUMES interface provides a full screen input editor.

Computational Requirements: 80486 (or greater) processor, 640k memory, 5 MB disk space.

Data Requirements: Moderate to high. Requires a complete description of discharge and ambient receiving water.

Output: Tabular description of dilution along centerline of plume.

Comments: Can be run in parallel with RSB, and results compared.

Model: RSB

Source: U.S. EPA Office of Research and Development, Environmental Research Laboratory-Narragansett, Newport, Oregon

Model Structure: Buoyant jet model, coupled with estimate of far field dilution.

Complexity: Moderate

Applicability: Submerged discharge, single and multiple ports, shallow or deep receiving water, buoyant plume.

User-friendly? Moderately

Computational Requirements: 80386 (or greater) processor, 640k memory, 1 MB disk space.

Data Requirements: Moderate to high. Requires a complete description of discharge and ambient receiving water.

Output: Tabular description of dilution along centerline of plume.

Comments: Can be run in parallel with UM-PLUMES, and results compared.

Model: UDKHDEN

Source: Unsupported

Model Structure: Buoyant jet model, coupled with estimate of far field dilution.

Complexity: High

Applicability: Submerged discharge, single and multiple ports, shallow or deep receiving water, buoyant plume.

User-friendly? No

Computational Requirements: 80486 (or greater) processor, 640k memory, 5 MB disk space.

Data Requirements: High. Requires a complete description of discharge and ambient receiving water, along with characteristics of mixing.

Output: Tabular description of dilution.

Comments: Most rigorous mixing zone model, but also the most difficult to apply.

Model: PDS

Source: Unsupported

Model Structure: Three-dimensional surface model.

Complexity: High

Applicability: Submerged discharge, single and multiple ports, shallow or deep receiving water, buoyant plume.

User-friendly? No

Computational Requirements: 80486 (or greater) processor, 640k memory, 5 MB disk space.

Data Requirements: Moderate.

Output: Tabular output of centerline dilution, average dilution, plume depth and width.

Comments: Output format amenable for further processing. Multiple simulations can be easily conducted (batch runs).

Model: PDSM

Source: Unsupported

Model Structure: Buoyant jet model, coupled with estimate of far field dilution.

Complexity: High

Applicability: Submerged discharge, single and multiple ports, shallow or deep receiving water, buoyant plume.

User-friendly? No

Computational Requirements: 80486 (or greater) processor, 640k memory, 5 MB disk space.

Data Requirements: Moderate.

Output: Tabular output of centerline dilution, average dilution, plume depth and width.

Comments: Output format amenable for further processing. Multiple simulations can be easily conducted (batch runs).

APPENDIX B

OBTAINING MODELS FROM EPA CENTER FOR EXPOSURE ASSESSMENT MODELING (CEAM)

APPENDIX B

OBTAINING MODELS FROM EPA CENTER FOR EXPOSURE ASSESSMENT MODELING (CEAM)

General Information About Electronic Access

Internet address: ftp.epa.gov (134.67.99.11)
US EPA home page: http://www.epa.gov/
US EPA gopher: gopher earth1.epa.gov
CEAM home page: ftp://ftp.epa.gov/epa_ceam/wwwhtml/ceamhome.htm
CEAM ftp: ftp ftp.epa.gov

> log in as anonymous
> cd epa_ceam
> then follow menu/file information screen instructions

General inquiries concerning US EPA public information on the Internet should be sent to internet_support@unixmail.rtpnc.epa.gov. General inquiries concerning CEAM should be sent to ceam@athens.ath.epa.gov.

FTP

CEAM software products for microcomputer (DOS) installation and application can be down loaded through Internet node earth1 (ftp.epa.gov) via "anonymous" ftp log in and file transfer commands and options. Start the ftp program from the user's Internet node system (type 'ftp'), establish earth1 connection (type 'open ftp.epa.gov'), log onto earth1 using anonymous account (type 'anonymous'). Respond to password prompt with users e-mail or Internet address. Then, upon log in completion, type 'cd epa_ceam', read CEAM Internet Welcome Screen, then type 'get CEAMNEWS.TXT -' to view latest news and list of CEAM software products available on the Internet.

World Wide Web (WWW)

CEAM software products are available through the WWW at the following Uniform Resource Locator (URL) file:

> ftp://ftp.epa.gov/epa_ceam/wwwhtml/ceamhome.htm

Diskette

Software products are available on diskette from CEAM at no charge. Users are encouraged to request one or two software products per written request; a request for three or more products lengthens the response time.

Program or user documentation, or instructions on how to order documentation, will accompany each response in either printed or electronic media form as an unformatted ASCII (non-binary) text or WordPerfect (binary) file.

