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CORMIX2: An Expert System for Hydrodynamic Mixing Zone Analysis of Conventional and Toxic Multiport Diffuser Discharges

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CORMIX2: AN EXPERT SYSTEM FOR HYDRODYNAMIC MIXING ZONE ANALYSIS OF CONVENTIONAL AND TOXIC MULTIPORT DIFFUSER DISCHARGES

by

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FOREWORD

As environmental controls become more costly to implement and the penalties of judgment errors become more severe, environmental quality management requires more efficient management tools based on greater knowledge of the environmental phenomena to be managed. As part of this Laboratory's research on the occurrence, movement, transformation, impact, and control of environmental contaminants, the Assessment Branch develops state-of-the-art mathematical models for use in water quality evaluation and management.

Special water quality regulations have been proposed to limit lethal acute concentrations of toxic pollutants to a spatially restricted toxic dilution zone. Predictive mathematical models are used to establish the initial dilution of a given discharge and the characteristics of its mixing zone. To assist the analyst in choosing the appropriate models, determining the limits of applicability, and establishing data needs, an expert system has been developed. The structured computer program uses knowledge and inference procedures that would be used by water quality experts. Operated on a personal computer, the program appears to be a highly flexible tool for regulatory analysis that is adaptable to the evaluation of alternatives in engineering design.

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Abstract

One of the most important tasks in the management of water quality is the ability to achieve pollutant concentrations within regulated standards. The Cornell Mixing Zone Expert System (CORMIX) is a series of software systems for the analysis, prediction, and design of aqueous toxic or conventional pollutant discharges into watercourses, with emphasis on the geometry and dilution characteristics of the initial mixing zone. Subsystem CORMIX1, reported by Doneker and Jirka (1990), deals with submerged single port discharges. The present development, subsystem CORMIX2 is concerned with submerged multiport discharges into flowing water environments, such as rivers, lakes, estuaries, and coastal waters. It includes effects of ambient stratification, dynamic attachment of the plume to the bottom of the receiving water, and the limiting case of stagnant conditions.

CORMIX2 collects the relevant data for the ambient and discharge situation, computes the physical parameters, and classifies the given discharge into one of many possible hydrodynamic configurations. Then, CORMIX2 executes the corresponding hydrodynamic simulation for the flow, interprets the results of the simulation relative to legal requirements including toxic discharge criteria, and finally, suggests possible design alternatives and improvements concerning the mixing characteristics.

CORMIX2, with its emphasis on rapid initial mixing, assumes a conservative pollutant discharge neglecting any physical, chemical, or biological decay processes. However, the predictive results can be readily converted to adjust for first-order reaction processes.

The results of the hydrodynamic simulation are in good agreement with available field and laboratory data. In particular, CORMIX2 correctly predicts highly complex discharge situations involving boundary interactions, internal layer formation, buoyant intrusions, and large-scale induced currents in shallow environments, all features that are beyond the predictive capabilities of other currently available initial mixing models for multiport diffusers.

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Glossary of Symbols

All symbols are defined where they first occur. Only more common symbols are summarized here.

a_o = discharge cross-sectional area

b = plane jet/plume half-width

b_h = horizontal half-width of diffuser plume

b_v = vertical half-width of diffuser plume

b_i, s_i, t_i = width, dilution, and trajectory constants for flow region i (Chapter 2)

B = equivalent slot width (section 2.2.2.2)

B_i, S_i, T_i = width, dilution, and trajectory constants for MOD i (Chapter 4)

C_D = drag coefficient for density current

D = discharge diameter

f = ambient flow Darcy-Weisbach friction factor

F_o = nozzle/port densimetric Froude number (Eq. 5.1).

F_{ro} = slot densimetric Froude number (Eq. 5.2).

g = gravitational acceleration

g'_o = discharge buoyant acceleration

h_o = height of discharge above bottom

h_{int} = height of pycnocline (lower layer depth)

H = ambient water depth

H_s = significant layer depth (H or h_{int})

J_o = discharge buoyancy flux

ℓ = average spacing between ports and nozzles

l_q = discharge (geometric) length scale

l_M = slot jet/plume transition length scale

l_m = slot jet/crossflow length scale

l_m' = slot jet/stratification length scale

l_b' = slot plume/stratification length scale

l_a = crossflow/stratification length scale

L_q = discharge (geometric) length scale

L_M = jet/plume transition length scale

L_m = jet/crossflow length scale

L_b = plume/crossflow length scale

L_m' = jet/stratification length scale

L_b' = plume/stratification length scale

L_D = diffuser length

M_o = discharge momentum flux

n = number of ports or nozzles

Q_o = discharge (volume flux)

R = jet/crossflow ratio (Eq. 5.3).

s = distance along jet/plume trajectory

S = bulk dilution in plume

S_c = centerline dilution in jet/plume

u_c = centerline velocity in jet/plume

u_a = ambient velocity

U_o = discharge velocity

W = width of ambient water body

x,y,z = Cartesian coordinate system

x',y',z' = Cartesian coordinate system relative to virtual origin

y'' = supplementary coordinate (section 4.2.1.1)

Y_B = distance of discharge to nearest shore

z = vertical coordinate

Greek Symbols:

α = supplementary angle (Eq. 4.2)

β = port (nozzle) horizontal orientation angle relative to diffuser line

γ = alignment angle of diffuser line relative to ambient current direction

δ = supplementary angle (Eq. 4.3)

$\Delta\rho_a$ = pycnocline density jump

$\Delta\rho_o$ = discharge density difference

η = supplementary coordinate (section 4.2.1.1)

ϵ = ambient buoyancy gradient

ρ_a = ambient density

ρ_o = discharge density

θ = vertical angle of discharge

σ = horizontal angle of discharge relative to ambient current

Subscripts:

c = centerline

f = final value within a MOD

i = initial value within a MOD

Acknowledgements

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The work was carried out using the computer facilities of the DeFrees Hydraulics Laboratory. Dr. Robert L. Doneker from the University of Portland, Oregon, provided valuable assistance in the final implementation and testing of the computer code and knowledge base software. Mr. Cameron Willkens, Electronics Technician, generously assisted with solutions for computer hardware and software problems. Ms. Doreen Balwierczak did skillful wordprocessing for the final manuscript.

This report is a revised version of the thesis submitted by Paul J. Akar, Graduate Research Assistant, to the Graduate School of Cornell University in partial fulfillment of the requirements for the degree of Masters of Science. Dr. Gerhard H. Jirka, Professor of Civil and Environmental Engineering, was project supervisor.

Chapter I

Introduction

One of the major environmental problems is the concern for an adequate water quality in all bodies of water, from streams, rivers and lakes to estuaries and coastal waters. In order to complete this goal, all waste water discharges in the United States are subject to Federal and/or State regulations. A key aspect of these regulations is the concept of a mixing zone.

The mixing zone is a legally defined spatial quantity that allows for the initial mixing and dilution of a discharge. Legal criteria specify the mixing zone shape and effluent concentrations which must be maintained outside and at the edge of the mixing zone. Mixing zone regulations are a descendant of Federal water quality legislation which started in 1948.

More recently, additional subregions within the mixing zone have been defined for discharges of aqueous toxic substances. The objective of these regulations is to require rapid mixing of toxic releases in order to limit the exposure to toxic materials of aqueous flora and fauna.

The purpose of this report is to document the development and implementation of an engineering tool, in the form of a micro-computer based expert system, for the analysis of <u>submerged multiport diffuser discharges</u> into water bodies with variable and complex conditions.

Due to their great flexibility in providing a high degree of initial mixing, submerged multiport diffusers are increasingly being used in water quality control. Installations range from sewage diffusers for the discharge of treated municipal wastewater, to thermal diffusers for heated cooling water flow from steam-electric power plants, to industrial diffusers for process water or brine discharges.

The goal of the expert system is to give reliable and accurate predictions of the mixing characteristics of these discharges along with information on any applicable legal requirements. The development of this multiport diffuser expert system is patterned closely after another expert system for submerged single port discharges as reported by Doneker and Jirka (1989).

1.1 Regulatory Background

A detailed overview of the legal background governing aqueous pollutant discharges in the United States has been given by Doneker and Jirka (1989). Some of the key aspects are summarized here.

1.1.1 The Clean Water Act of 1977

In 1977 the Congress amended the Federal Water Pollution Control Act of 1972, with those amendments being known as the Clean Water Act (CWA). The Act covered general categories of pollutants which are; i) conventional, ii) nonconventional, iii) toxics, iv) heat, and v) dredge and fill spoil.

Conventional pollutants are defined as pollutants that are naturally occurring, biodegradable, oxygen demanding materials and solids. Pollutants which are "nonconventional" would be "those which are not toxic or conventional" (Congressional Research Service, 1977). A detailed list covering the different effluent standards set by USEPA under the 1977 amendments can be found in Doneker and Jirka (1989).

A new class of effluent standards called "best conventional pollution control technology" (BCT) were created for conventional pollutants. Cost consideration could be taken into account by USEPA in determining BCT effluent regulations for conventional pollutants, but not for nonconventional pollutants or toxics. On the other hand, "best available technology economically achievable" (BAT) effluent limitations which require a high pollutant percentage removal and a high cost in the reduction process, apply to nonconventional and toxic pollutants. A variance provision for BAT standards for nonconventional pollutants is contained in section 301 (g) of the Act. With State approval, this provision gives authority to the USEPA to expand effluent standards for nonconventional pollutants on the condition that it will not interfere with water quality standards or public health (for further details, see Doneker and Jirka 1989).

1.1.2 The Concept of Mixing Zone

1.1.2.1 Mixing Zone: Regulations and Development

The mixing zone concept is defined as an allocated impact zone where water quality standards can be exceeded as long as acutely toxic conditions are prevented. A mixing zone is defined as a limited area or volume where the initial dilution of a discharge occurs (Water Quality Standards Handbook, 1982). The water quality standards have to be met at the mixing zone boundary but not within the mixing zone itself.

The mixing zone requirements established by USEPA state that "the area or volume of an individual zone or group of zones be limited to an area or volume as small as practicable that will not interfere with the designated uses or with the established community of aquatic life in the segment for which the uses are designated" and the shape be "a simple configuration that is easy to locate in the body of water ". The USEPA has published guidelines for additional requirements (such as avoidance of settling materials, debris, etc.) that should be met within any mixing zone.

The proposed rules for mixing zones recognize the State has discretion whether or not to adopt a mixing zone and to specify its dimensions. USEPA allows the use of a mixing zone in permit applications except where one is prohibited in State regulations. Typically, State standards require that water quality criteria be met at the edge of the regulatory mixing zone in order to provide a continuous zone of free passage that meets water quality criteria for free-swimming and drifting organisms and to prevent impairment of critical resource areas. Actual mixing zone definitions are established on basis of a downstream distance, or plume width or cross-sectional area or plume surface area or other criteria depending on the type of water body. A summary of mixing zone definitions is found in USEPA Technical Guidance Manual (USEPA, 1984, see also Doneker and Jirka, 1989).

1.1.2.2 Special Mixing Zone Requirements For Toxic Substances

When dealing with toxic discharges, the USEPA advises careful mixing evaluation in order to prevent areas of chronic toxicity that extend for large distances because of poor mixing. Two regulatory criteria for toxic substances are maintained by USEPA, these are: a <u>criterion maximum concentration</u> (CMC) for protecting against acute or lethal effects; and a <u>criterion continuous concentration</u> (CCC) for protecting against chronic effects. The CCC is less restrictive but must be met at the edge of the same regulatory mixing zone specified for conventional and nonconventional discharges.

The key aspect for the CMC criterion is that the CMC must be met within a short distance from the outfall in order to prevent lethal concentrations of toxics in the regulatory mixing zone. One requirement for the toxic dilution zone (TDZ) is that a minimum exit velocity of 3 meters per second (10 feet per second) must be met in order to provide sufficiently rapid mixing which will minimize organism exposure time to toxic material. Other geometric restrictions for a TDZ are required (for example, the CMC must be met within 10% of the distance from the edge of the outfall structure to the edge of the regulatory mixing zone in any spacial direction, and the CMC should be met within 50 times the discharge length scale for each multiport nozzle), and are discussed in the Technical Support Document for Water Quality-based Toxics Control (USEPA, 1985).

1.1.3 Regulatory Practice

In order to discharge any pollutant into watercourses, the discharge must obtain a permit issued under the National Pollution Discharge Elimination System (NPDES). The permit is structured to insure that the discharge meets all applicable standards.

In order to implement the mixing zone requirements, it is necessary for the applicant to predict the discharge initial dilution and the mixing zone characteristics. Given the large number of possible combinations of ambient environments, discharge conditions, and mixing zone locations, the analyst must possess substantial skill, training, and expertise in order to pursue accurate and reliable effluent mixing analysis.

In general, effluent mixing is induced by different mechanisms along the discharge trajectory. In the "near field" region of the discharge, jet-induced entrainment can provide dilution, and further downstream in the "far field" the discharge velocity decreases and ambient diffusion is the main mechanism for mixing.

As an alternative to mathematical models, the determination of pollutant concentrations can be achieved in two ways, either by physical measurement for existing discharges, or by a non-pollutant tracer injection which will indicate an effluent dilution. These studies require specialized field trained personnel and require extensive effort and time.

For these reasons and due to the complexity of the physical mixing processes, permit writers are increasingly relying on mathematical models to analyze the transport behavior of pollutants (Tait, 1984). However, many of the present models are very specialized and give precise results only for particular cases. A few models which have been developed for dilution prediction are, PLUME, OUTPLM, DHKPLM, MERGE, and LINE (see Mullenhoff, et. al., 1985).

1.1.4 The Role of Expert Systems in Mixing Zone Analysis

Available predictive models vary from simple analytical equations to intricate numerical solutions to differential equations. The USEPA (Mullenhoff, et. al., 1985) has published advice on the use of such models, but often the user has little detailed guidance for model choice and applicability. An example of this may be seen in use of USEPA models which may violate the assumption of an infinite receiving environment. The plume actually may become bottom attached or may be vertically completely mixed.

Also, after running the model, the user is faced with the problem of analyzing the results. This task can be very challenging for the inexperienced user due to its complexity. In summary, the user must be an "expert" in the interpretation of the model results, and must understand the limitations of the models. It is expensive and costly to train all potential users to become experts in this field, and for this purpose the development of expert systems would be helpful and efficient.

Expert systems mimic the logic that an expert might use in solving a given problem. As cited in (Doneker and Jirka, 1989), "an expert system is a structured computer program that uses knowledge and inference procedures obtained from experts for solving a particular type or class of problem called a 'domain' ". This knowledge base employs reasoning procedures similar to those used by an expert when anlayzing the problem.

Expert systems possess great utility for solving environmental science problems. As mentioned by Barnwell et al. (1986), several preconditions must be satisfied before using this technology. Those preconditions are related to having a restricted well defined problem domain, a logical knowledge base for solving a problem, and finally an appropriate formalization of concepts compatible with the shell used.

Expert systems can be a powerful tool for the analyst if these requirements are satisfied. The analysis and the simulation of the effluent mixing problem satisfy these precon..tions because the mixing zone processes are hydrodynamically well defined.

A final justification for the expert systems approach for multiport diffuser analysis can be found in the implemention of such a system in analyzing single port discharges in ambient water (Doneker and Jirka, 1989). The system has been found to be very successful in its ability to predict mixing characteristics for complex problems, involving a large variety of discharge/environmental conditions.

1.2 CORMIX2: An Expert System for Mixing Zone Analysis of Multiport Diffuser Discharges

1.2.1 Scope and Objective

The purpose of this study is to create a tool for the analysis and design of submerged multiport diffusers discharges into ambient receiving environments, including the cases of positively or negatively buoyant discharges issuing into stratified or non-stratified flowing water-courses. Furthermore, the limitations of a neutrally buoyant discharge and of a stagnant ambient are included. The expert system will be labeled CORMIX2, for Cornell Mixing Zone Expert System, Subsystem 2. The first subsystem, CORMIX1 (Doneker & Jirka, 1989), deals with single port discharges into water-courses.

The objective of the expert system is to provide the analyst with accurate and reliable predictions of discharge mixing processes. The expert system should be easy, and it should provide the analyst with detailed information and advice regarding the initial mixing for a discharge design.

It is very difficult to create a system that applies to every conceivable mixing zone and discharge configuration. However, the goal of the present study is to develop an expert system that works for better than 80% of typical diffuser discharges, ranging from simple to fairly complex cases. The rest of the cases may require a specialist using either sophisticated numerical modeling or a detailed hydraulic model study.

1.2.2 Summary of Present Study

The expert system CORMIX2 is applicable to the prediction of mixing behavior of multiport diffusers emphasizing discharge geometry, the characteristics of the legal mixing zone (LMZ), and the zone of toxic dilution (TDZ). CORMIX2 collects all input data, conducts hydrodynamic analyses, summarizes dilution characteristics including any legal regions if specified, and finally recommends design changes in order to improve dilution characteristics.

Since its emphasis is on initial mixing mechanisms with their short time scales, CORMIX2 assumes a conservative pollutant or tracer in the effluent. Thus, any physical, chemical, biological reaction, or decay processes are neglected. However, if first-order processes are assumed, the predictive results can be readily converted to include such processes (see Section 5.4).

