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

Health and Environmental Sciences Department
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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. Conservatism 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 policies 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:

$$C_{eff,allow} = C_{WQC} \times S_{crit} \quad (1-1)$$

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.

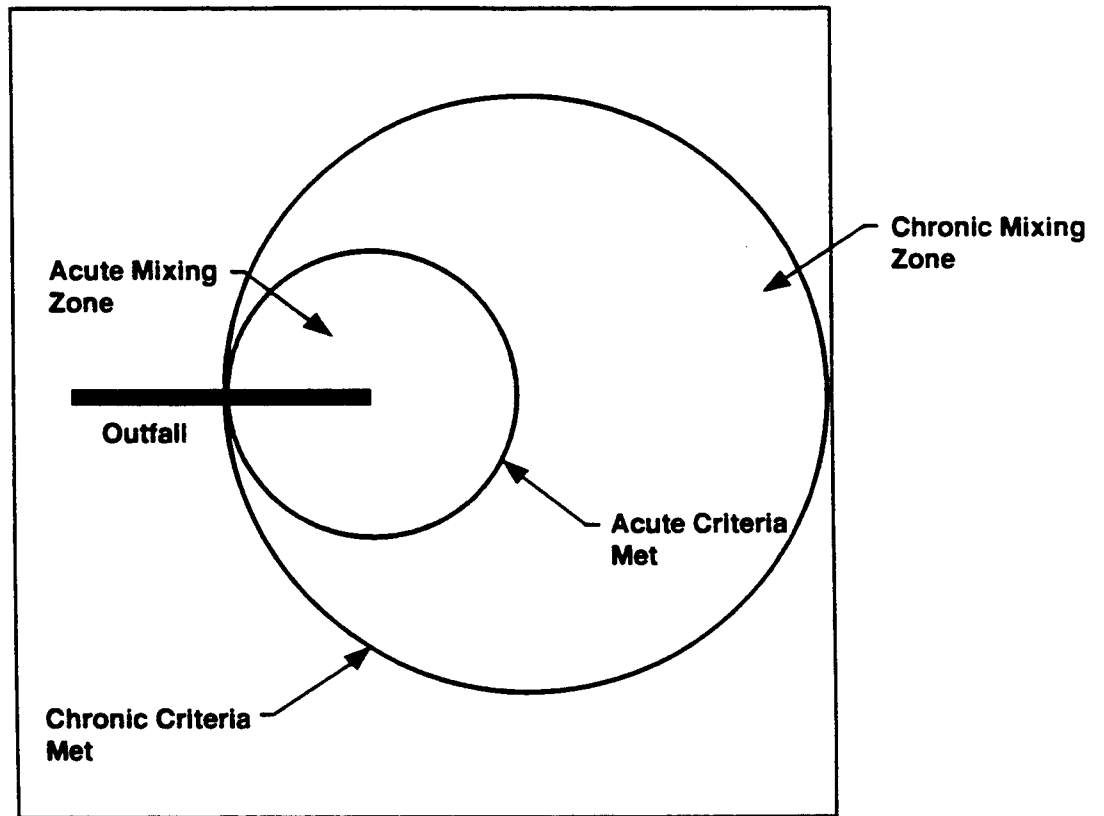


Figure 1-1. Diagram of the Two Parts of the Mixing Zone

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.

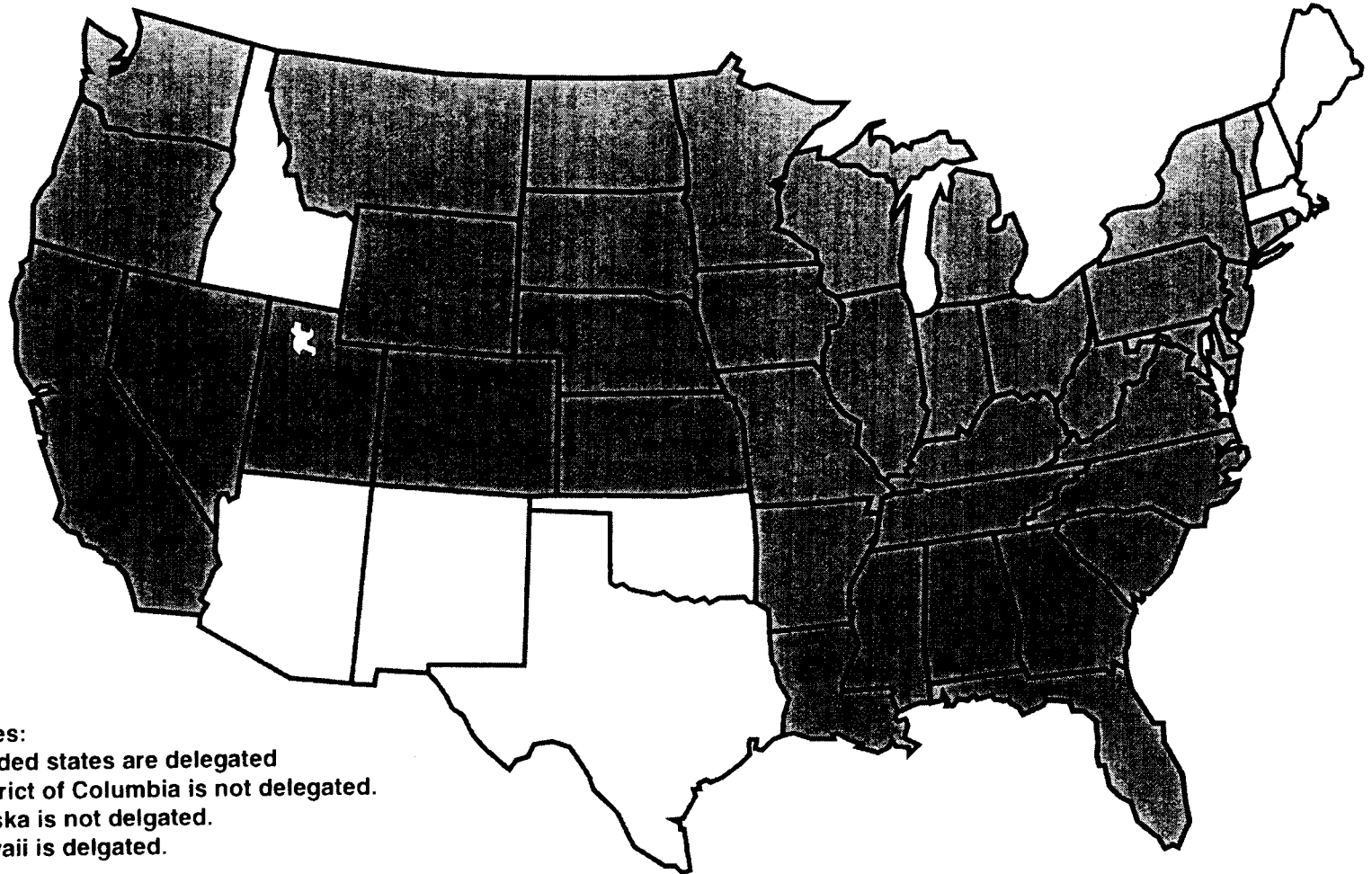
2.1 Water-Quality-Based NPDES Permits

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



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 policies 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 default 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.