There are no fees for CEAM software product diskette distribution. CEAM has a diskette exchange policy. CEAM must receive the following before shipping software products: (1) a cover letter requesting the software product(s) (with a complete return address) and (2) diskettes. CORMIX requires 5 diskettes; PLUMES requires 2. Send the appropriate number of 3.5 inch, high density (DS/HD, 1.44MB) diskettes to:

Model Distribution Coordinator
CEAM
c/o U.S. EPA
960 College Station Road
Athens, GA 30605-2700 USA

Domestic requests are sent first class or priority mail. Delivery time is approximately 10 days from the date sent. Foreign requests are sent air mail. Estimated time of delivery varies. Requests are processed on a first come, first serve basis by CEAM. CEAM does not send information via fax.

APPENDIX C

SAMPLE MIXING ZONE MODEL OUTPUT

APPENDIX C

SAMPLE MIXING ZONE MODEL OUTPUT

Attached to this appendix are sample outputs for the mixing zone models PDS, UM-PLUMES, CORMIX, and UDKHDEN, along with a brief description of output format. In each case, the output begins with a restatement of the inputs, followed by the output data which are arranged in columns.

PDS

The top portion of the PDS sample output shows a restatement of the inputs. Below the inputs, the PDS program output is arranged in columns. The headers which describe the column content are defined as follows: distance along the plume centerline (S), distance downstream of the discharge in the direction of the ambient current (X), distance out into the receiving water normal to the ambient current (Y), local plume flow direction relative to the ambient current (TH), excess temperature at plume centerline (EX. TEMP), time it has taken a particle of fluid to travel from the point of the discharge to the printout point traveling along the plume centerline (TIME), average dilution (Q/Q0), minimum centerline dilution (QM/Q0), depth of plume (DEPTH), and width of plume (WIDTH).

UM-PLUMES

The top portion of the output shows a restatement of the inputs. Below the inputs are several lines of the initial dilution calculation. These calculations are arranged in columns, describing, from left to right: plume depth (plume dep), plume diameter (plume dia), pollutant concentration (poll conc), dilution (dilution), and horizontal distance (hor dis). Below the initial dilution calculation is a section displaying the far field calculations. UM-PLUMES performs the far field calculations using two different methods: (1) the 4/3 power law, and (2) constant eddy diffusion, which are each recorded in columns of concentration (conc) and dilution. Both columns of far field calculations are paired with columns to their right showing horizontal distance (distance) and time.

CORMIX

The first page of the CORMIX output shows a restatement of the inputs. The first module of output, the discharge module, begins at the bottom of the first page and continues onto the top of the second page. Other modules of outputs, each separated by two horizontal lines, follow on the succeeding pages. Each of these outputs are arranged similarly, in columns with the following headers: distance downstream from the outlet (X), lateral distance (Y), change in depth (Z), dilution factor (S), concentration (C), and width of the plume (B).

UDKHDEN

The table in the top portion of the UDKHDEN output restates the inputs for ambient conditions. Below this, the output is arranged in columns with the column headings, from left to right reading: horizontal distance perpendicular to the ambient current (X), horizontal distance parallel to the ambient current (Y), vertical distance from the discharge port (Z), local horizontal flow angle relative to the X coordinate (TH1), initially, angle of the discharge port with respect to the horizontal (TH2), plume diameter or, if merging occurs, width of the plume (WIDTH), excess velocity (DUCL), excess density (DRHO), ratio of the instantaneous centerline concentration of a tracer to the discharge concentration of that tracer, assuming an ambient concentration of 0.0 (DCCL), time (TIME), and average dilution (DILUTION).

PDS SAMPLE OUTPUT

```
1
SAMPLE RUN OF PDS PROGRAM
     2.0        0.5        1.0       0.2      17.0      15.0      90.0
     0.0    0.00001       0.05       0.2      0.02     500.0


SAMPLE RUN OF PDS PROGRAM

FLOATING WARM WATER JETS --  SAMPLE RUN OF PDS PROGRAM                                       PAGE 1
AMBIENT CONDITIONS    :  TEMP. TA=  15.0 DEG. C  ,    VEL. UA=     .20 M/SEC  ,HEAT CONVECTION  =   .100E-04
DISCHARGE CONDITIONS :  TEMP. TO=  17.0 DEG. C ,VEL. UO=  1.00 M/SEC  ,WIDTH WO=   2.00 M.  ,DEPTH HO=    .50 M.  ,ANGLE  90.0DEG
FRO = 25.0    E =  .0500   CD = 1.0000    CF =  .0000   RE =  .000E+00   EV =  .200E+00  EH =  .200E-01
```