Detailed explanations and descriptions of CORMIX2 are presented in the following chapters. Chapter II presents both the hydrodynamic flow processes occurring in effluent mixing and the hydrodynamic flow classification. The hydrodynamic flow processes are related to the various stages of mixing of buoyant multiport diffuser discharges in the ambient water. The flow classification describes the interaction processes controlling the near-field discharge mixing.

Chapter III describes the overall system structure and the various program elements of CORMIX2.

Chapter IV covers the detailed hydrodynamic protocols used to simulate the model.

Chapter V is devoted to the validation of CORMIX2 with experimental and field data. The chapter also presents some applications through design case studies in order to illustrate the flexibility and limitations of CORMIX2.

Chapter VI summarizes CORMIX2 capability and performance and presents recommendations and suggestions for future improvements of CORMIX2.

Chapter II

Hydrodynamic Processes and Flow Classification

2.1 Introduction

The key ingredient for a predictive expert system must be the study and understanding of the hydrodynamic processes occurring in the environment, including the interaction between the discharge configuration and the ambient environment.

The hydrodynamics of an effluent continuously discharged into water bodies can be conceptualized as a mixing process occurring in two separate zones (Figure 2.1). In the first region, called the "near-field", the initial multiport diffuser momentum flux, buoyancy flux, and outfall geometry control the diffuser plume trajectory and its mixing characteristics. This region covers the multiport diffuser's subsurface flow and any surface and bottom interaction, or in the case of a stratified ambient, the terminal layer interaction.

Further downstream (away from the source), the multiport diffuser geometry becomes less important, and hence ambient conditions will control the mixing characteristics and trajectory through buoyant motions and passive diffusion due to ambient turbulence. This region is called the "far-field".

The mixing processes in this study are treated in two steps: classification of flows based on length scale analysis, discussed in section 2.3, and predictive models for each flow zone covered in section 2.4.

2.2 Physical Conditions

The general ambient environment is complex and sometimes difficult to model due to complicated topographic conditions. A simple configuration or schematization representing the ambient geometry is introduced in the expert system CORMIX2. Other difficulties are a stratified ambient and current effects which further complicate the modelling process, and therefore need some simplifying assumptions.

Similarly, diffuser geometries may exhibit a great degree of complexity. Therefore, restrictions to simplified generic types have been made in CORMIX2.

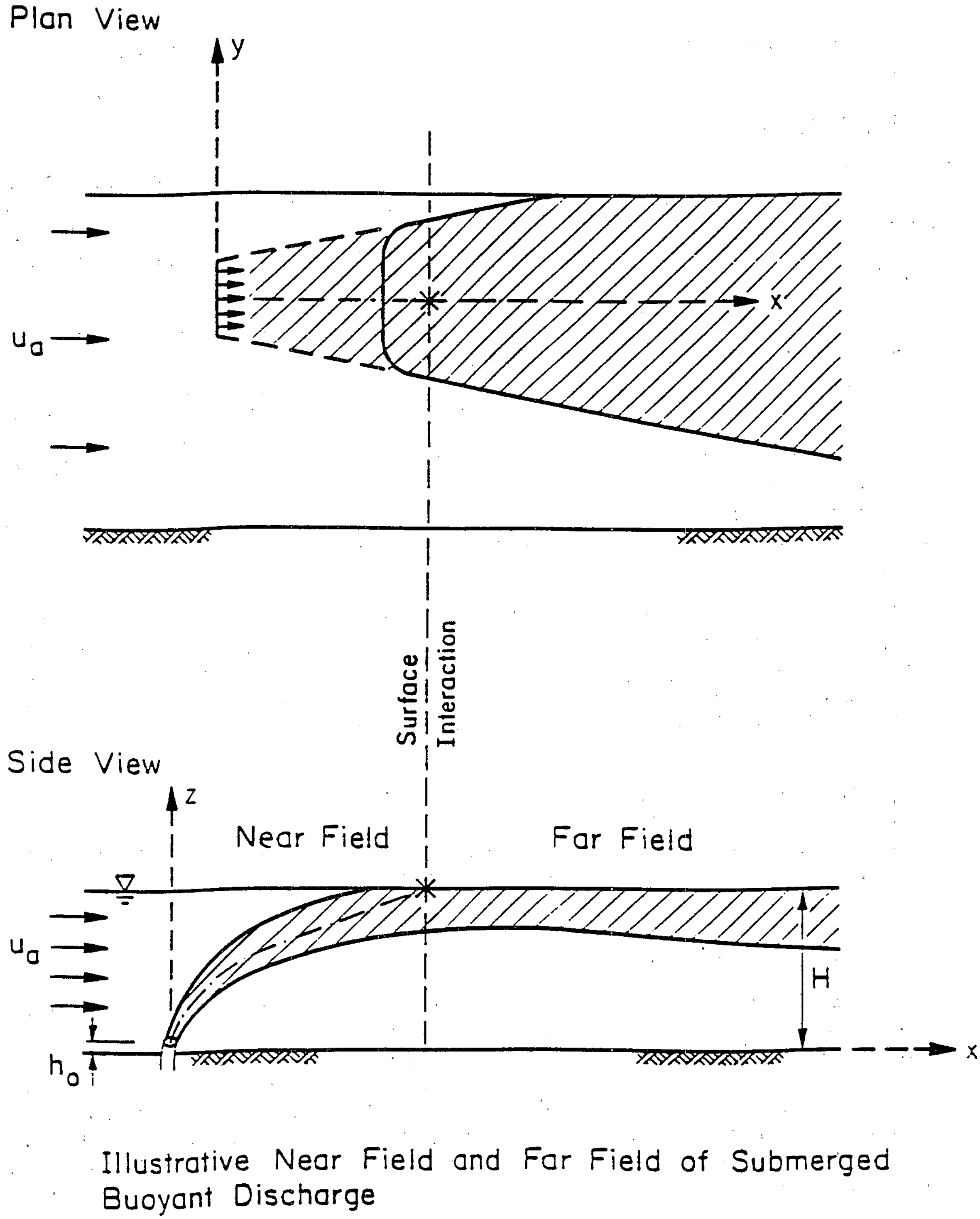


Figure 2.1 Illustrative Near-Field and Far-Field Regions of Submerged Positively Buoyant Discharge: An Example of Unidirectional Perpendicular Diffuser in Unstratified Ambient Water and Without Bottom Attachment.

2.2.1 Ambient Conditions

Ambient conditions are defined by the hydrographic and the geometric conditions in the vicinity of the discharge. For this purpose, typical cross-sections normal to the ambient flow direction at the discharge site and further downstream need to be considered. CORMIX2 considers two cases of cross-sections: bounded and unbounded cross-sections. A bounded cross-section is defined as a cross-section having both sided bounded by banks - as rivers, streams, narrow estuaries, and other narrow watercourses. An unbounded cross-section represents a discharge which is located close to one boundary while the other boundary is for practical purposes very far away (e.g. discharges into wide lakes, estuaries, and coastal areas).

2.2.1.1 Ambient Geometry

2.2.1.1.1 Bounded Cross-Section

The methodology assumes a rectangular cross-section (Figure 2.2) that is defined by a width and a depth both of which are constant in the downstream direction following the ambient flow. This schematization may be quite evident for well-channeled and regular rivers or artificial channels. For highly irregular cross-sections, it may require more judgement and experience to define water-courses geometry. One way of achieving this is by the repeated use of the program so that the user can appreciate the sensitivity of the results.

In order to measure the roughness characteristics in the channel, the value of the Manning "n", or alternatively of the Darcy-Weisbach friction factor "f", must be specified. These parameters influence the mixing process only in the final far-field stage.

2.2.1.1.2 Unbounded Cross-Section

Most of the hydrographic and geometric information is closely related to the bounded case. CORMIX2 will conduct its analysis by assuming an "equivalent cross-sectional area" defined by depth, by distance from one bank to the discharge position, and by ambient velocity.

2.2.1.2 Ambient Currents

Ambient currents are usually encountered in the ambient environment. CORMIX2 will assume a uniform ambient current and will not deal with complicated representation of current patterns, including shear effects and other non-uniformities.

Data related to the ambient flow condition must be available either as an average ambient velocity or as an ambient discharge.

2.2.1.3 Stratification Effects

A variation of density with respect to the depth is common in many water bodies. For example, seasonal temperature conditions can affect the density and lead to stratification of the ambient environment. Also often, ambient density stratification plays an important role in discharge design objectives. For example, in sewage discharges the prevention of plume rise to the water surface can be accomplished by internal trapping induced by the density gradient.

The methodology considers four cases of density profiles which are shown in Figure 2.3. The user must choose among the four profiles the one that best fits the actual ambient profile. The four profiles are:

Stratification Type A: The density varies linearly between top and bottom.

Stratification Type B: There is an upper mixed layer with uniform density, a sudden density jump at an intermediate level, the so-called pycnocline (thermocline), and a lower layer with uniform density.

Stratification Type C: There is an upper mixed layer with a uniform density, a sudden density jump, and a lower layer in which the density varies linearly down to the bottom value.

Stratification Type D: There is an upper mixed layer with uniform density. At an intermediate level, the density begins to vary linearly down to the bottom value.

In each type, a linear buoyancy gradient ε is defined as

$$\varepsilon = -(g/\rho_a) d\rho_a/dz \qquad (2.1)$$

where

g : gravitational acceleration,
ρ_a : ambient density (reference value),
$d\rho_a/dz$: ambient density gradient.

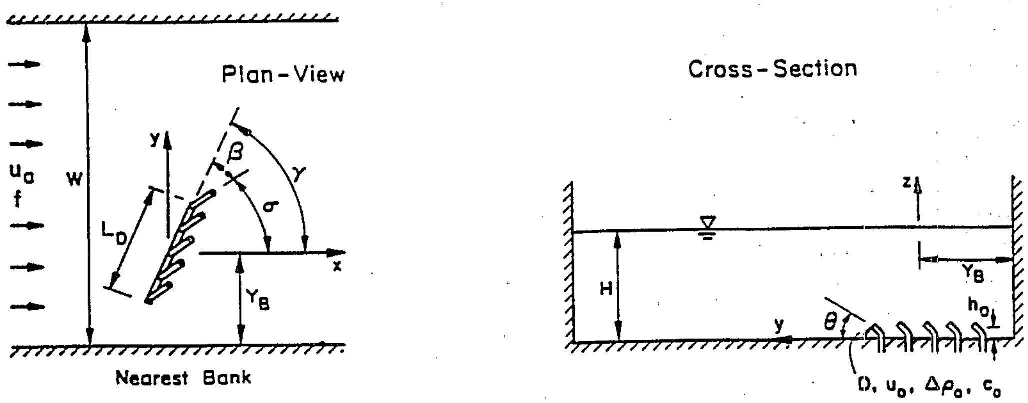


Figure 2.2 Definition Diagram for Multiport Diffuser Discharge Geometry in Ambient Channel with Rectangular Cross-Section. Width W of the Water Body may be Finite or Unlimited.

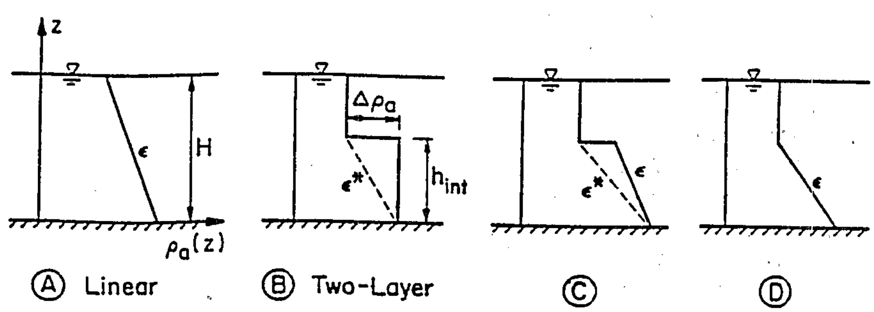


Figure 2.3 Representative Stable Density Profiles (Four Stratification Types) (Ref. Doneker and Jirka, 1989).

2.2.2 Discharge Conditions

Discharge conditions are related to the discharge flow characteristics, the geometry of the discharge structure, and the flow parameters.

2.2.2.1 Diffuser Geometry

The discharge geometry is defined by the multiport diffuser. A multiport diffuser is a structure consisting of many closely spaced ports or nozzles which inject a series of high velocity turbulent jets into the receiving water. One can distinguish among two forms of port openings, a simple pipe with port openings (holes in the pipe), or a pipe with attached risers leading to the actual port or nozzle (with the possibility of multiple ports for each riser). The diffuser installation can consist of the diffuser pipe laid on the bottom, half buried in a trench, or deeply buried, or a tunnel below the bottom.

A summary of all schematic ambient and discharge characteristics is shown in Figure 2.2. The following variables define the diffuser geometry:

- L_D = diffuser length.
- N = number of diffuser openings (ports or nozzles).
- ℓ = $L_D/(N-1)$ = average port spacing.
- D = port (or nozzle) diameter.
- h_o = port height above bottom.
- θ = vertical discharge angle.
- σ = horizontal discharge offset angle.
- γ = alignment angle.
- β = orientation angle.

The general multiport diffuser arrangement together with its important geometric features is shown in Figure 2.4. Multiport diffusers can have a large amount of geometric detail. Each geometric parameter can play an important role in the flow behavior. For example, a variation of the horizontal port orientation angle, β, can induce a change in the discharge trajectory. Three major types of multiport diffuser geometries, each with highly different mixing behavior, have evolved in actual engineering practice: the unidirectional, staged, and alternating diffuser (see Figure 2.5). These diffuser types are classified mainly based on their angle orientation relative to the diffuser axis β. In the unidirectional diffuser, all the ports point in the same direction perpendicular to the diffuser axis ($\beta = 90°$). In the staged diffuser, the ports all point in the same direction parallel to the diffuser axis ($\beta = 0°$). In the alternating diffuser, the ports are arranged in an alternating fashion and point in opposite directions ($\beta = \pm 90°$). The unidirectional and the staged diffusers possess a net horizontal momentum input with a tendency to induce

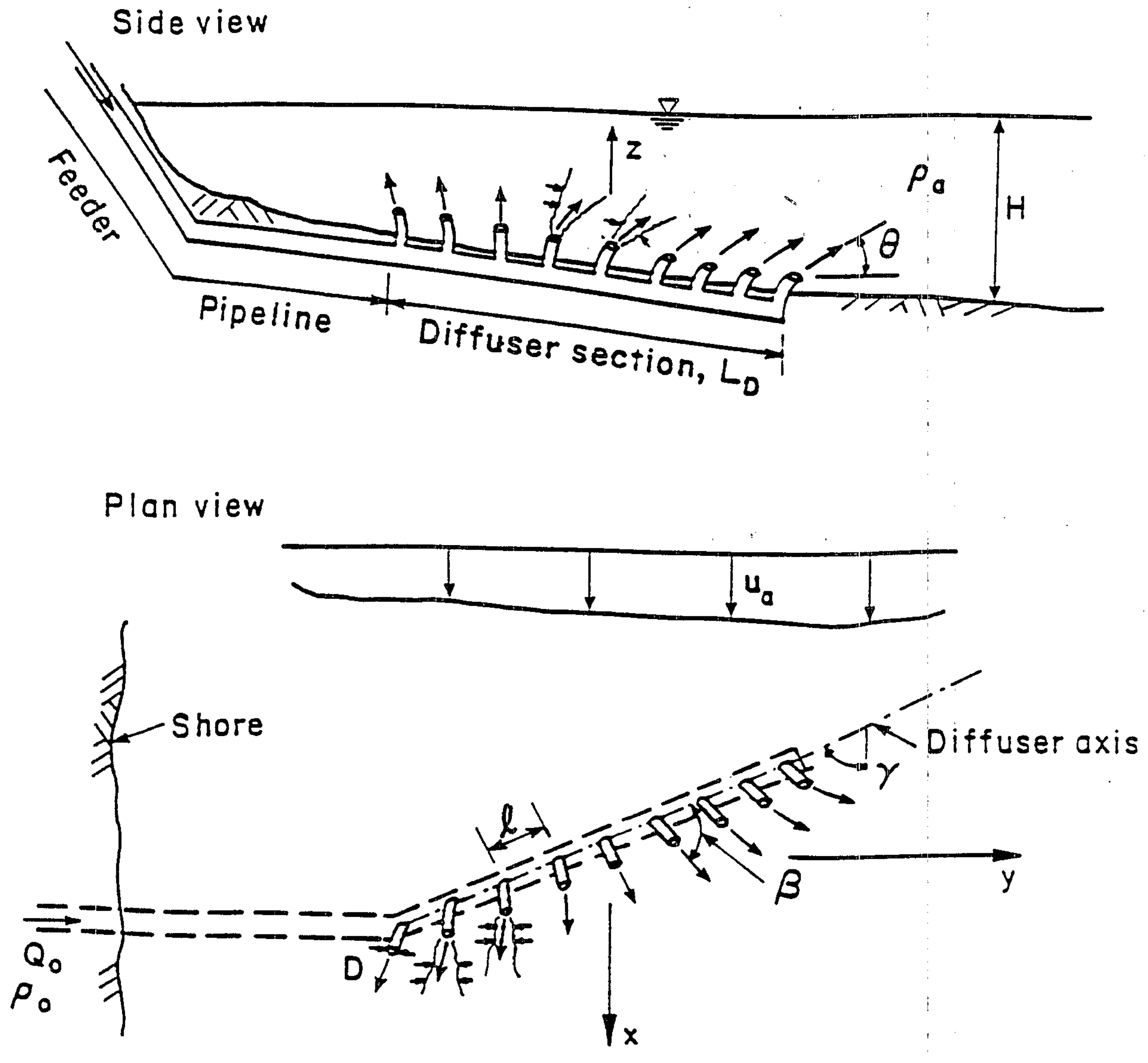


Figure 2.4 Submerged Multiport Diffuser: General Discharge Configuration (Adapted from Jirka, 1982).

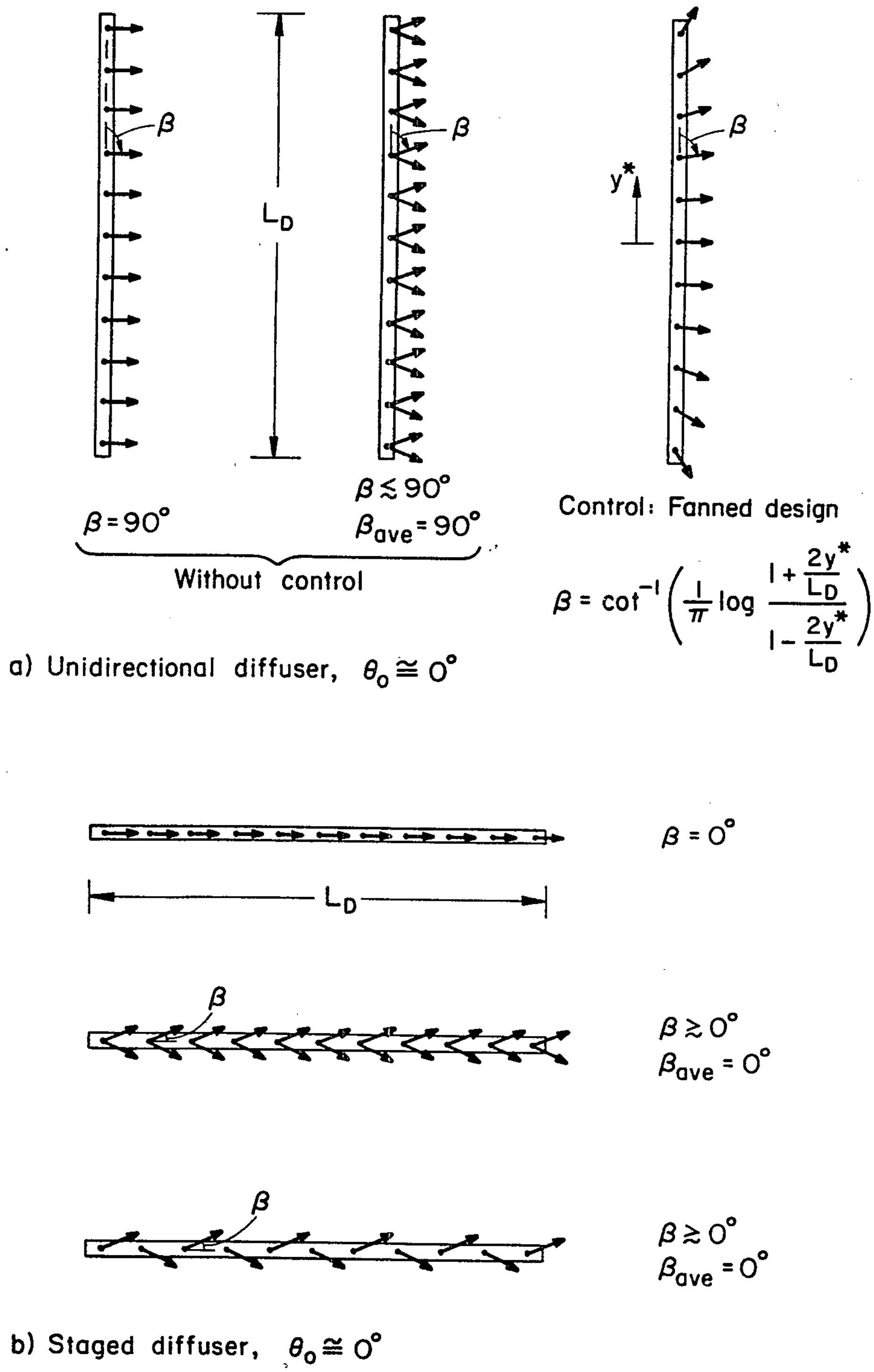
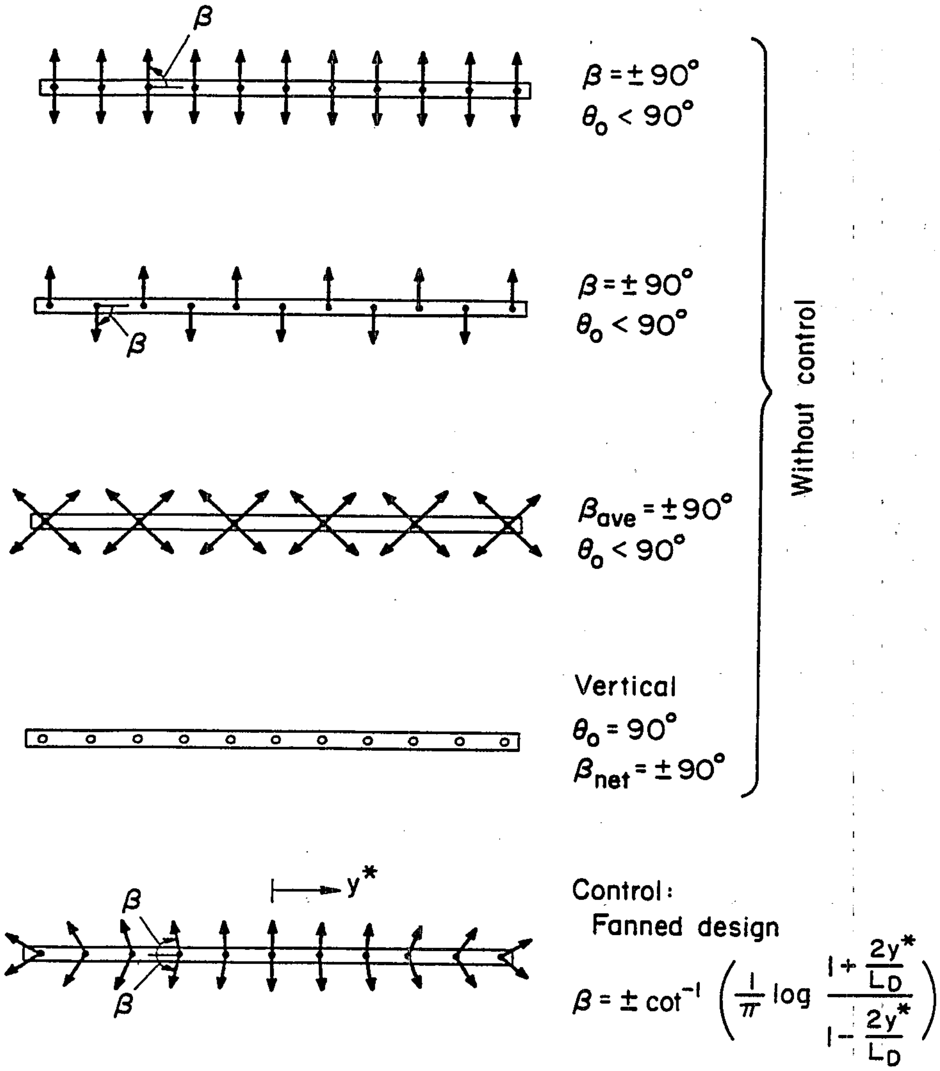


Figure 2.5 Schematic Plan Views of Three Major Diffuser Types. a) Unidirectional Diffuser, b) Staged Diffuser, c) Alternating Diffuser. Any of those diffusers may have a variable alignment γ relative to the ambient current.



c) Alternating diffuser, θ_o = variable

Figure 2.5 (Continued)

currents within the ambient water body. The alternating diffuser has a zero net horizontal momentum, and a lesser tendency to generate currents and circulations.

Of course, there are variations on the basic theme for each of the three diffuser types. A few of these possibilities are shown on Figure 2.5. For example, there may be double or triple port arrangements (with a small internal angle) for both unidirectional or staged diffusers, and the port orientation angle β may differ somewhat from the nominal value, $\approx 90^\circ$ or $\approx 0^\circ$, respectively. Or in case of the alternating diffuser, there may be multiple port assemblies for each riser with several ports arranged in a circular fashion. A special case of an alternating diffuser is a diffuser with a vertical discharge, possessing zero horizontal momentum input.

Furthermore, the designer can exercise some control over the behavior of the discharge plume and other induced circulations in the ambient water body. This is especially important for diffuser discharges into shallow water that are prone to vertical instabilities (see Section 2.3.1) leading to concentrated high velocity diffuser plumes. These concentrated flows can be controlled if the diffuser nozzles have a "fanned design" with a variable orientation angle along the diffuser

$$\beta = \cot^{-1}\left[\frac{1}{\pi}\log\frac{1+\frac{2y^*}{L_D}}{1-\frac{2y^*}{L_D}}\right] \tag{2.2}$$

in which y* is the distance measured from the diffuser mid-point. A variable nozzle orientation with control according to Eq. 2.2 has been shown (Jirka and Harleman, 1973; Jirka, 1982) to improve diffuser mixing while reducing the strength of diffuser induced velocities in the ambient water body.

Many of those diffuser design possibilities are addressed in the input element of CORMIX2.

The effectiveness of each type of diffuser will further depend on the direction of the ambient current relative to the diffuser axis called the alignment angle γ. One can discern two extreme cases: (1) Perpendicular alignment ($\gamma \approx 90^\circ$), (2) and Parallel alignment ($\gamma \approx 0^\circ$).

2.2.2.2 Flow Parameters

The general diffuser flow field is, of course, three-dimensional. However, for near-field mixing analyses the two-dimensional flow parameters are dynamically relevant.

For this purpose, the details of individual discharge jets with port diameter D and spacing ℓ are neglected and replaced by an equivalent slot width $B = \frac{\pi D^2}{4\ell}$ on the basis of equivalency of momentum flux per unit diffuser length. This concept has been discussed by Jirka (1982), and by Jirka and Akar (1991), and has been shown to be an accurate dynamic representation. The main parameters for the two-dimensional slot discharge are, the diffuser total flowrate Q_o, and the discharge buoyancy g'_o. This leads to the following flux parameters (per unit diffuser length), all expressed in kinematic units

$q_o = Q_o/L_D$ = volume flux (flowrate).

$m_o = q_o u_o = u_o^2 B$ = momentum flux.

$j_o = q_o g'_o = u_o g'_o B$ = buoyancy flux.

in which

$u_o = Q_o/(An)$ = port velocity.

$A = \pi D^2/4$ = port cross-sectional area.

$g'_o = g(\rho_a - \rho_o)/\rho_a$ = buoyant acceleration.

ρ_o = discharge density.

2.3 Hydrodynamic Mixing Processes

As discussed previously in Section 2.1, the effluent mixing process is divided into two regions (the near and far field).

2.3.1 Near-Field Processes

The essential feature of the near-field of a diffuser discharge is given by buoyant jet mixing. In a jet, the high velocity of the efflux flow rapidly entrains ambient fluid causing a high degree of dilution. The additional effect of buoyancy can, depending on the direction of buoyancy (acting upward or downward), further increase the mixing intensity. Ambient currents and stratification have a further influence on the jet mixing process.

An important aspect of the near-field dynamics of multiport diffuser is the determination under what combinations of discharge and ambient characteristics the near-field will be stable or unstable (see Figure 2.6). As explained by Jirka (1982), a near-field for buoyant

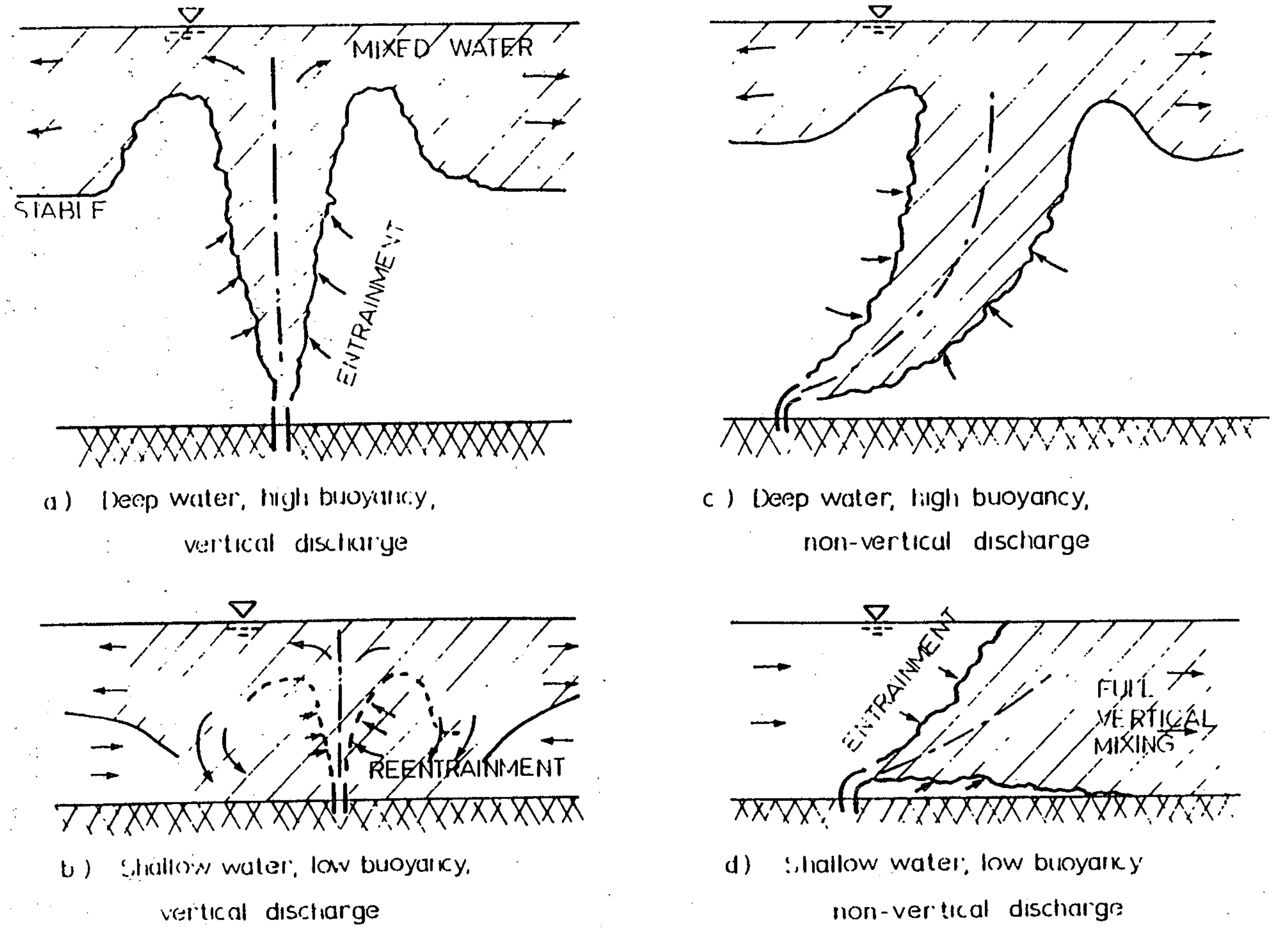


Figure 2.6 Stable and Unstable Near-Field Flows Produced by Multiport Diffusers: Examples of Buoyant Discharges into Unstratified Ambient. a,c: Stable Examples, b,d: Unstable Examples.

discharges is stable when a buoyant surface layer is formed which does not communicate with the initial buoyant jet zone. An unstable near field is defined whenever the layered flow structure breaks down in the discharge vicinity, resulting in recirculating zones or mixing over the entire water depth (see Figure 2.6).

The stability criterion for the near-field region of a buoyant diffuser discharge in a stagnant unstratified ambient is given by the interplay of momentum flux, buoyancy flux, and water depth H (Jirka, 1979, 1982)

$$m_o/(j_o^{2/3}H) = C/(1 + \cos^2\theta)^2 \qquad (2.3a)$$

where all the parameters involved were defined in the previous section and C is a constant. If an ambient crossflow exists in the environment, then another destabilizing factor is introduced, the ambient momentum flux per unit length, $m_a = u_a^2 H$, where u_a is the ambient current. The additional effect of cross-flow of velocity u_a can be represented by an additional parameter $m_a/(j_o^{2/3} H)$ which is added to the previous stabilty equation. Hence the stability criterion for the near field of a perpendicular diffuser discharge into a flowing water body is given by Jirka (1982) as

$$m_o/(j_o^{2/3}H) + (m_a + m_o \cos\theta)/(j_o^{2/3}H) = C \qquad (2.3b)$$

As examples, the application of those criteria (Eqs. 2.3a and b) to municipal and industrial wastewater diffusers in coastal waters in which the effluent possesses freshwater density usually indicates a stable regime. On the contrary, thermal diffusers operate with and usually in very high flowrates, with a small density difference less deep water, and thus an unstable regime will be present. Detailed analysis of the stability criterion and further applications are discussed in Jirka (1982).