S(M.)	X(M.)	Y(M.)	TH(DEG.)	EX.TEMP (DEG. C)	TIME(SEC.)	Q/Q0	QM/Q0	DEPTH(M.)	WIDTH(M.)
2.27	.49	2.21	77.5	2.000	.458E+01	2.000	1.000	.722	3.447
2.42	.52	2.36	76.8	1.952	.490E+01	2.049	1.024	.740	3.522
2.58	.56	2.52	76.1	1.907	.523E+01	2.097	1.049	.758	3.598
2.73	.60	2.67	75.4	1.864	.557E+01	2.146	1.073	.775	3.673
2.89	.64	2.82	74.7	1.823	.592E+01	2.194	1.097	.792	3.749
3.05	.68	2.97	74.0	1.784	.628E+01	2.242	1.121	.809	3.825
3.20	.73	3.12	73.3	1.747	.664E+01	2.290	1.145	.826	3.900
3.52	.82	3.42	72.0	1.677	.739E+01	2.385	1.193	.858	4.051
3.83	.92	3.71	70.6	1.613	.818E+01	2.480	1.240	.889	4.202
4.14	1.03	4.01	69.3	1.554	.900E+01	2.574	1.287	.920	4.352
4.45	1.14	4.30	67.9	1.500	.985E+01	2.667	1.334	.949	4.502
5.08	1.39	4.87	65.3	1.403	.116E+02	2.852	1.426	1.004	4.799
5.70	1.66	5.43	62.8	1.318	.136E+02	3.034	1.517	1.055	5.093
6.33	1.96	5.98	60.4	1.245	.156E+02	3.212	1.606	1.103	5.382
6.95	2.28	6.52	58.1	1.180	.178E+02	3.388	1.694	1.148	5.666
7.58	2.62	7.04	56.0	1.123	.201E+02	3.561	1.781	1.189	5.946
8.20	2.98	7.56	53.9	1.072	.225E+02	3.731	1.866	1.227	6.221
8.83	3.35	8.05	51.9	1.026	.251E+02	3.898	1.949	1.262	6.490
9.45	3.75	8.54	50.0	.984	.277E+02	4.062	2.031	1.295	6.754
10.70	4.58	9.47	46.6	.913	.333E+02	4.382	2.191	1.353	7.267
11.95	5.46	10.36	43.5	.852	.393E+02	4.692	2.346	1.404	7.761
13.20	6.39	11.19	40.8	.801	.457E+02	4.992	2.496	1.448	8.236
14.45	7.35	11.99	38.3	.757	.524E+02	5.282	2.641	1.486	8.694
16.95	9.37	13.47	34.2	.685	.667E+02	5.839	2.919	1.550	9.565
19.45	11.48	14.81	30.8	.628	.820E+02	6.367	3.183	1.602	10.381
21.95	13.66	16.04	28.1	.582	.982E+02	6.870	3.435	1.644	11.152
24.45	15.89	17.17	25.8	.544	.115E+03	7.353	3.677	1.679	11.884
26.95	18.16	18.22	23.9	.512	.133E+03	7.819	3.910	1.710	12.582
29.45	20.46	19.19	22.2	.484	.151E+03	8.270	4.135	1.737	13.249
34.45	25.13	20.97	19.5	.438	.188E+03	9.139	4.569	1.785	14.506
39.45	29.87	22.55	17.4	.402	.227E+03	9.967	4.984	1.825	15.680
44.45	34.67	23.97	15.8	.372	.267E+03	10.770	5.385	1.861	16.784
49.45	39.50	25.27	14.4	.346	.308E+03	11.552	5.776	1.895	17.831
54.45	44.35	26.47	13.2	.325	.350E+03	12.320	6.160	1.927	18.829
59.45	49.23	27.57	12.3	.306	.393E+03	13.078	6.539	1.958	19.784
64.45	54.12	28.60	11.4	.289	.435E+03	13.828	6.914	1.989	20.702
69.45	59.03	29.55	10.7	.274	.479E+03	14.574	7.287	2.019	21.587
74.45	63.95	30.45	10.1	.261	.523E+03	15.317	7.658	2.048	22.443
79.45	68.87	31.30	9.5	.249	.567E+03	16.058	8.029	2.078	23.273
84.45	73.81	32.10	9.0	.238	.611E+03	16.800	8.400	2.107	24.080
89.45	78.75	32.86	8.5	.228	.656E+03	17.542	8.771	2.137	24.865
94.45	83.70	33.58	8.1	.219	.701E+03	18.285	9.143	2.166	25.630
99.45	88.65	34.27	7.7	.210	.746E+03	19.031	9.515	2.195	26.378
104.45	93.61	34.92	7.3	.202	.792E+03	19.779	9.890	2.225	27.109
109.45	98.57	35.55	7.0	.195	.838E+03	20.531	10.266	2.254	27.825