Stable discharge conditions can also be referred to as a diffuser operating in deep water ("stable or deep water diffuser") while unstable conditions indicate a shallow water condition ("unstable or shallow water diffuser"). This terminology is used interchangeably in the following. The related near-field equations for trajectory and dilution of deep and shallow cases will be presented in Section 2.6.

2.3.2 Far-Field Processes

The far field zone begins after the flow interacts with the water surface, pycnocline, or bottom. This zone is composed of one or two regions, depending on the discharge characteristics. In the general case, the flow possesses enough buoyancy and thus a region of buoyant spreading will be established followed by a passive diffusion region. The region of surface/pycnocline/bottom spreading is represented by horizontal dynamic spreading and gradual vertical thinning of the flow after interaction with the surface as described by Roberts (1979) and by Koh and Brooks (1975). In the present situation, occurrence of boundary interaction may be possible, and hence the flow may become laterally fully mixed in the bounded sections.

In the region of passive diffusion, the dilution is mainly controlled by the presence of turbulent mixing in the flowing ambient water body. Again boundary interaction may occur, and the flow may become both laterally and vertically fully mixed in this region. For cases of non-buoyant or weakly buoyant flow, buoyant spreading will not be present and only passive diffusion will take place. For the case of stagnant ambient, the far field zone will be ignored due to the absence of any advection.

For the case of a near-field jet flow trapped by linearly stratified ambient, the far field is composed of two regions: internal buoyant spreading, and passive diffusion. The internal buoyant spreading behaves in the same way as the surface buoyant spreading except that the spreading occurs at the terminal layer rather than at the water surface. The passive diffusion has the same characteristics as the unstratified case with a reduced vertical mixing due to the damping effect of ambient stratification.

2.4 Length Scales Definitions

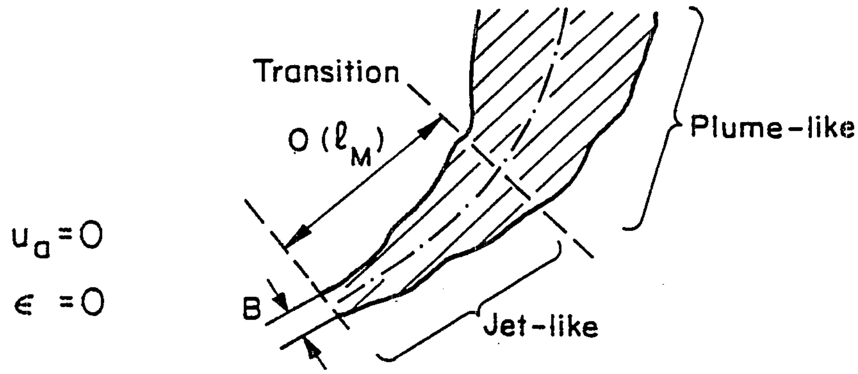
Length scales are used to describe the relative importance of discharge momentum flux, buoyancy flux, ambient crossflow, and density stratification in controlling flow behavior, especially in the near-field. The equivalent slot concept is used in the following considerations.

2.4.1 Jet to Crossflow Length Scale

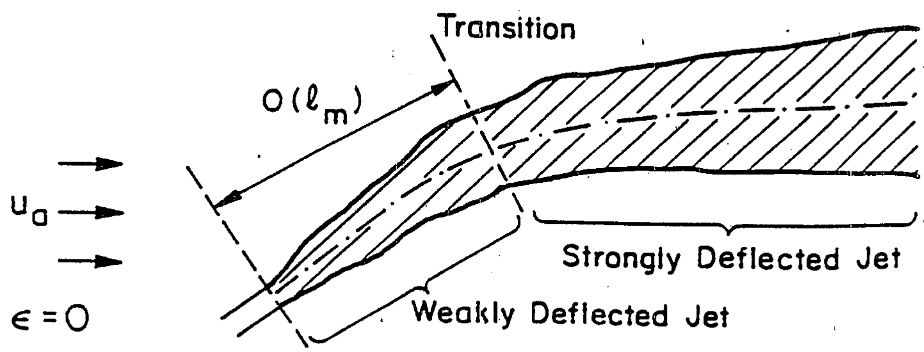
When an ambient crossflow of velocity u_a is present, the plane jet with perpendicular alignment will be deflected as shown in Figure 2.7b. The behavior of the jet in that case is related to the momentum flux and to the crossflow. In order to find the distance to the position where the jet becomes affected by the crossflow, one can obtain from dimensional analysis a jet/crossflow length scale l_m

$$l_m = m_o/u_a^2 \qquad (2.4)$$

Using this length scale together with the distance along the trajectory s, one can deduce that for $s/l_m << O(1)$ the initial plane jet momentum flux per unit length will control

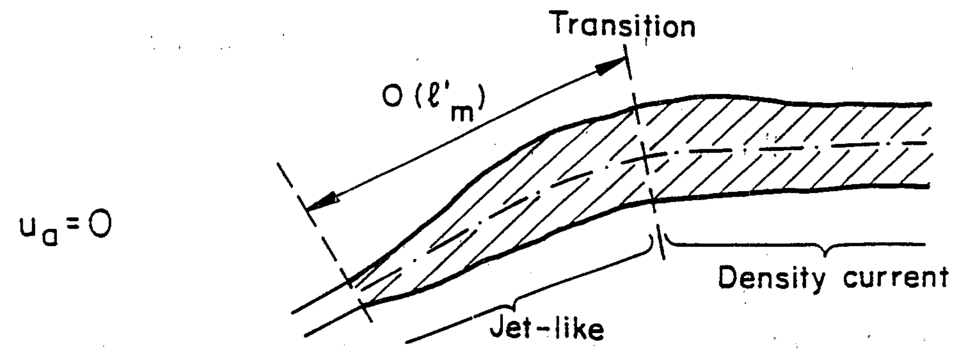


a) Buoyant Plane Jet in Stagnant Uniform Environment

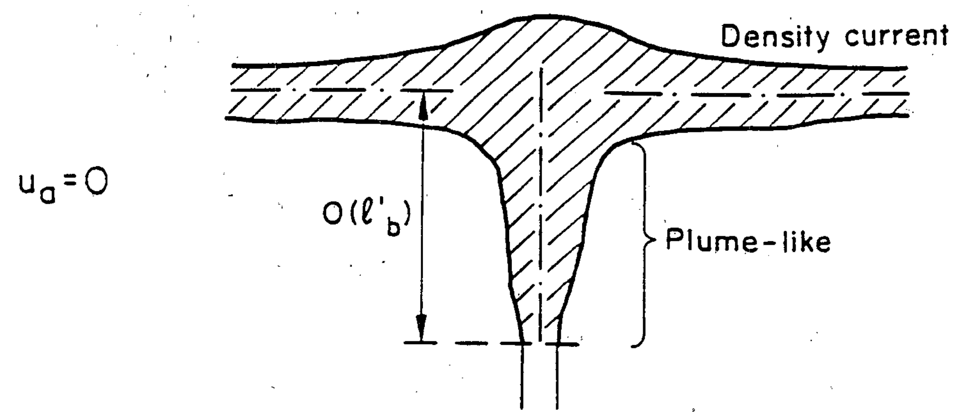


b) Plane Jet in Uniform Cross-flow

Figure 2.7 Examples of Combined Effects of Momentum Flux, Buoyancy Flux, Crossflux, and Density Stratification on Flow Behavior.



c) Plane Jet in Stagnant Stratified Ambient



d) Plane Plume in Stagnant Stratified Ambient

Figure 2.7 (Continued)

the flow, and for $s/l_m >> O(1)$ the crossflow velocity will have more influence on the plane jet behavior.

2.4.2 Jet to Plume Length Scale

Flows, in general, contain both momentum and buoyancy. Initially, the momentum controls the flow until the buoyant acceleration overcomes the momentum factor and ultimately dominates the flow. The distance at which there is a transition between momentum domination to buoyancy control in a stagnant environment, is represented by a jet/plume length scale (see Figure 2.7a) l_M

$$l_M = m_o/j_o^{2/3} \tag{2.5}$$

Thus, for $s/l_M << O(1)$ the flow behavior will be controlled by momentum and for $s/l_M >> O(1)$ the flow will be dominated by buoyancy.

2.4.3 Jet/Stratification Length Scale

When the additional effect of ambient stratification is introduced, other important length scales will be involved in the analysis. In the case of a stagnant ambient, the length scale describing the height of rise of a nonbuoyant jet in a stratified fluid is related to the momentum flux and the buoyancy gradient ε (see Figure 2.7c). The jet/stratification length scale is given dimensionally by

$$l_m' = (m_o/\varepsilon)^{1/3} \tag{2.6}$$

As explained by Wright (1977), the combined effect of stratification and crossflow will introduce two limiting possibilities in either the momentum dominated jet or buoyancy dominated plume: either the jet is still weakly deflected when it reaches its maximum height of rise or else it will be significantly bent over until the stratification causes it to stop rising. The ratio of $l_m'/l_m << O(1)$ indicates that the nonbuoyant jet will reach its maximum height of rise in the strongly deflected stage.

2.4.4 Plume/Stratification Length Scale

In the case of a stagnant ambient, the length scale describing the height of rise of a buoyant plume in a stratified fluid, is related to the buoyancy flux and the buoyancy gradient ε (see Figure 2.7d). This length l'_b is defined as

$$l_b' = j_o^{1/3}/\varepsilon^{1/2} \tag{2.7}$$

For a vertical distance of $z/l_b' << O(1)$ the effect of density stratification on plume behavior will be negligible.

2.4.5 Crossflow/Stratification Length Scale

When reaching the maximum elevation, a near vertical jet will still possess some vertical momentum which causes the jet to rise above the neutral buoyant position, but it will face back due to its negative buoyancy. Thus, an oscillation of the flow with decreasing amplitude will occur (Wright, 1977). The length scale l_a associated with this flow behavior is characterized by an interaction of crossflow and stratification

$$l_a = u_a/\varepsilon^{1/2} \qquad (2.8)$$

2.4.6 Additional Comments

It is interesting to note that no plume to crossflow length scale can be defined on dimensional ground for the two-dimensional plume. This is in contrast to the three-dimensional round plume (Doneker and Jirka, 1989). This arises from the fact that the vertical velocity of a two-dimensional plume is constant, $\sim j_o^{1/3}$, leading in the presence of a constant crossflow to a straight line trajectory. Thus, no distinction of a plume region can be made. However, it is possible to define a non-dimensional parameter j_o/u_a^3 whose magnitude will be a measure of the slope of that trajectory (see Section 2.6.1.1.5). This parameter j_o/u_a^3 is the inverse of a Froude number defined by Roberts (1977).

The multiport geometry controls the flow in the initial region after the discharge. For a strictly two-dimensional equivalent slot diffuser a length scale l_q can be defined from its volume and momentum flux,

$$l_q = q_o^2/m_o \qquad (2.9)$$

which is identical to the equivalent slot width, $l_q = B$. The actual multiport geometry, however, overshadows this length scale, as the merging distance for the individual three-dimensional jets is typically considerably larger than l_q.

2.5 Hydrodynamic Flow Classification

In this section, a rigorous flow classification scheme is developed that classifies any given discharge/environment situation into one of several flow classes with distinct hydrodynamic features. The classification scheme places major emphasis on the near-field behavior of the discharge and uses the length scale concept as a measure of the influence of each potential mixing process. Flow behavior in the far-field, mostly in the form of boundary interactions, is also discussed herein.

2.5.1 Near-Field Flow Classification

The objective of the hydrodynamic flow classification is to predict for a given discharge/ambient situation the type of flow configuration that will occur. Once a reliable classification has been established, it becomes much easier to provide actual predictions for flow properties, including pollutant concentration distributions, within the distinct hydrodynamic zones pertaining to each flow class.

The present flow classification procedure uses the length scale concept. The dynamic length scales characterizing the discharge are summarized in Table 2.1. There are five major length scales based on the two-dimensional properties (per unit length) of the jet: l_m, l_M, l_m', l_b', and l_a. In addition, if the diffuser is seen globally (over its entire length) then additional length scales can be defined based on the three-dimensional bulk variables, total momentum flux $M_o = m_o L_D$ and total buoyancy flux $J_o = j_o L_D$. These definitions are, on dimensional grounds, entirely analogous to the round buoyant jet (Doneker and Jirka, 1989) and are also included in Table 2.1. All these lengths interact with the geometric features of the ambient water body, its depth H and its stratification parameter ε, and with the geometry properties of the diffuser, mainly the angles γ, and θ.

Thus, in total, a large number of length scales plus two angles seem to influence the near field flow configuration. Therefore, this means that there exist a wide variety of flow configurations that may occur in environmental applications. The classification procedure presented below yields 31 generic flow configurations. The actual number of flow classes that can be modeled with the full predictive methodology (Chapter IV) is considerably larger (at least twice as many) since each of the 31 generic flow classes may apply to a layer corresponding to the full water depth or to the region below a pycnocline.

2.5.1.1 General Procedure

The flow classification is a 12 step procedure that is summarized in Table 2.2. This procedure is used to determine which flow class within the three major flow categories the given discharge will exhibit. The three major flow categories are: i) flows affected by linear stratification

Table 2.1 Summary of Length Scales Applicable for Multiport Diffuser

A) Based on Two-Dimensional Slot Parameters:

$l_q = q_o^2/m_o = B$ = discharge geometric scale (Eq. 2.9).

$l_m = m_o/u_a^2$ = plane jet/crossflow scale (Eq. 2.4).

$l_M = m_o/j_o^{2/3}$ = plane jet/plane plume scale (Eq. 2.5).

$l_m' = (m_o/\varepsilon)^{1/3}$ = plane jet/stratification scale (Eq. 2.6).

$l_b' = j_o^{1/3}/\varepsilon^{1/2}$ = plane plume/stratification scale (Eq. 2.7).

$l_a = u_a/\varepsilon^{1/2}$ = crossflow/stratification scale (Eq. 2.8).

B) Based on Global Three-Dimensional Parameters:

$L_q = Q_o/M_o^2$ = discharge geometric scale.

$L_b = J_o/u_a^3$ = plume/crossflow scale.

$L_m = M_o^{1/2}/u_a$ = jet/crossflow scale.

$L_M = M_o^{3/4}/J_o^{1/2}$ = jet/plume transition scale.

$L'_m = (M_o/\epsilon)^{1/4}$ = jet/stratification scale.

$L'_b = (J_o/\epsilon^{3/2})^{1/4}$ = plume/stratification scale.

where: $Q_o = q_o L_D$, $M_o = m_o L_D$, and $J_o = j_o L_D$.

Table 2.2 Near-Field Flow Classification Procedure

Step 1:	Test for density profile stability. If the ambient is unstratified or the given stratification is dynamically impossible according to a flux Richardson number criterion, approximate ambient density with mean value and recompute discharge parameters. Conclude stratification is not important and go to Step 10.
Step 2:	Ambient has stable density stratification. Check for density step change. If the ambient does not contain a density step change (Types A or D in Figure 2.1) go to Step 4.
Step 3:	Ambient density profile contains step change. Since the Stratification Type is B or C, approximate the actual lower layer stratification and the step change with a surrogate linear stratification (Figure 2.1). Calculate surrogate gradient $\varepsilon*$ and surrogate stratification length scales l_{ms}', l_{bs}', and l_{as}.
Step 4:	Possible flow trapping in linear density stratification. Test for internal layer formation (flow trapping), using the scheme outlined in the upper portion of Figure 2.8). Use height H_s ($H_s = H$ for stratification type A, and $H_s = h_{int}$ for types B, C or D). If $(Z_t + h_o)/H_s > O(1)$, density stratification will not trap flow. Therefore conclude ambient density stratification is not dynamically important.Approximate ambient density with mean value, recompute discharge parameters, and go to step 10.
Step 5:	Stratification is important and flow trapping may occur. If there is no density jump in the profile (Types A or D) go to Step 8.
Step 6:	Test for trapping at density jump or in linearly stratified layer. If stratification type is C, perform a second test for internal layer formation using the scheme outlined in the upper portion of Figure 2.8 based on the actual density gradient ε. If $(Z_t + h_o)/H_s < O(1)$, conclude the flow will become trapped in the linearly stratified layer below the density jump, go to Step 8.

Table 2.2 (continued)

Step 7: Trapping at the density jump (pycnocline). The linear stratification below the density jump is dynamically unimportant. The effluent flow will be confined to the lower layer of Stratification Types B or C due to the strong density jump. For Type C, approximate linear ambient density profile of lower layer with mean, and recompute discharge parameters. Set $H_s = h_{int}$ and go to Step 10.

Step 8: Check for flow interaction with bottom for flows influenced by linear density stratification. Flow may interact with bottom if the buoyancy is negative or jet is directed downward. If $Z_t + h_o < 0$, flow will interact with the bottom. Proceed to Step 12.

Step 9: Complete flow classification for buoyant jet in linearly stratified layer. Eight flow classes exist (MS1 to MS8) as shown in Figure 2.8.

Step 10: Test for discharge buoyancy in uniform ambient density layer height H_s. If discharge is negatively buoyant go to Step 12.

Step 11: Perform flow classification for positively buoyant (for neutral) jet in uniform density layer. Nine major flow classes (MU1 to MU9) exist as shown in Figure 2.9.

Step 12: Perform flow classification for negatively buoyant or downward directed jet in uniform density layer. Fourteen major flow classes exist (MNU1 to MNU14) as shown in Figure 2.10. STOP.

leading to internal trapping (MS classes, Figure 2.8), ii) buoyant flows in uniform ambient layers (MU classes, Figure 2.9), and iii) negatively buoyant flows in uniform ambient layers (MNU classes, Figure 2.10).

Even though a stable ambient density profile may be specified for a given situation, that profile may be weak or even dynamically impossible in the presence of the destabilizing effect of an ambient flow with mean velocity u_a. In **Step 1** of Table 2.2 a flux Richardson criterion (see Doneker and Jirka, 1989) is used to check for such destabilization which would enforce a uniform profile.

Steps 2 through **8** in Table 2.2 determine the effect of ambient density stratification (if present) on the flow. In general, if the predicted terminal height of rise Z_t for near-field flows is greater than the actual layer height H_s, then the effect of the linear stratification will be unimportant and the buoyant jet will transverse this layer as if it were in fact of uniform density.

If the terminal height of rise Z_t is less than the layer height H_s additional tests (**Steps 3** through **7**, Table 2.2) are performed. In the case of a profile with a density jump (Stratification Types B and C in Figure 2.1) these tests determine if the flow will be trapped by the pycnocline, or, in the case of Stratification Type C, trapped within the lower density layer. If the flow is trapped by the pycnocline, the details of stratification below the pycnocline are unimportant and the region below the pycnocline will be represented by a uniform density layer in all cases.

Step 9 is the detailed flow classification for those flow classes whose dynamics are directly affected by linear ambient stratification. The linearly stratified layer may extend over the full water depth or be confined to the region below the pycnocline. Further details on this classification are given in Section 2.5.1.2.

Steps 10 to **12** examine the flow behavior for those categories for which the ambient layer can be take as uniform (either existing or because any stratification is weak and dynamically unimportant compared to the discharge fluxes). The detailed classification for positively buoyant (or neutral) discharges in such a layer is contained in **Step 11** (see Section 2.5.1.3) and for negatively buoyant discharges in **Step 12** (see Section 2.5.1.4).

The detailed classification schemes for each flow category (Figures 2.8 to 2.10) are discussed in the following sections. It is stressed that all criteria presented in this Chapter and listed on Figure 2.8 to 2.10 are "order of magnitude" relations. The precise form of the criteria

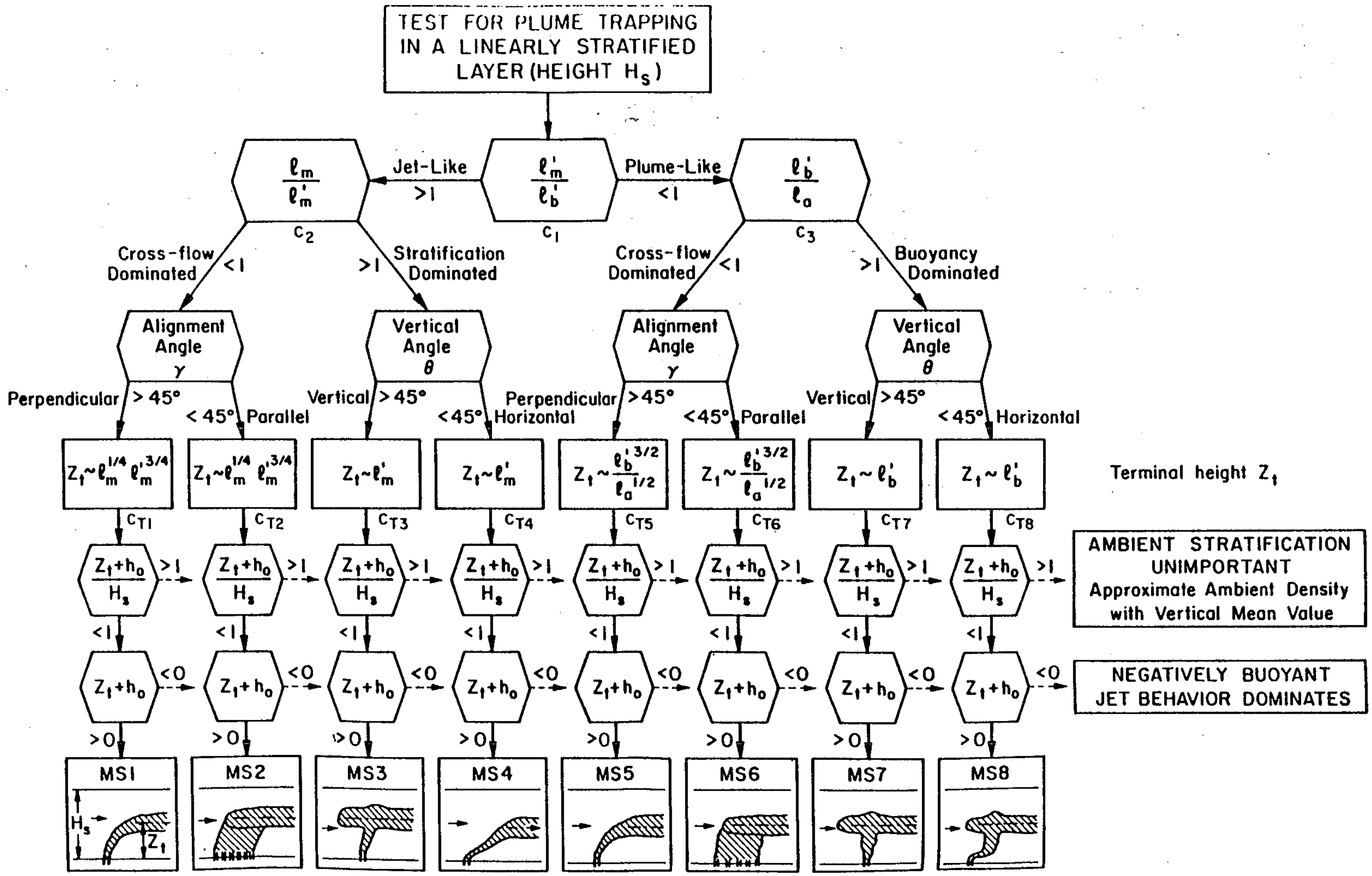


Figure 2.8 Sub-Classification: Assessment of Ambient Density Stratification and Different Flow Classes for Internally Trapped Discharges.

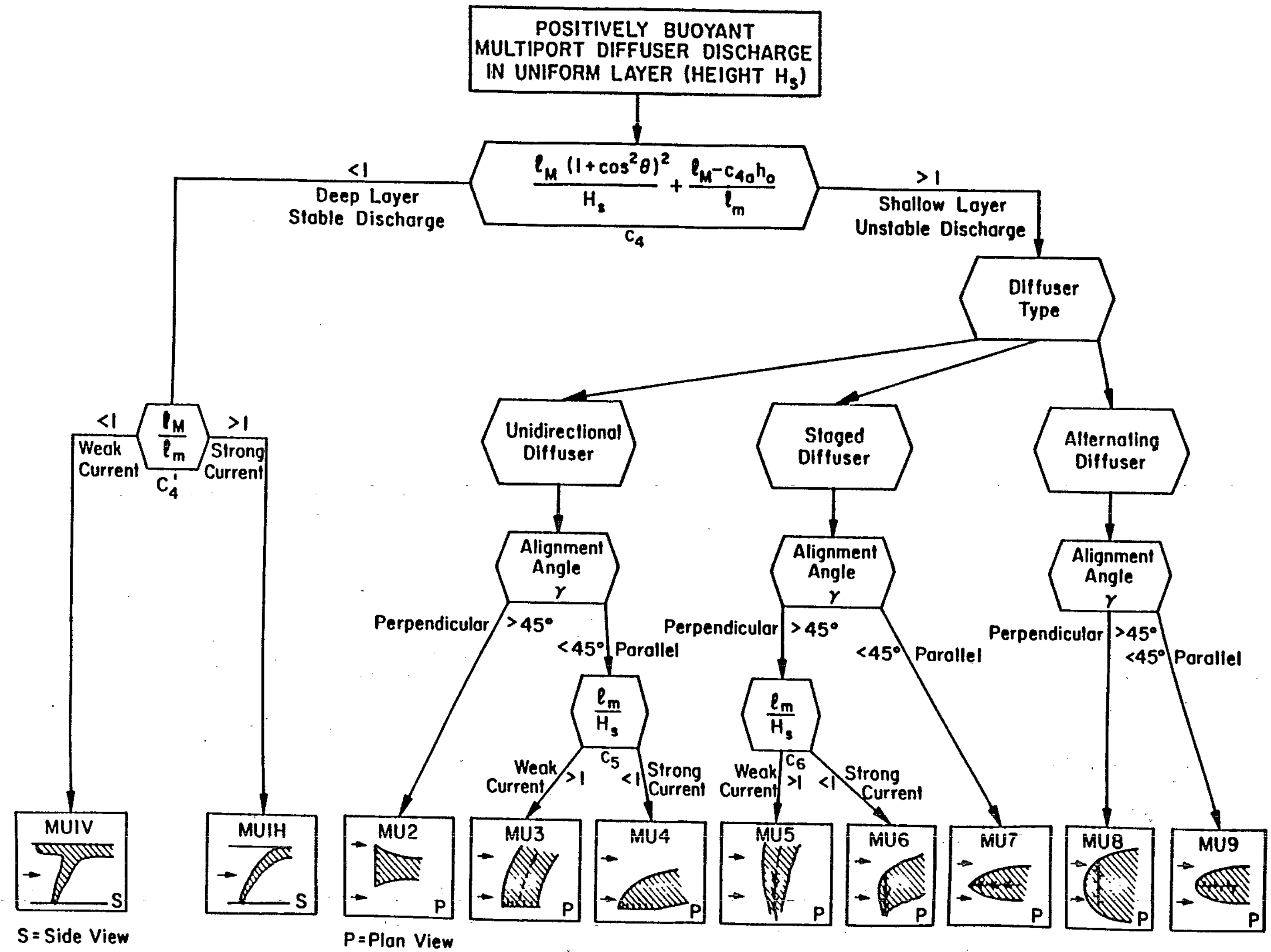


Figure 2.9 Sub-Classification: Behavior of Positively Buoyant Discharges in Uniform Ambient Layer.

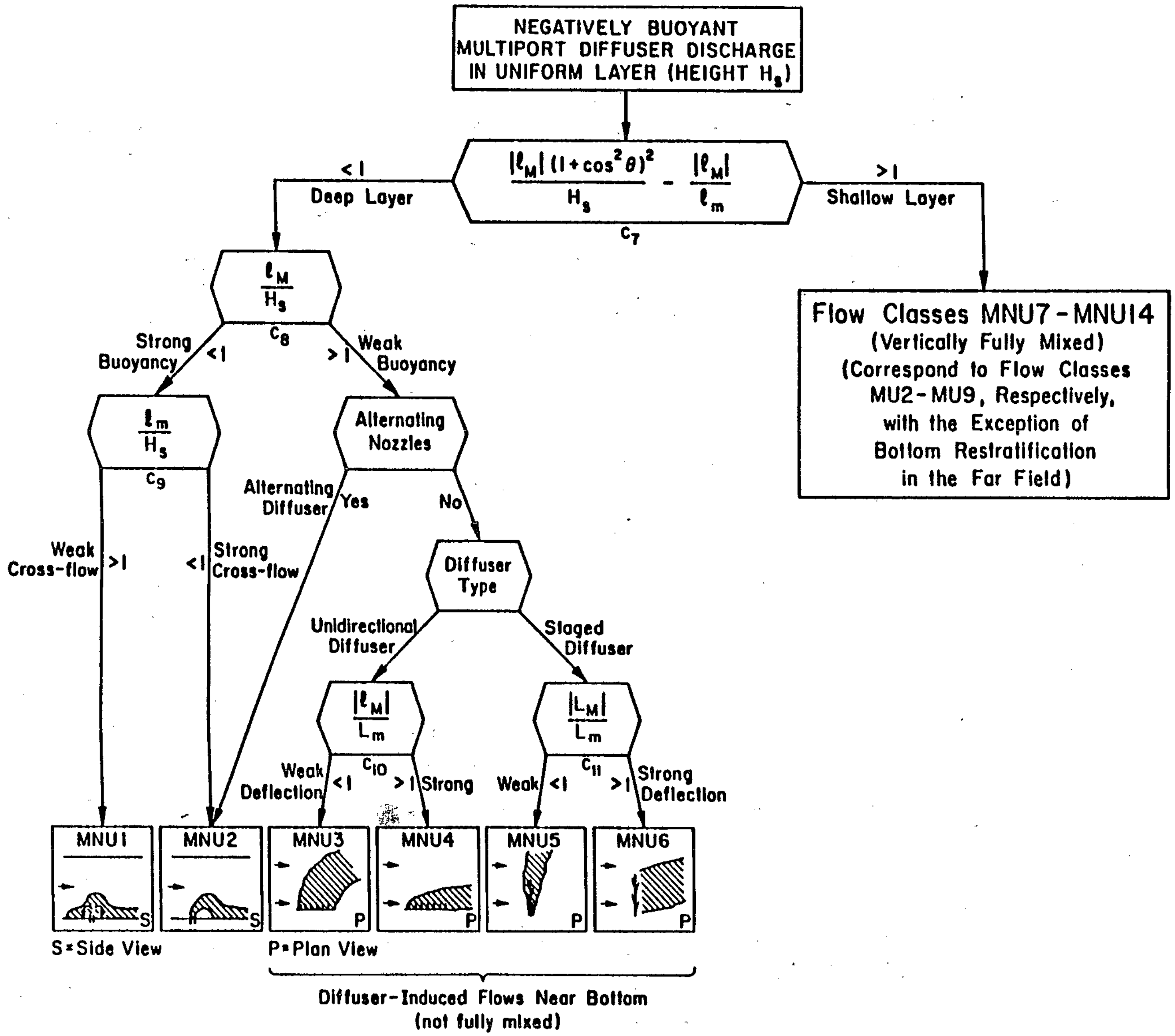


Figure 2.10 Sub-Classification: Behavior of Negatively Buoyant Discharges in Uniform Ambient Layer.

as well as the numerical constants are given in Chapter IV.

2.5.1.2 Flow Classes MS for Linear Ambient Stratification

Referring to Figure 2.8, the first test level of the flow classification for a buoyant jet in a linearly stratified layer is to determine whether the flow is mostly jet-like or mostly plume-like as it rises in the stratified layer. This is achieved through the comparison of the stratification length scales, l_m'/l_b'.

The next determination is the relative importance of crossflow on these stratified flows. For jet-like stratified flows, if $l_m/l_m' < O(1)$ the crossflow will have strongly deflected the buoyant jet flow by the time the stratification starts to influence the flow leading to a "crossflow dominated" regime, and thus the alignment angle γ will become an important factor in classifying the flows. But for $l_m/l_m' > O(1)$ the crossflow is weak and the flow is "stratification dominated", and hence the vertical angle θ will become the decision variable for classifying.

For plume-like stratified flows, because of the non-existence of the two-dimensional plume to crossflow length scale (see Section 2.4.6), a comparison of the effect of stratification relative to the crossflow effect uses the length scale l_a. If $l_b'/l_a < O(1)$ the crossflow will have strongly deflected the buoyant plume flow before the buoyancy begins to affect the flow leading to a "crossflow dominated" regime (γ is the further decision parameter). On the other hand, $l_b'/l_a > O(1)$ signifies a "buoyancy dominated" flow (θ is the decision parameter).

The terminal heights of rise Z_t equations for any of these flows are indicated on Figure 2.8. Detailed references for these equations are in Section 4.3.2. In general, the height of rise depends on l_m', or l_b' or l_a with an added influence of l_m for crossflow affected stratified flow. The sketches at the bottom of Figure 2.7 indicate the schematic flow configuration for each flow class. Once the terminal height has been reached, some flows (MS1, or MS2, or MS5, or MS6) are further deflected by the strong crossflow leading to far-field buoyant spreading and diffusion phases. Other flows (MS3, or MS7, or MS8) have weak crossflow and are more nearly vertical in their approach ("impingement") to the terminal layer with an ensuing upstream spreading phase. Flow class MS4 with strong horizontal momentum experiences a near-horizontal "injection" into the terminal layer.

2.5.1.3 Flow Classes MU for Buoyant Discharges into Uniform Ambient Layers

The flow classification system for positively buoyant discharges in uniform ambient layers appears in Figure 2.9. In this classification, the stability criterion (expressed here in terms of length scale), defined in Section 2.3.1 (Eq. 2.3), is used to characterize the discharge as "deep water" or "shallow water". A deep water discharge will have relatively weak momentum as the flow contacts the surface, while a shallow discharge will have a strong momentum as the flow impinges on the surface.

In the case of deep water (stable conditions), buoyancy tends to have a stabilizing effect on the flow as it contacts the surface. The study distinguishes between two kinds of flow, one with a low ambient current where $l_M/l_m < O(1)$ (MU1V) and one with a high ambient current where $l_M/l_m > O(1)$ (MU1H).

In the case of shallow water, the flow has a strong vertical momentum at surface contact and tends to be unstable. The jet is deflected downward by the surface and an unstable recirculation zone occurs around the jet as it re-entrains the deflected fluid flow. Therefore, the flow is vertically completely mixed in the near-field. For these unstable conditions, the diffuser geometry, particularly its total net momentum input, becomes an important factor (flow classes MU2-MU9). As defined in Section 2.2.2.1, there are three kinds of diffusers (unidirectional, staged, and alternating), and hence a flow configuration pattern is assigned to each one.