FLOATING WARM WATER JETS -- SAMPLE RUN OF PDS PROGRAM
AMBIENT CONDITIONS : TEMP. TA= 15.0 DEG. C , VEL. UA= .20 M/SEC ,HEAT CONVECTION = .100E-04
DISCHARGE CONDITIONS : TEMP. TO= 17.0 DEG. C ,VEL. UO= 1.00 M/SEC ,WIDTH WO= 2.00 M. ,DEPTH HO= .50 M. ,ANGLE 90.0DEG.
FRO = 25.0 E = .0500 CD = 1.0000 CF = .0000 RE = .000E+00 EV = .200E+00 EH = .200E-01

S(M.)	X(M.)	Y(M.)	TH(DEG.)	EX.TEMP (DEG. C)	TIME(SEC.)	Q/QO	QM/QO	DEPTH(M.)	WIDTH(M.)
114.45	103.53	36.14	6.7	.188	.884E+03	21.286	10.643	2.284	28.526
119.45	108.50	36.72	6.4	.181	.930E+03	22.044	11.022	2.313	29.215
124.45	113.47	37.27	6.2	.175	.976E+03	22.806	11.403	2.342	29.891
129.45	118.44	37.80	6.0	.169	.102E+04	23.572	11.786	2.371	30.555
134.45	123.42	38.31	5.7	.164	.107E+04	24.340	12.170	2.401	31.209
139.45	128.39	38.80	5.5	.159	.112E+04	25.113	12.556	2.430	31.852
144.45	133.37	39.27	5.3	.154	.116E+04	25.888	12.944	2.459	32.486
149.45	138.35	39.73	5.2	.150	.121E+04	26.667	13.334	2.487	33.111
154.45	143.33	40.17	5.0	.145	.126E+04	27.449	13.725	2.516	33.727
159.45	148.31	40.60	4.8	.141	.130E+04	28.235	14.117	2.545	34.334
164.45	153.29	41.01	4.7	.137	.135E+04	29.024	14.512	2.573	34.934
169.45	158.28	41.41	4.5	.134	.140E+04	29.815	14.908	2.602	35.527
174.45	163.26	41.80	4.4	.130	.144E+04	30.610	15.305	2.630	36.112
179.45	168.25	42.18	4.3	.127	.149E+04	31.408	15.704	2.658	36.690
184.45	173.24	42.55	4.2	.124	.154E+04	32.209	16.105	2.686	37.262
189.45	178.22	42.90	4.0	.121	.159E+04	33.013	16.507	2.713	37.827
194.45	183.21	43.25	3.9	.118	.164E+04	33.820	16.910	2.741	38.387
199.45	188.20	43.59	3.8	.115	.168E+04	34.629	17.315	2.768	38.940
204.45	193.19	43.92	3.7	.112	.173E+04	35.442	17.721	2.796	39.488
209.45	198.18	44.24	3.6	.110	.178E+04	36.257	18.128	2.823	40.031
214.45	203.17	44.55	3.5	.108	.183E+04	37.074	18.537	2.850	40.569
219.45	208.16	44.86	3.5	.105	.187E+04	37.894	18.947	2.876	41.101
224.45	213.15	45.15	3.4	.103	.192E+04	38.717	19.358	2.903	41.629
229.45	218.14	45.45	3.3	.101	.197E+04	39.542	19.771	2.930	42.152
234.45	223.13	45.73	3.2	.099	.202E+04	40.370	20.185	2.956	42.670