For the special cases of a predominantly parallel alignment ($\gamma < 45°$) for the unidirectional diffuser and of a predominantly perpendicular alignment ($\gamma \geq 45°$) for the staged diffuser, respectively, thus, for cross-flowing discharges a test is performed to determine whether momentum or crossflow control the fully mixed diffuser plume in the ambient layer depth H_s. If $l_m/H_s > O(1)$ the flow is controlled by momentum, and crossflow has a minor role in flow behavior (flow classes MU3 and MU5), and in the case of $l_m/H_s < O(1)$, crossflow will play the dominant role relative to both momentum and buoyancy factors (flow classes MU4 and MU6). In the remainder of the flow classes the diffuser discharge is predominantly co-flowing, or has no net-horizontal momentum in the case of alternating diffusers.

2.5.1.4 Flow Classes for MNU Negatively Buoyant Discharges in Uniform Ambient Layers

The classification system for negatively buoyant discharges (Figure 2.10) bears some similarities to that for positively buoyant discharges described above. Several negatively buoyant flow classes have a "mirror image" analogy to the positively buoyant flows.

Again, using a similar stability criterion as before, one can distinguish between deep and shallow cases. In the deep water case, the first step is to determine whether momentum or buoyancy dominates the flow with respect to the ambient layer depth H_s. If $l_M/H_s < O(1)$, the flow will be buoyancy dominated after a short distance and therefore will not have any surface interaction. If $l_M/H_s > O(1)$, the flow will be momentum dominated in relation to the ambient layer depth H_s. Additional testing is performed in the buoyancy dominated branch where the momentum length scale is compared to the ambient layer depth H_s. If $l_m/H_s > O(1)$, crossflow is weak, and hence the flow will rise slightly before falling to the bottom (MNU1). If $l_m/H_s < O(1)$, the effect of crossflow is high, and the flow, after rising slightly, becomes advected downstream with a gradual approach to the bottom (MNU2). For the momentum dominated branch, the discharge geometry becomes important. For the alternating diffuser, the flow will behave similarly to the previous one (MNU2). For the unidirectional diffuser, additional tests are performed to determine whether momentum and buoyancy or crossflow dominate the flow. The overall length scale L_m (see Table 2.1) is used for that purpose. If $l_M/L_m < O(1)$, the flow has a weak deflection (MNU3), otherwise, the flow possesses a strong deflection due to crossflow (MNU4). The same comparison is done for the staged diffuser but using the overall length scale L_M (see Table 2.1) instead of l_M. Weak deflection is indicated for $L_M/L_m < O(1)$ (MNU5), and strong deflection for $L_M/L_m > O(1)$ (MNU6), respectively.

In the fully mixed shallow water cases, the same decision tree is used as for positively buoyant discharges (Figure 2.9) to describe the flow configuration (MNU7-MNU14) with the exception of bottom restratification in the far-field.

2.5.2 Far-Field Flow Behavior

After the effluent flow has interacted with the water surface, bottom, pycnocline, or terminal layer and has thus completed its near-field phase, the far-field mixing begins. In the general case, the discharge flow contains sufficient buoyancy and there will be a buoyant spreading region followed by a passive diffusion region. The buoyant spreading region is characterized by dynamic horizontal spreading and gradual vertical thinning of the mixed effluent flow, while being advected by the ambient current. Vertical boundary interaction may occur, and the flow may contact one or both lateral boundaries (shorelines). In the passive diffusion region, the dilution is controlled by the turbulent mixing action of the flowing ambient water body. Again, boundary interaction may occur, and the flow may become both laterally and vertically fully mixed within the layer height H_s in this region. If the flow is non-buoyant or weakly buoyant there is no buoyant surface spreading region, only a passive diffusion region.

In contrast to the near-field flow there is no need for an advance classification scheme to determine the behavior of the far-field flow for a given discharge/environment situation. Since effluent flow in the far-field is always advected in the direction of the ambient flow, the various interaction processes are simply calculated as part of the downstream modeling process of the applicable far-field solutions. This applies also to the transition between buoyant spreading and passive ambient diffusion (based on a flux Richardson number criterion). These aspects are discussed in Doneker and Jirka (1990).

2.6 Analysis of Individual Flow Processes

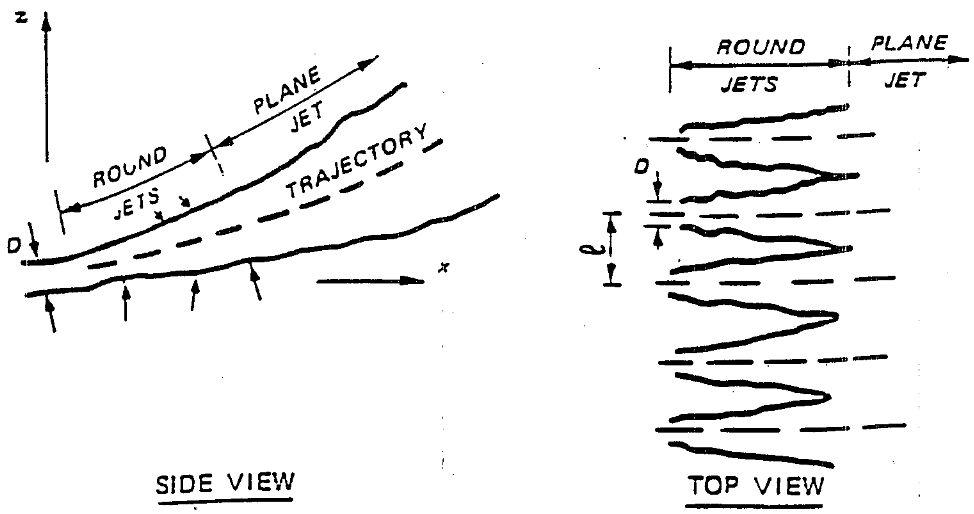
The dynamics of individual mixing processes and their analysis are discussed in this Section. The first subsection deals with jet/plume dynamics in deep water including boundary interaction processes. The second subsection addresses the diffuser-induced fully mixed plume motions in shallow water. Finally, specific features of buoyant spreading and diffusion processes in the far-field are discussed.

2.6.1 Buoyant Plane Jet Processes in Deep Water

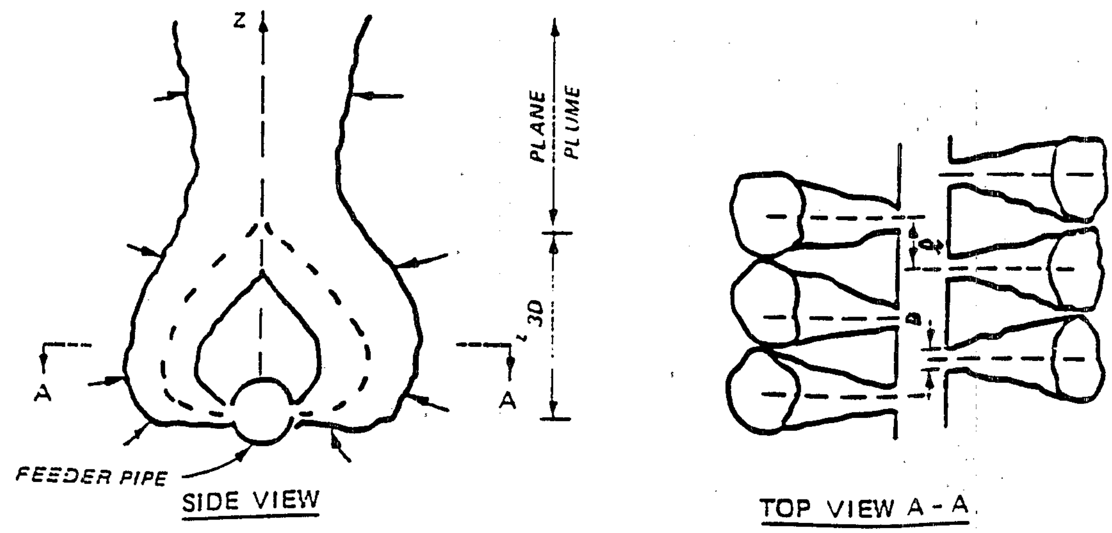
The effluent leaving the diffuser ports behaves as a series of round buoyant jets (see Figure 2.11, Holley and Jirka, 1986) and hence round buoyant jet analysis can be used for prediction. At some distance, the adjacent plumes merge with each other, and from then on the flow can essentially be considered as two-dimensional. The initial round plume region (three-dimensional region) will not be considered in the following analysis.

2.6.1.1 Unstratified Ambient

This section presents analytical results for plane jets and plumes issued vertically upward from a slot of width B, perpendicular to the crossflow. First, the simple plane jet and plume solutions in stagnant environment are introduced. Then the theory is expanded to include the effects of ambient crossflow and stratification. The procedure is based on <u>perturbation solutions</u>, in the sense that a simple analytical solution is being perturbed by assuming a small



Jets merging in unidirectional diffuser



Jets merging in alternating diffuser

Figure 2.11 Interference of Individual Round Jets from Multiport Diffuser Discharges forming Two-Dimensional (Slot) Jets or Plumes (Ref. Lee and Jirka, 1991).

effect of an additional variable (e.g. a weak crossflow).

For the following development the simplest possible assumptions are being made: a plane source, either vertical or horizontal orientation, and only one perturbing variable. The results can be readily generalized to more complex conditions (e.g. arbitrary orientation or multiple influences). Indeed, such generalizations are implemented in the predictive elements presented in Chapter IV.

2.6.1.1.1 Simple Plane Jet in Stagnant Environment

Consider a plane jet (2-D) in a stagnant ambient fluid (Figure 2.12). In the initial stage (when flow exits from the equivalent slot diffuser), the velocity distribution is near uniform. After a short distance s along the jet trajectory, the velocity profile approaches a bell-shaped (Gaussian) distribution.

The maximum velocity u_c occurs along the trajectory centerline and a similarity profile is assumed for the velocity distribution. Similar conditions hold for the centerline concentration c_c of pollutant or tracer mass. The jet centerline velocity u_c decreases with distance s from the point of transition as the plane jet entrains the stagnant ambient fluid. The momentum flux per unit length m_o is conserved along the trajectory, and the variation and magnitude of the plane jet centerline velocity depend essentially upon m_o and the distance along the trajectory s, $u_c \propto (m_o, s)$. Using dimensional analysis, one obtains

$$u_c = c(m_o/s)^{1/2} \tag{2.10}$$

where c is a constant.

The width b of the plane jet can, in principle, also depend on m_o and s, but for dimensional reason, the only possibility is a linear spreading

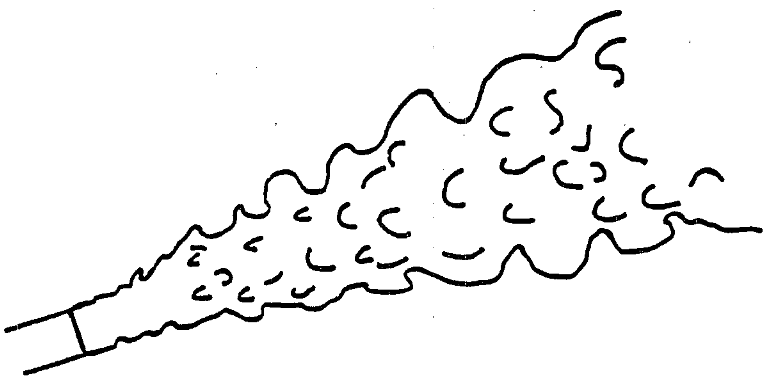
$$b = b_1 s \tag{2.11}$$

where b_1 is a constant.

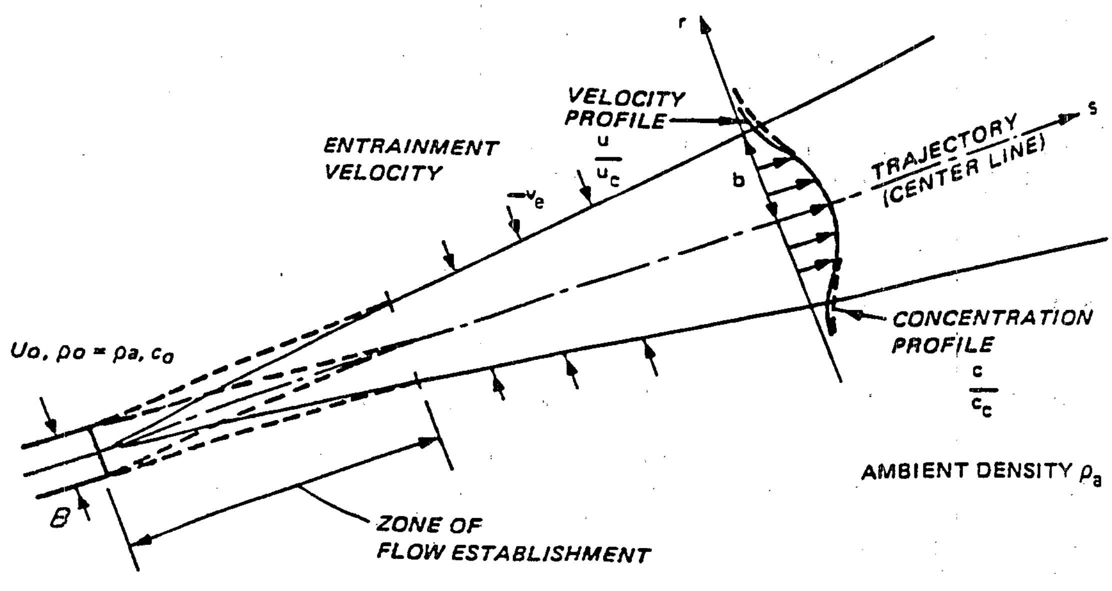
The volumetric dilution S at any cross-section along the jet is defined by $S = c_o/c_c$, where c_o is the initial concentration (at the ports). The dilution S is related to m_o, s, and q_o, and by conservation of mass, one obtains

$$S = s_1(m_o s)^{1/2}/q_o = s_1(s/l_q)^{1/2} \tag{2.12}$$

where s_1 is a constant.



Instantaneous appearance



Time-averaged conditions

Figure 2.12 Plane Jet in Stagnant Environment (Reg. Holley and Jirka, 1986).

2.6.1.1.2 Simple Plane Plume in Stagnant Environment

A plane plume rises vertically and experiences an increase in vertical momentum flux per unit length with distance z above the source (Figure 2.13). The buoyancy flux per unit length is constant for any plume cross-section as it rises in an unstratified ambient. By dimensional analysis, the centerline velocity is independent of z

$$u_c = c(j_o)^{1/3} \tag{2.13}$$

where c is a constant.

The width b of the plane plume depends on distance z

$$b = b_3 z \tag{2.14}$$

where b_3 is a constant.

The dilution for a plane plume can be expressed by the buoyant acceleration g'_o (buoyancy is conserved in the plane plume) which decreases with distance s as the plume rises and becomes diluted by the ambient fluid. The decrease in g'_o is directly proportional to the amount of ambient fluid entrained in the plume, so that $S = g'_o/g_o$. Using the continuity equation for buoyancy flux

$$S = s_3 j_o^{1/3} s/q_o = s_3 s/(l_q l_M)^{1/2} \tag{2.15}$$

where s_3 is a constant.

2.6.1.1.3 Weakly Deflected Plane Jet in Crossflow

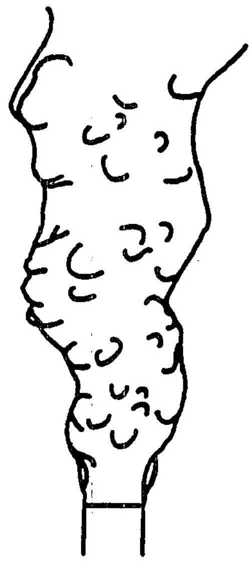
For a relatively weak crossflow, the plane jet would behave in the same manner as if it were in a stagnant environment, except that it is slightly advected by the ambient current (Figure 2.7b). This region is defined for $z/l_m << O(1)$.