A R E A S O F E X C E S S T E M P E R A T U R E F O R
SAMPLE RUN OF PDS PROGRAM

EXC. TEMP. (DEG. C)	AREA (SQ. M)
.10	.207E+04
.20	.556E+03
.30	.224E+03
.40	.111E+03
.50	.639E+02
.60	.404E+02
.70	.272E+02
.80	.195E+02
.90	.146E+02
1.00	.111E+02
1.10	.865E+01
1.20	.683E+01
1.30	.552E+01
1.40	.444E+01
1.50	.361E+01
1.60	.301E+01
1.70	.248E+01
1.80	.204E+01
1.90	.167E+01
2.00	.113E+01

```
 Jul 31, 1996,  16:41:50  ERL-N PROGRAM PLUMES, Jun 11, 1993   Case:    1 of  
 Example Run                                                             linear
  tot flow   # ports port flow   spacing  effl sal effl temp   far inc   far di
   0.1533          1    0.1533      1000                           0.2         6
  port dep  port dia plume dia total vel horiz vel vertl vel asp coeff print fr
      29.9     0.254    0.2540     3.025     2.979    0.5254      0.10        50
 port elev ver angle cont coef  effl den poll conc     decay  Froude # Roberts
       0.6        10       1.0    -1.613      3500         0     64.17 0.000639
 hor angle red space p amb den p current   far dif   far vel K:vel/cur Stratif
        90    1000.0   -0.7222     0.015  0.000453     0.015     201.7   0.0219
     depth   current   density  salinity      temp  amb conc  N (freq) red grav
       0.0     0.015    -3.022    -1.691        20         0   0.02747  0.00875
       35.   0.01500 -0.329926     1.843        20         0 buoy flux puff-the
                                                              0.001341      22.0
                                                             jet-plume jet-cros
                                                                 15.34      45.4
                                                             plu-cross jet-stra
                                                                 397.5      4.97
                                                             plu-strat
                                                                 2.836
                                                               hor dis>=

CORMIX1 flow category algorithm is turned off.
 0                                                                0.0 to any  range
Help: F1.  Quit: <esc>.  Configuration:ATNOO.  FILE: plmstuff.var;
UM INITIAL DILUTION CALCULATION (linear mode)
```

plume dep	plume dia	poll conc	dilution	hor dis	
m	m			m	
29.90	0.2540	3500	1.000	0.000	
28.38	3.527	242.7	14.41	8.212	-> trap level
27.30	6.408	131.0	26.70	15.58	-> bottom hit
27.27	6.934	120.5	29.02	16.98	-> bottom hit

-> end curvature, cylinder entrainment -> local maximum rise or fall

FARFIELD CALCULATION (based on Brooks, 1960, see guide)

Farfield dispersion based on wastefield width of 6.934m

--4/3 Power Law--		-Const Eddy Diff-				
conc	dilution	conc	dilution	distance	Time	
				m	sec	hrs
120.0	29.1	120.0	29.1	17.00	1.540	0.0
120.3	29.1	120.3	29.1	17.20	14.87	0.0
120.4	29.0	120.4	29.0	17.40	28.21	0.0
120.4	29.0	120.4	29.0	17.60	41.54	0.0
120.5	29.0	120.5	29.0	17.80	54.87	0.0
120.5	29.0	120.5	29.0	18.00	68.21	0.0
120.4	29.0	120.4	29.0	18.20	81.54	0.0
120.3	29.1	120.4	29.1	18.40	94.87	0.0
120.1	29.1	120.2	29.1	18.60	108.2	0.0
119.7	29.2	120.0	29.1	18.80	121.5	0.0
119.2	29.3	119.7	29.2	19.00	134.9	0.0
118.6	29.5	119.4	29.3	19.20	148.2	0.0
118.0	29.6	119.0	29.4	19.40	161.5	0.0
117.2	29.8	118.5	29.5	19.60	174.9	0.0
116.3	30.1	118.0	29.6	19.80	188.2	0.1
115.3	30.3	117.4	29.8	20.00	201.5	0.1
114.3	30.6	116.8	29.9	20.20	214.9	0.1
113.3	30.9	116.2	30.1	20.40	228.2	0.1
112.2	31.2	115.5	30.3	20.60	241.5	0.1
111.0	31.5	114.8	30.5	20.80	254.9	0.1
109.8	31.8	114.1	30.6	21.00	268.2	0.1
108.6	32.2	113.4	30.8	21.20	281.5	0.1

CORMIX1 Prediction File for dye test in Shallow River

```
CORMIX1 PREDICTION FILE:
1111111111111111111111111111111111111111111111111111111111111111111111111111111
                        CORNELL MIXING ZONE EXPERT SYSTEM
Subsystem CORMIX1:                                           Subsystem version:
 Submerged Single Port Discharges          CORMIX_v.3.10__________June_1995
-------------------------------------------------------------------------------
-------------------------------------------------------------------------------
CASE DESCRIPTION
 Site name/label:           Shallow^River
 Design case:               Dye^Test
 FILE NAME:                 cormix\sim\dye1     .cx1
 Time of Fortran run:       04/14/96--11:03:24

ENVIRONMENT PARAMETERS (metric units)
 Bounded section
 BS    =      50.00 AS     =      30.00 QA     =      23.70 ICHREG= 2
 HA    =        .60 HD     =        .60
 UA    =       .790 F      =       .084 USTAR = .8081E-01
 UW    =      2.000 UWSTAR= .2198E-02
 Uniform density environment
 STRCND=  U          RHOAM =  998.2051

DISCHARGE PARAMETERS (metric units)
 BANK  =  LEFT       DISTB =      20.00
 D0    =       .200 A0     =       .031 H0     =        .15
 THETA =        .00 SIGMA =        .00
 U0    =      2.929 Q0     =       .092        = .9200E-01
 RHO0  =   997.7714 DRHO0 = .4337E+00 GP0    = .4260E-02
 C0    = .5600E+03 CUNITS=  ppb
 IPOLL =  1          KS    = .0000E+00 KD     = .0000E+00

FLUX VARIABLES (metric units)
 Q0    = .9200E-01 M0     = .2694E+00 J0     = .3920E-03 SIGNJ0=       1.0
 Associated length scales (meters)
 LQ    =        .18 LM     =      18.89 Lm     =        .66 Lb     =        .00
                                        Lmp    =   99999.00 Lbp    =   99999.00

NON-DIMENSIONAL PARAMETERS
 FR0   =     100.31 R      =       3.70

FLOW CLASSIFICATION
 111111111111111111111111111111111111111111
 1  Flow class (CORMIX1)       =    H5-0  1
 1  Applicable layer depth HS =       .60  1
 111111111111111111111111111111111111111111

MIXING ZONE / TOXIC DILUTION / REGION OF INTEREST PARAMETERS
 C0    = .5600E+03 CUNITS=  ppb
 NTOX  =  0
 NSTD  =  0
 REGMZ =  0
 XINT  =    1000.00 XMAX   =    1000.00

X-Y-Z COORDINATE SYSTEM:
    ORIGIN is located at the bottom and below the center of the port:
        20.00 m  from the LEFT  bank/shore.
    X-axis points downstream, Y-axis points to left, Z-axis points upward.
NSTEP = 20 display intervals per module
-------------------------------------------------------------------------------
-------------------------------------------------------------------------------
BEGIN MOD101: DISCHARGE MODULE

 COANDA ATTACHMENT immediately following the discharge.
```

X	Y	Z	S	C	B
.00	.00	.00	1.0	.560E+03	.14

END OF MOD101: DISCHARGE MODULE

BEGIN CORJET (MOD110): JET/PLUME NEAR-FIELD MIXING REGION

Bottom-attached jet motion.

Profile definitions:
B = Gaussian 1/e (37%) half-width, normal to trajectory
Half wall jet, attached to bottom.
S = hydrodynamic centerline dilution
C = centerline concentration (includes reaction effects, if any)

X	Y	Z	S	C	B
.00	.00	.00	1.0	.560E+03	.10
1.05	.00	.00	1.2	.483E+03	.16
2.10	.00	.00	1.7	.337E+03	.21
3.15	.00	.00	2.1	.263E+03	.26
4.21	.00	.00	2.6	.216E+03	.29
5.26	.00	.00	3.0	.185E+03	.32
6.31	.00	.00	3.4	.163E+03	.35
7.36	.00	.00	3.8	.146E+03	.38
8.41	.00	.00	4.2	.132E+03	.40
9.46	.00	.00	4.6	.121E+03	.42
10.51	.00	.00	5.0	.112E+03	.44
11.56	.00	.00	5.3	.105E+03	.46
12.62	.00	.00	5.7	.983E+02	.48
13.67	.00	.00	6.0	.927E+02	.50
14.72	.00	.00	6.4	.878E+02	.51
15.77	.00	.00	6.7	.834E+02	.53
16.82	.00	.00	7.0	.795E+02	.55
17.87	.00	.00	7.4	.761E+02	.56
18.92	.00	.00	7.7	.729E+02	.57
19.97	.00	.00	8.0	.701E+02	.59
21.03	.00	.00	8.3	.675E+02	.60

Cumulative travel time = 14. sec

END OF CORJET (MOD110): JET/PLUME NEAR-FIELD MIXING REGION

BEGIN MOD133: LAYER BOUNDARY IMPINGEMENT/FULL VERTICAL MIXING

Control volume inflow:

X	Y	Z	S	C	B
21.03	.00	.00	8.3	.675E+02	.60

Profile definitions:
BV = layer depth (vertically mixed)
BH = top-hat half-width, in horizontal plane normal to trajectory
ZU = upper plume boundary (Z-coordinate)
ZL = lower plume boundary (Z-coordinate)
S = hydrodynamic average (bulk) dilution
C = average (bulk) concentration (includes reaction effects, if any)