Considering a plane jet issuing perpendicular to the crossflow, after the region of flow establishment the vertical velocity is given by Eq. (2.10). The kinematic relationship for a plane jet moving horizontally with the crossflow velocity u_a is, in the first order

$$dx/u_a = dz/u_c \tag{2.16}$$

Substituting Eq. (2.10) into (2.16) and integrating gives the trajectory relationship for the weakly deflected plane jet flow expressed in terms of the jet to crossflow length scale

$$z/l_m = t_1(x/l_m)^{2/3} \tag{2.17}$$



Instantaneous appearance

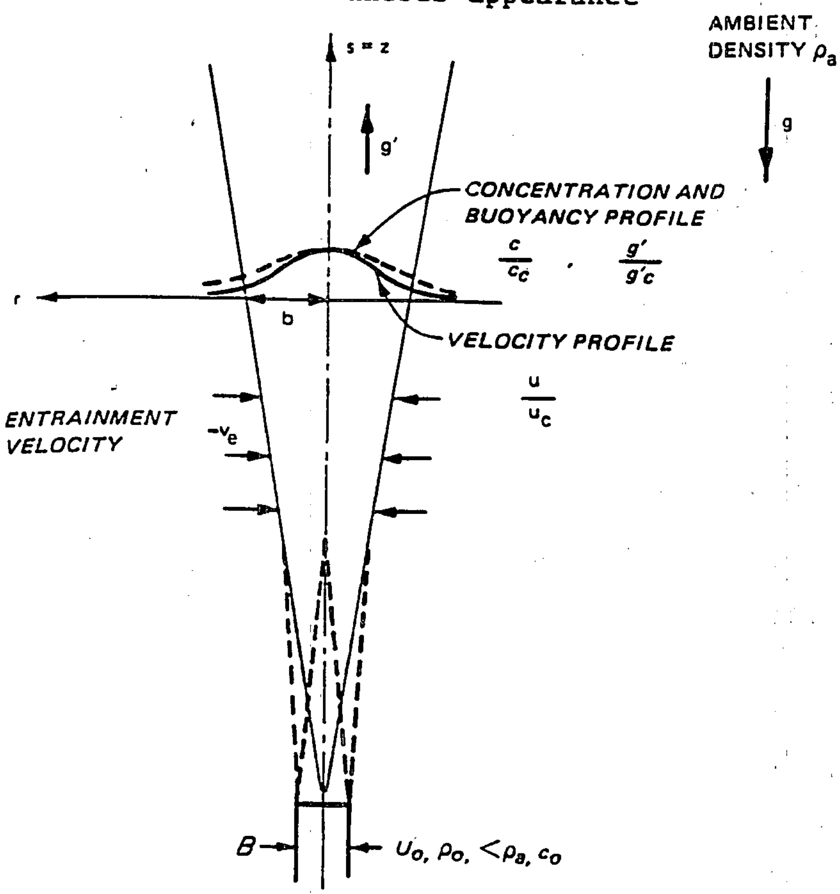


Figure 2.13 Plane Plume in Stagnant Environment (Ref. Holley and Jirka, 1986).

where t_1 is a trajectory constant.

The plane jet width is similar to the width in the stagnant case, and is given by Eq. (2.11).

The equation for dilution is similar to Eq. (2.12), and expressed in terms of the length scale is

$$S = s_1(z/l_q)^{1/2} \qquad (2.18)$$

where s_1 is the dilution constant.

2.6.1.1.4 Strongly Deflected Plane Jet in Crossflow

For $z/l_m >> O(1)$ the ambient flow will have a more direct effect on the flow pattern. For a strongly deflected plane jet, the vertical velocity has decayed to less than the value for the ambient crossflow; thus the ambient crossflow will have significantly deflected the plane jet as shown in Figure 2.7b.

The equations for the strongly deflected plume jet are derived on the basis of a "plume impulse" model analogous to the line impulse model used for the deflection of a single round jet (see Doneker and Jirka, 1989). Using the impulse model, the characteristic variables are the distributed momentum impulse m′ ($m' = m_o/u_a$), the vertical rise z, and the ambient velocity u_a. Applying this concept to the plane jet, the vertical velocity of rise u_c is proportional to $m_o/u_a z$. Applying Eq. (2.16) one finds the trajectory relation for the strongly deflected jet flow in non-dimensional form

$$z/l_m = t_2(x/l_m)^{1/2} \qquad (2.19)$$

where t_2 is a trajectory constant.

Similar to Eq. (2.11) the jet width is proportional to position z

$$b = b_2 z \qquad (2.20)$$

where b_2 is a constant.

The continuity equation provides the dilution S at any position z

$$S = s_2 z/(l_m l_q)^{1/2} \qquad (2.21)$$

where s_2 is a dilution constant.

Little is known about the appropriate constants for such deflected jets. Assuming that the two-dimensional plane jet is penetrated by the crossflow and broken-up into three-dimensional elements, the coefficients t_2, b_2, and s_2 can be assumed to have the same values as those used for the three-dimensional counterpart (see Doneker and Jirka, 1989).

2.6.1.1.5 Weakly and Strongly Deflected Plane Plume in Crossflow

As remarked in Section 2.4.6, in the two-dimensional case, a plume to crossflow length scale does not exist. Therefore, in order to investigate the deflected plume dynamics, one can compare the vertical plume centerline velocity u_c to the ambient velocity u_a. Two cases are possible:

a) If $u_c >> u_a$, the initial buoyancy will dominate and crossflow is of secondary importance. Therefore the flow will behave as plume in a stagnant environment but will be weakly advected with the crossflow. In analogy to the weakly deflected jet flow (Section 2.6.1.1.3), the trajectory equation for the weakly-deflected plane plume flow expressed in terms of length scales is

$$z = t_3 x (l_m/l_M)^{1/2} \qquad (2.22)$$

where t_3 is the trajectory constant.

The plane plume width is similar to the plume issuing in a stagnant environment and is given by Eq. (2.17).

The dilution S is similar to Eq. (2.18), and expressed in terms of length scale is

$$S = s_3 z/(l_M l_q)^{1/2} \qquad (2.23)$$

where s_3 is the dilution constant.

b) If $u_c << u_a$, the high ambient velocity will cause a strongly deflected plane plume behavior. It is reasonable to assume that this bent-over plume behaves as a distributed thermal, an instantaneous release of buoyancy-driven fluid along a line source. The characteristic variables are the buoyancy release, $j' = j_o/u_a)$, the vertical rise z, and the ambient velocity u_a. Applying these concepts to the plane plume, the vertical velocity u_c is proportional to $(j_o/u_a)^{1/2}$, and the trajectory relation for the strongly-deflected plane plume flow is

$$z = t_4 x (l_m/l_M)^{3/4} \qquad (2.24)$$

where t_4 is a trajectory constant.

Plane plume width is similar to Eq. (2.14),

$$b = b_4 z \tag{2.25}$$

where b_4 is a constant for the bdh flow. Using the continuity equation to find the dilution S at any position z,

$$S = s_4 z/(l_m l_q)^{1/2} \tag{2.26}$$

where s_4 is a dilution constant.

2.6.1.1.6 Horizontal Plane Jet with Vertical Buoyant Deflection

For a horizontally discharging jet with weak vertical deflection induced by the discharge buoyancy, the centerline velocity is given in first order by the simple plane jet solution, Eq. (2.10), or $u_c \cong (m_o/x)^{1/2}$ in which x is the horizontal coordinate direction. The small vertical deflection due to the local buoyancy-induced velocity w is

$$dz/dx = w/u_c \tag{2.27}$$

The local buoyant vertical acceleration of a jet element is given by

$$dw/dt \cong j_o/(bu_c) \tag{2.28}$$

in which $b \cong x$ is the plane jet width. With the Galilean transformation $dt = dx/u_c$, and after substitution for b and u_c, Eq. (2.27) and (2.28) can be solved to give the normalized trajectory relation

$$z/l_M = t_5(x/l_M)^{5/2} \tag{2.29}$$

The appropriate width and dilution equations are

$$b = b_5 x \tag{2.30}$$

and

$$S = s_5(x/l_q)^{1/2} \tag{2.31}$$

where the constants b_5 and s_5 should be numerically similar to those for the weakly deflected jet in crossflow, $b_5 \cong b_1$, and $s_5 \cong s_1$, respectively. In either case the perturbation effects are small and the equations must be identical if no perturbation is present. The above solutions are valid in the region $x/l_M < O(1)$.

2.6.1.1.7 Vertical Plane Plume with Horizontal Momentum Deflection

The final phase of a horizontal buoyant jet will be a vertically rising plume which is weakly deflected by the effect of the horizontal discharge momentum (see Fig. 2.5a). This will occur in the region $z/l_M > O(1)$. The plume will have a local vertical centerline velocity given in first order by the plane plume solution, Eq. (2.13). The small horizontal deflection of the plume trajectory is given by

$$dx/dz = u_h/u_c \tag{2.32}$$

where u_h is the induced horizontal velocity due to the discharge momentum flux m_o. Conservation of horizontal impulse implies

$$bu_h \cong m_o/u_c \tag{2.33}$$

in which $b \cong z$ is the plume width. The trajectory relation is obtained after substitution and integration

$$x = x_F + t_6 l_M \ln(z/z_F) \tag{2.34}$$

in which x_F and z_F are the ultimate value of the horizontal and vertical deflection for the final stage (z approaches infinity) of the vertically rising plume. The width and dilution are given directly by Eqs. (2.14) and (2.15), or using the appropriate length scales,

$$b = b_6 z \tag{2.35}$$

and

$$S = s_6 z/(l_M l_q)^{1/2} \tag{2.36}$$

As before, the constants b_6 and s_6 should be the same as those for the weakly deflected plume, $b_6 \cong b_3$ and $s_6 \cong s_3$, respectively.

2.6.1.2 Typical Regimes of Buoyant Plane Jets in Linear Stratification

This section presents analytical results for plane jets and plumes issued from a slot of width B discharging into a stratified ambient.

2.6.1.2.1 Plane Jet in Linear Stratification

The ratio $l_m'/l_m << O(1)$ indicates that the nonbuoyant jet will reach its maximum height of rise before it is bent over by the effect of crossflow. Therefore, in order to find solutions to that region (region beginning from the discharge point to the maximum height) where the effect of crossflow is negligible, one has to use the differential equations of the simple plane jet in an unstratified stagnant ambient and extend them to include the factor of stratification. Two extreme cases of vertical and horizontal jets are addressed.

a) **Vertical Jet in Linear Stratification**

Using the jet differential equations (Section 2.6.2, Holley and Jirka,1986) and adding the effect of stratification to the buoyancy term (Section 2.7, Holley and Jirka), one can get a solution for the zone described. The solution details are omitted here. The equation for terminal height of rise expressed in length scale is

$$z_t = t_6 l_m' \qquad (2.37)$$

where t_6 is a constant.

The width of the plane jet is similar to Eq. (2.14),

$$b = b_6 s \qquad (2.38)$$

where b_6 is a constant.

The dilution S is found to be related to the momentum flux m_o, the discharge q_o, the stratification parameter ε, and the trajectory distance s. The equation of S expressed with appropriate length scales is

$$S = (s_6 s^{1/2}/l_q^{1/2})(1 - s_{61}(s/l_m')^3)^{1/2} \qquad (2.39)$$

where s_6 and s_{61} are dilution constants.

b) **Horizontal Jet in Linear Stratification**

Using the solution for the plane jet in an unstratified ambient (Holley and Jirka, 1986), the equations for plane jet width and plane jet dilution are

$$b = b_7 s \qquad (2.40)$$

$$S = s_7 (s/l_q)^{1/2} \qquad (2.41)$$

where b_7 and s_7 are respective constants.

2.6.1.2.2 Buoyant Plane Plume in Stratified Stagnant Ambient

In contrast to the preceding solution for the pure jet there does not exist an explicit solution for the pure plume in stratified stagnant ambient. However, in the region below the terminal height, $z << Z_t$, stratification will be of second order and the solution can be approximated by the line plume solution in unstratified ambient. This leads to the dilution equation,

$$S = s_8 z / (l_M l_q)^{1/2} \tag{2.42}$$

where s_8 is the dilution coefficient, and the width equation

$$b = b_8 z \tag{2.43}$$

where b_8 is a constant.

The constant related to the dilution s_8 should be similar to s from Eq. (2.15), and constant b_8 similar to b_3 from Eq. (2.14).

2.6.1.3 Surface, Bottom, and Terminal Layer Interaction Processes

Ambient water bodies always have vertical boundaries: these are the water surface and the bottom, but in addition "internal boundaries" may exist in the form of layers of abrupt density changes (pycnoclines). Depending on the dynamic and geometric characteristics of the discharge flow, a large number of interaction phenomena can occur at such boundaries. Furthermore, in the case of a linearly stratified ambient where flow trapping may occur, other interaction phenomena may take place.

In essence, these interaction processes provide a transition between the jet mixing process in the near-field (Section 2.6.1), and between buoyant spreading (Section 2.6.3) and passive diffusion (Section 2.6.4) in the far-field.

Several possible interaction processes are analyzed in detail by Doneker and Jirka (1989). These processes pertain to single port as well as to multiport discharges. They are: (i) near-vertical surface/bottom/pycnocline impingement with buoyant upstream spreading, (ii) near-vertical surface/bottom impingement with unstable recirculation, buoyant restratification, and upstream spreading, (iii) stratified terminal layer impingement with buoyant upstream spreading, and (iv) stratified near-vertical surface injection with upstream spreading.

A control volume approach is used for the following section. When the flow contacts the boundary, b_v and b_h are defined as the vertical depth and horizontal half-width of the subsequent flow, respectively. The variable subscripts "i" (initial) and "f" (final) (e.g. b_i, S_f) denote control volume inflow and outflow quantities, respectively.

In the surface approach the bent over flow approaches the water surface near horizontally at impingement angle θ_i < 45°. The flow is advected with the ambient velocity field at a rate equal to u_a. This situation occurs for crossflow dominated jet-like and plume-like cases that are relatively weakly buoyant, hence the flow will be strongly deflected when it contacts the surface.

Experimental evidence (Jirka and Harleman, 1973) suggests that within a short distance after surface impingement the concentration distribution for a 2-D flow changes from the assumed Gaussian distribution to a top-hat or uniform distribution. Using a control volume approach the initial centerline dilution is related to the final bulk dilution, and a bulk mixing process is assumed with $S_f = cS_i$, where c is a constant. The width of this section is given by the diffuser length and the alignment, $2b_{hf} = L_D \sin\gamma$. The continuity equation for the control volume is then

$$S_f Q_o = u_a b_{vf} L_D \sin\gamma / 2 \qquad (2.44)$$

where b_{vf} is the final flow vertical width, and b_{hf} is the final flow horizontal half-width.

A dynamically analogous situation exists for the bottom approach of a downward oriented jet or negatively buoyant flow. Also the approach process to any internal pycnoclines is quite similar, even though the layer configuration will adjust itself hydrostatically along the pycnocline depending on the density jump conditions (see Doneker and Jirka, 1990).

For the case of unstratified ambient, one more interaction process exists which is the near-vertical surface impingement with buoyant upstream spreading. A full discussion on this particular flow can be found in Doneker and Jirka (1990).

For the case of stratified ambient, two possible flow regions can exist for terminal flow interaction; i) near-vertical terminal layer approach with buoyancy upstream spreading, and ii) terminal layer injection with surface spreading (see also, Doneker and Jirka, 1990).

2.6.2 Diffuser Induced Jet Mixing in Shallow Water

As mentioned before, when the stability criterion is exceeded in Eq. (2.3a) (stagnant case) or Eq. (2.3b) (with ambient crossflow), then the flow becomes unstable, and therefore the diffuser geometry and flux parameters are the important elements. For these cases, the unstable near-field is typically vertically well-mixed, although the mixed flow may re-stratify in the later far-field. Significant currents and large-scale circulation may be introduced in the shallow receiving water. The most frequent use of shallow water diffuser theory is in the design of submerged cooling water discharges.

2.6.2.1 Unidirectional Diffuser

The flow generated by a unidirectional diffuser (Figure 2.5) is generated by pressure gradients which are set up by the momentum input (Jirka, 1982). The induced flow separates near the diffuser ends into a contracting slipstream, i.e. an acceleration zone (Lee and Jirka, 1980). The flow structure is shown in Figure 2.14. The equations related to the unidirectional diffuser are found when analyzing the contracted slipstream. In the following the acceleration zone solutions for the diffuser in a stagnant ambient are presented, and then extended to include the effect of an ambient current.

2.6.2.1.1 Stagnant Ambient

The solutions for that case are given by Lee and Jirka (1980). The bulk dilution in the acceleration zone is in the present notation

$$S = (H/2l_q)^{1/2} \qquad (2.45)$$

The diffuser horizontal half-width is found to be related to the streamline approach angle θ_1, the distance x along trajectory, and the diffuser length L_D. For stagnant conditions, the approach angle θ_1 is close to 60°, and the transition to diffusion zone was found to occur at a distance of about $L_D/2$. Due to the difficulty of mapping, the contracting slipstream half-width b_h is fit by the following equation as an approximation to Lee and Jirka (1980) solution

$$b_h = L_D/2\ [\sigma_1 + (1 - \sigma_1)\ \exp(-3x^*(1 + x^{*3}))] \qquad (2.46)$$

with $x^* = 2x/L_D$ and σ_1 = contraction ratio = 1/2.