X	Y	Z	S	C	BV	BH	ZU	ZL
20.43	.00	.60	8.3	.675E+02	.00	.00	.60	.60
20.55	.00	.60	8.3	.675E+02	.60	.11	.60	.00
20.67	.00	.60	8.3	.675E+02	.60	.15	.60	.00
20.79	.00	.60	8.3	.675E+02	.60	.19	.60	.00
20.91	.00	.60	8.3	.675E+02	.60	.22	.60	.00
21.03	.00	.60	8.3	.675E+02	.60	.24	.60	.00
21.15	.00	.60	8.8	.637E+02	.60	.27	.60	.00
21.27	.00	.60	9.9	.568E+02	.60	.29	.60	.00
21.39	.00	.60	10.8	.517E+02	.60	.31	.60	.00

21.51	.00	.60	11.4	.493E+02	.60	.33	.60	.00
21.63	.00	.60	11.6	.482E+02	.60	.35	.60	.00

Cumulative travel time = 15. sec

END OF MOD133: LAYER BOUNDARY IMPINGEMENT/FULL VERTICAL MIXING

BEGIN MOD153: VERTICALLY MIXED PLUME IN CO-FLOW

Phase 1: Vertically mixed, Phase 2: Re-stratified

Phase 1: The plume is VERTICALLY FULLY MIXED over the entire layer depth.
This flow region is INSIGNIFICANT in spatial extent and will be by-passed.

Phase 2: The flow has RESTRATIFIED at the beginning of this zone.

This flow region is INSIGNIFICANT in spatial extent and will be by-passed.

END OF MOD153: VERTICALLY MIXED PLUME IN CO-FLOW

** End of NEAR-FIELD REGION (NFR) **

The initial plume WIDTH values in the next far-field module will be
CORRECTED by a factor 3.25 to conserve the mass flux in the far-field!
The correction factor is quite large because of the small ambient velocity
relative to the strong mixing characteristics of the discharge!
This indicates localized RECIRCULATION REGIONS and internal hydraulic JUMPS.
Flow appears highly UNSTEADY and prediction results are UNRELIABLE!

BEGIN MOD141: BUOYANT AMBIENT SPREADING

Discharge is non-buoyant or weakly buoyant.
Therefore BUOYANT SPREADING REGIME is ABSENT.

END OF MOD141: BUOYANT AMBIENT SPREADING

BEGIN MOD161: PASSIVE AMBIENT MIXING IN UNIFORM AMBIENT

Vertical diffusivity (initial value) = .970E-02 m^2/s
Horizontal diffusivity (initial value) = .242E-01 m^2/s

The passive diffusion plume is VERTICALLY FULLY MIXED at beginning of region.

Profile definitions:
BV = Gaussian s.d.*sqrt(pi/2) (46%) thickness, measured vertically
= or equal to layer depth, if fully mixed
BH = Gaussian s.d.*sqrt(pi/2) (46%) half-width,
measured horizontally in Y-direction
ZU = upper plume boundary (Z-coordinate)
ZL = lower plume boundary (Z-coordinate)
S = hydrodynamic centerline dilution
C = centerline concentration (includes reaction effects, if any)

Plume Stage 1 (not bank attached):

X	Y	Z	S	C	BV	BH	ZU	ZL
21.63	.00	.60	11.6	.482E+02	.60	1.12	.60	.00
70.55	.00	.60	25.3	.222E+02	.60	2.44	.60	.00
119.47	.00	.60	33.8	.166E+02	.60	3.26	.60	.00
168.39	.00	.60	40.5	.138E+02	.60	3.92	.60	.00
217.30	.00	.60	46.3	.121E+02	.60	4.48	.60	.00
266.22	.00	.60	51.5	.109E+02	.60	4.98	.60	.00
315.14	.00	.60	56.1	.998E+01	.60	5.43	.60	.00
364.06	.00	.60	60.5	.926E+01	.60	5.84	.60	.00
412.98	.00	.60	64.5	.869E+01	.60	6.23	.60	.00
461.90	.00	.60	68.3	.820E+01	.60	6.60	.60	.00

510.81	.00	.60	71.9	.779E+01	.60	6.95	.60	.00
559.73	.00	.60	75.3	.744E+01	.60	7.28	.60	.00
608.65	.00	.60	78.5	.713E+01	.60	7.59	.60	.00
657.57	.00	.60	81.7	.686E+01	.60	7.90	.60	.00
706.49	.00	.60	84.7	.661E+01	.60	8.19	.60	.00
755.41	.00	.60	87.6	.639E+01	.60	8.47	.60	.00
804.33	.00	.60	90.4	.619E+01	.60	8.74	.60	.00
853.24	.00	.60	93.2	.601E+01	.60	9.01	.60	.00
902.16	.00	.60	95.8	.584E+01	.60	9.27	.60	.00
951.08	.00	.60	98.4	.569E+01	.60	9.52	.60	.00
1000.00	.00	.60	101.0	.555E+01	.60	9.76	.60	.00

Cumulative travel time = 1249. sec

Simulation limit based on maximum specified distance = 1000.00 m.
This is the REGION OF INTEREST limitation.

END OF MOD161: PASSIVE AMBIENT MIXING IN UNIFORM AMBIENT

CORMIX1: Submerged Single Port Discharges End of Prediction File

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PROGRAM UDKHDEN
SOLUTION TO MULTIPLE BUOYANT DISCHARGE PROBLEM WITH
AMBIENT CURRENTS AND VERTICAL GRADIENTS. AUG 1985

UNIVERSAL DATA FILE: MARC.IN
CASE I.D. #2 EFFLUENT AS G/CM3, AMBIENT AS S & T, 0.02 M/SEC CURRENT, IxI=IxO=1
DISCHARGE= 1.2660 CU-M/S DENSITY=0.99744 G/CM3 ** DIAMETER= 0.0915-M
** NUMBER OF PORTS= 148 ** SPACING= 3.00-M ** DEPTH= 55.20-M

AMBIENT STRATIFICATION PROFILE

DEPTH (M)	DENSITY (G/CM3)	VELOCITY (M/S)
0.00	1.02261	0.020
20.00	1.02275	0.020
45.00	1.02302	0.020
50.00	1.02344	0.020
55.00	1.02348	0.020
60.00	1.02365	0.020
60.96	1.02367	0.020

FROUDE NO= 8.50, PORT SPACING/PORT DIA= 32.79, STARTING LENGTH= 0.570

ALL LENGTHS ARE IN METERS-TIME IN SEC. FIRST LINE ARE INITIAL CONDITIONS.

X	Y	Z	TH1	TH2	WIDTH	DUCL	DRHO	DCCL	TIME	DILUTION
0.00	0.00	0.00	90.00	0.00	0.09	1.000	1.000	1.000	0.00	1.00
0.00	0.57	0.03	90.00	6.68	0.25	1.000	0.993	0.993	0.44	2.00
0.00	1.27	0.22	90.00	25.85	0.74	0.349	0.308	0.308	1.52	6.71
0.00	1.86	0.66	90.00	46.08	1.23	0.249	0.157	0.157	3.43	13.24
0.00	2.30	1.24	90.00	57.79	1.74	0.214	0.091	0.092	5.82	22.48
0.00	2.65	1.88	90.00	63.86	2.28	0.193	0.059	0.059	8.53	34.54
0.00	2.96	2.54	90.00	67.07	2.85	0.178	0.041	0.041	11.52	49.36

PLUMES MERGING

0.00	3.23	3.22	90.00	68.37	3.38	0.168	0.030	0.031	14.73	65.44
0.00	3.50	3.90	90.00	69.11	3.80	0.164	0.024	0.025	18.06	80.11
0.00	3.76	4.59	90.00	69.67	4.18	0.160	0.020	0.021	21.47	94.42
0.00	4.01	5.28	90.00	70.07	4.55	0.156	0.016	0.018	24.97	108.47
0.00	4.26	5.96	90.00	70.03	4.98	0.146	0.010	0.015	28.62	122.23
0.00	4.77	7.33	90.00	68.29	6.15	0.113	0.000	0.011	37.12	148.07

PLUMES HAVE REACHED EQUILIBRIUM HEIGHT - STRATIFIED ENVIRONMENT

0.00	5.13	8.18	90.00	65.66	7.68	0.093	-0.004	0.009	43.80	162.82
0.00	5.45	8.83	90.00	61.85	9.10	0.079	-0.007	0.009	49.94	173.88
0.00	5.83	9.46	90.00	54.49	11.23	0.061	-0.009	0.009	57.21	184.01
0.00	6.33	9.99	90.00	36.05	14.63	0.037	-0.013	0.009	66.80	192.31
0.00	7.02	10.15	90.00	-14.07	16.85	0.024	-0.014	0.009	80.69	195.61

PLUMES HAVE REACHED MAXIMUM HEIGHT - STRATIFIED ENVIRONMENT

TRAPPING LEVEL= 47.79 METERS BELOW SURFACE, DILUTION= 149.49

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Washington, D.C. 20005
202-682-8000
http://www.api.org

Order No. I46640