2.6.2.1.2. Ambient Crossflow

With the presence of an ambient current, it is necessary to know the alignment of the diffuser relative to the crossflow. Two cases are discussed here, the case of predominantly perpendicular ($\gamma \approx 90^\circ$) and parallel ($\gamma \approx 0^\circ$) alignment.

a) **Perpendicular Alignment ($\gamma \approx 90^\circ$)**

The "Coflowing Diffuser" in which the diffuser axis is perpendicular to the crossflow, has the same flow features as those under stagnant conditions. The result for the bulk dilution (Adams, 1972, and Lee and Jirka, 1980) expressed in length scales, is

$$S = H/2(l_m l_q)^{1/2} + ((H^2 + 2Hl_m)/l_m l_q)^{1/2} \qquad (2.47)$$

Using the same procedure as for the stagnant case, with the exception of having the approach slipstream angle as function of dilution S, port velocity u_o, and ambient velocity u_a, the horizontal diffuser half-width is approximated by

$$b_h = L_D/2\ [\sigma_1 + (1 - \sigma_1)\ \exp(-3x^*(1 + x^{*3}))] \qquad (2.48)$$

where

$$x^* = 2x/L_D \qquad (2.49)$$

$$\sigma_1 = (S(l_m/l_q)^{1/2} + 0.5)/(S(l_m/l_q)^{1/2} + 1) \qquad (2.50)$$

The performance of the unidirectional diffuser has been found effective in a coflowing current. But under current reversals (e.g. in tidal conditions) the diffuser performance is poor with intense effluent concentration buildup zones occurring whenever the nozzle direction opposes the incoming current (counterflowing diffuser) (Adams, 1980, Harleman and Jirka, 1971).

b) **Parallel Alignment ($\gamma \approx 0^\circ$)**

The "Tee Diffuser" in which the diffuser axis is parallel to the ambient current, behaves in a slightly different way than the coflowing diffuser. Experimentally, it has been found that the mixing performance depends on the ambient to discharge momentum flux, m_a/m_o, or expressed by the ratio, H/l_m. For weak currents, $H/l_m < 0.1$, the dilution S is similar to the previous one in Eq. (2.47); however, for larger values of H/l_m, the near-field dilution drops. Analysis over a wide range of data (Adams and Stolzenbach, 1977) leads to an empirical reduction factor r_s, which gives a dilution reduction relative to the perpendicular case value S, Eq. (2.47)

$$r_s = [1 + 5(H/l_m)]^{-1/2} \qquad (2.51)$$

The cause of this reduction in dilution is related to the interaction of individual jets, where the pressure distribution set up by the ambient current limits the quantity of water which can enter from behind the diffuser (Jirka and Lee). As for the horizontal half-width, the same equation used for the coflowing case (Eq. 2.51) applies here.

Due to large induced flow involvement, the tee diffuser must be located far offshore in order to provide enough space for back entrainment flow. With a shoreline boundary placed at a separation distance x_s from and parallel to the tee diffuser line, theoretical and experimental work (Figure 2.15) show that significant reduction of induced flows and bulk mixing can occur if the separation distance is less than $L_D/2$ (Adams et al, 1982, and Lee, 1984).

2.6.2.2 Staged Diffuser

The jets in a staged diffuser (Figure 2.4b) possess a small nozzle orientation angle $\beta \approx 0°$ with respect to the diffuser axis. As mentioned in Jirka (1982), experimental observation suggests a region composed of two zones; an acceleration zone along the whole diffuser length in which momentum is imparted, and, beyond the diffuser, a deceleration zone with lateral diffusion and bottom frictional dissipation (Figure 2.16). The induced flow contains a boundary layer geometry and can be modelled as a momentum line source imparted to the ambient flow over the diffuser length.

2.6.2.2.1 Stagnant Ambient

Using the results of Lee (1980), the dilution equation for the acceleration zone is

$$S = s_s \, (H/l_q)^{1/2} \qquad (2.52)$$

where s_s is a dilution constant.

Using simple geometric reasoning, the horizontal diffuser half-width, which depends on the distance along the trajectory and the nozzle orientation relative to the diffuser axis β,

$$b_h = (b_s + 0.5 \tan \beta) x \qquad (2.53)$$

where b_s is a constant.

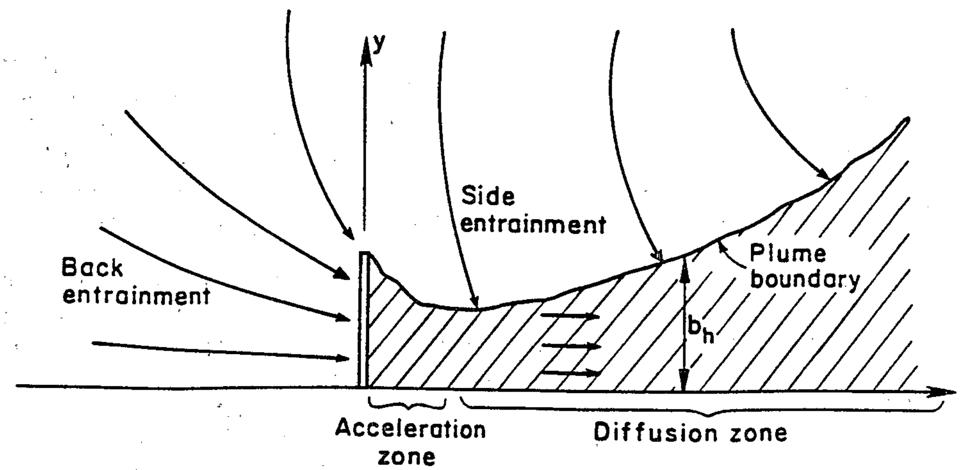


Figure 2.14 Flow Field Induced by Unidirectional Diffuser (Ref. Jirka, 1982): Structure of Diffuser Plume (half-plane with symmetry line).

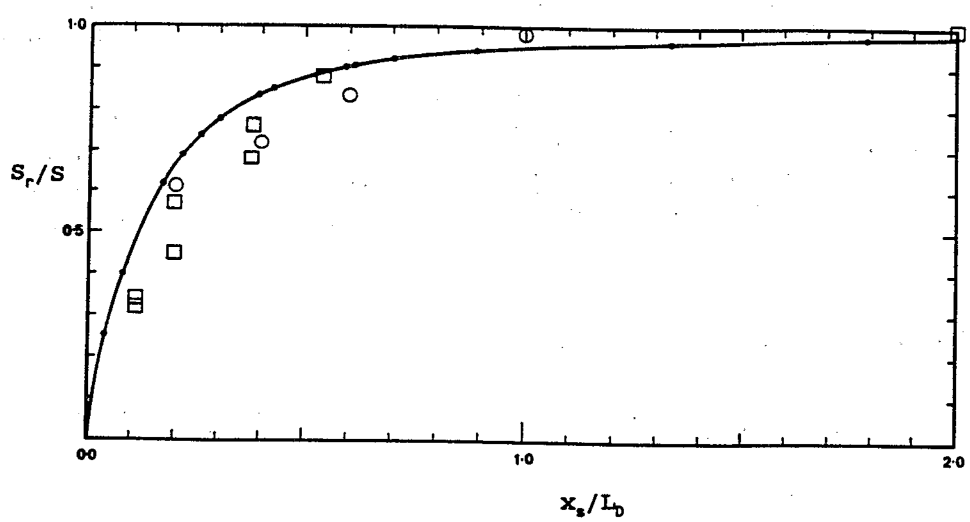


Figure 2.15 Effect of Limited Separation Distance x_s/L_D between Diffuser Line and Shoreline (S_r: reduced dilution, S: original dilution) (Ref. Lee, 1984).

2.6.2.2.2 Ambient Crossflow

With the presence of ambient current, the mixing performance will improve relative to the stagnant case. The dilution S is determined by adding a term related to crossflow to Eq. (2.52), and hence

$$S = s_s\ ((1 - l_m/l_q H/l_q)^{1/2} \qquad (2.54)$$

For the special case of strong ambient current, the dilution equation for the perpendicular diffuser alignment is (Jirka, 1982)

$$S = s_{s1}(H/l_q)^{1/2}(1 + 2.23H/l_m)^{1/2} \qquad (2.55)$$

where s_{s1} is a dilution constant.

The plume half-width is similar to the stagnant case and is given by Eq. (2.53).

2.6.2.3 Alternating Diffuser

As described earlier, the alternating diffuser (Figure 2.5c) does not impart any net horizontal momentum, because its jets alternately discharge in opposite directions. As remarked earlier, the alternating diffuser category also includes other nozzle (port) arrangements that do not impart any net horizontal momentum e.g. vertical discharge orientation or nozzle clusters radially attached to risers.

2.6.2.3.1 Stagnant Ambient

Outside the unstable recirculation zone (Figure 2.17), a stratified counterflow region is generated and the bulk dilution is influenced by buoyancy effects instead of pure momentum effects (Jirka, 1982). The transition to this region occurs at an approximate distance of 2.5H (Jirka, 1982).

Using the two-dimensional channel analysis described by Jirka (1982), the dilution is found (taking $\Phi_c = 0.1$ in Figure 18 of Jirka, 1982), as

$$S = s_a H/(l_M l_q)^{1/2} \qquad (2.56)$$

where s_a is the appropriate dilution constant. This dilution factor characterizes the fully mixed near-field zone extending for a width 2.5H on both sides of the diffuser axis. A stratified counterflow system exists outside that near-field.

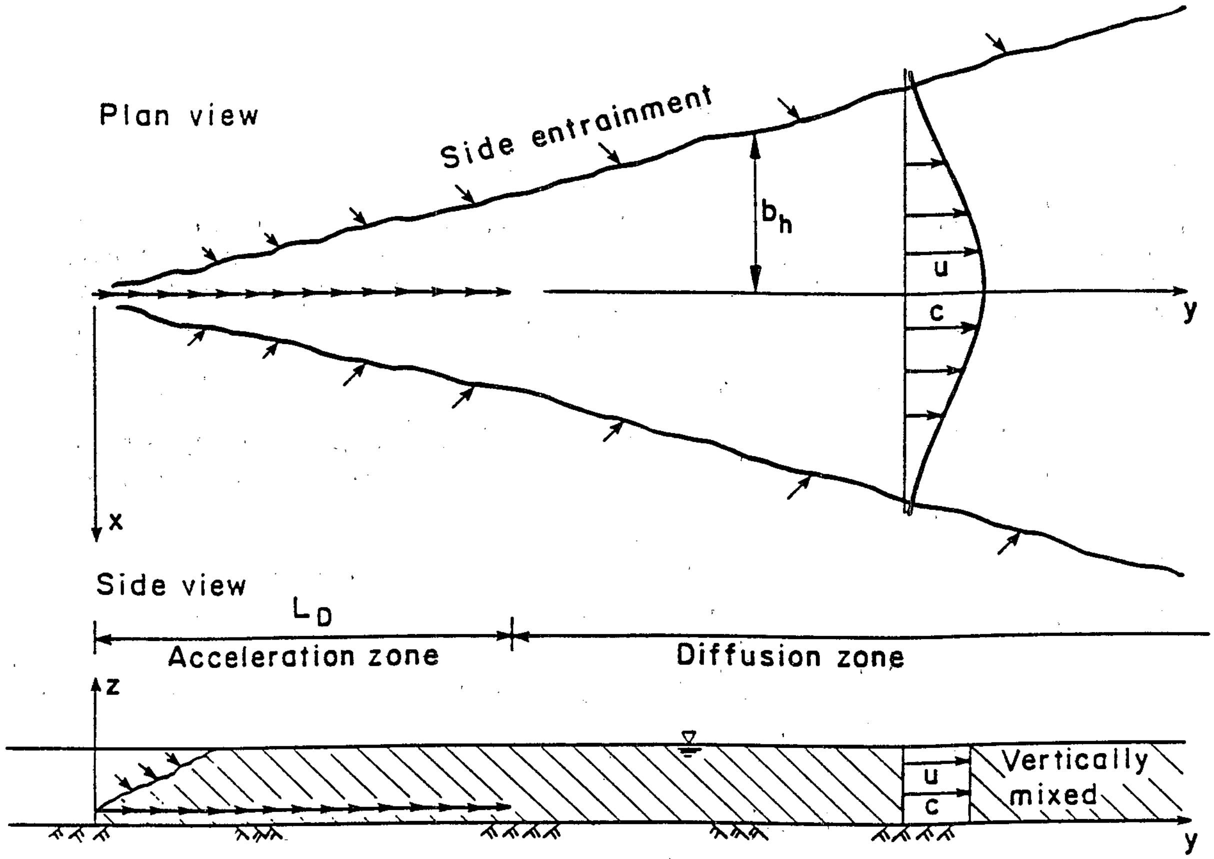


Figure 2.16 Flow Induced by Staged Diffuser (Ref. Jirka, 1982): Structure of Diffuser Plume.

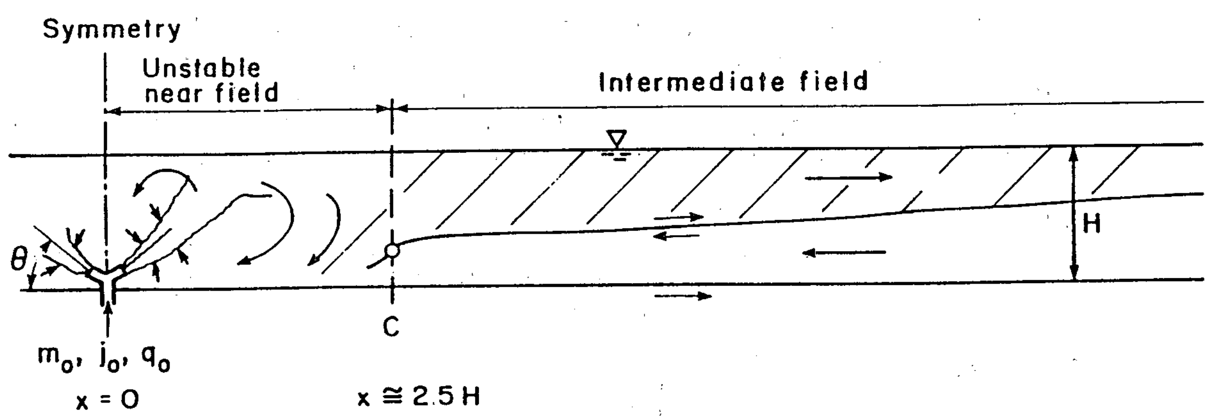


Figure 2.17 Alternating Diffuser in Stagnant Ambient: Side View: Stratified Counterflow Characteristics in Two-Dimensional Representation (Adapted from Jirka, 1982).

2.6.2.3.2 Ambient Crossflow

The dilution in an ambient current may be estimated by a vector addition of the stagnant water dilution and the ambient flow dilution (Jirka, 1982). Hence adding the ambient term, the dilution for the perpendicular alignment,

$$S = H[(0.25l_m + l_M)/l_M l_m l_q]^{1/2} \qquad (2.57)$$

The initial half-width of the flow downstream from the alternating diffuser is

$$b_h = 2.5H + L_D/2 \qquad (2.58)$$

A reduction of 20% from the perpendicular alignment dilution (Eq. 2.57) is typical for the parallel alignment dilution (Jirka and Harleman, 1973).

2.6.2.4 Fully Mixed Diffuser Plumes (Intermediate Field)

Following the terminology used by Jirka (1982) the gradually expanding diffuser plume induced outside the acceleration zone of either the unidirectional (Figure 2.14) or staged (Figure 2.15) diffuser is referred to as the "intermediate field".

The intermediate field plume is divided into two regions: region 1, and region 2.

Region 1 starts immediately after the acceleration zone, and extends up to a distance where restratification occurs. This distance is determined by the initial value of a densimetric Froude number, $F_c = u_c/(g'_c H_s)^{1/2}$, with $g'_c = g'_o/S$). As typical for intrusion processes the initial value F_c is of order unity (Jirka, 1982). The transition distance for region 1 is

$$s_t = cL_M^4/F_c^4 H^3 \qquad (2.59)$$

where c is a constant and is dominated by the length scale L_M representative for the entire diffuser.

The model for the vertically mixed two-dimensional jet flow associated with this region has the same characteristics as the regime related to the momentum dominated near field (see Section 2.6.1.1.3) with the exception of having a different momentum to crossflow length scale, and a different discharge to momentum length scale respectively. Hence, the model uses the same mixing and trajectory of relations, Eq. (2.17) and (2.18), with a change of l_m to d_m, and l_q to d_q, respectively, where

$$d_m = l_m L_D/H \qquad (2.60)$$

and

$$d_q = l_q L_D / H \tag{2.61}$$

In Region 2 the diffuser plume becomes stratified. Thus, a lateral buoyant spreading motion is superimposed on the diffusing plume. While using the same dilution and trajectory equations as before (region 1), it is necessary to account for the additional spreading. The buoyant spreading rate is given by the ratio of lateral spreading velocity to plume centerline velocity u_c. Therefore, the theory of buoyant spreading is used, where instead of using the velocity current as a dependent variable, the jet centerline velocity u_c is used (Table 3, Holley and Jirka, 1986) in the width differential equation, and hence

$$(db/dx)_B = (g'_o h / u_c^2 C_D)^{1/2} \tag{2.62}$$

where h is the height (vertical thickness) of diffusing plume and C_D is the drag coefficient (of order unity). The horizontal width b_h is

$$b_h = b_c (H^{1/2} / l_M^{1/2} L_D^{1/6}) (s^{7/4} - s_t^{7/4})^{2/3} + b_{hi} \tag{2.63}$$

where b_{hi} is the initial horizontal at transition s_t and b_c is the width constant.

The vertical width is found to be

$$b_v = S_i b_{hi} H / S b_h \tag{2.64}$$

which decreases due to restratification.

2.6.3 Buoyant Spreading Processes

In the context of this study, buoyant spreading processes are defined as the horizontally transverse spreading of the mixed effluent flow while it is being advected downstream by the ambient current. Such spreading processes arise due to the buoyant forces caused by the density difference of the mixed flow relative to the ambient density (see Figure 2.18).

The buoyant spreading phenomena is a far-field mixing process. Usually it is preceded by buoyant jet mixing in the near-field and is followed by passive diffusion, another far-field mixing process. If the discharge is nonbuoyant, or weakly buoyant, and the ambient is unstratified, there is no buoyant spreading region in the far-field, only a passive diffusion region.

Depending on the type of near-field flow and ambient stratification several types of buoyant spreading may occur:

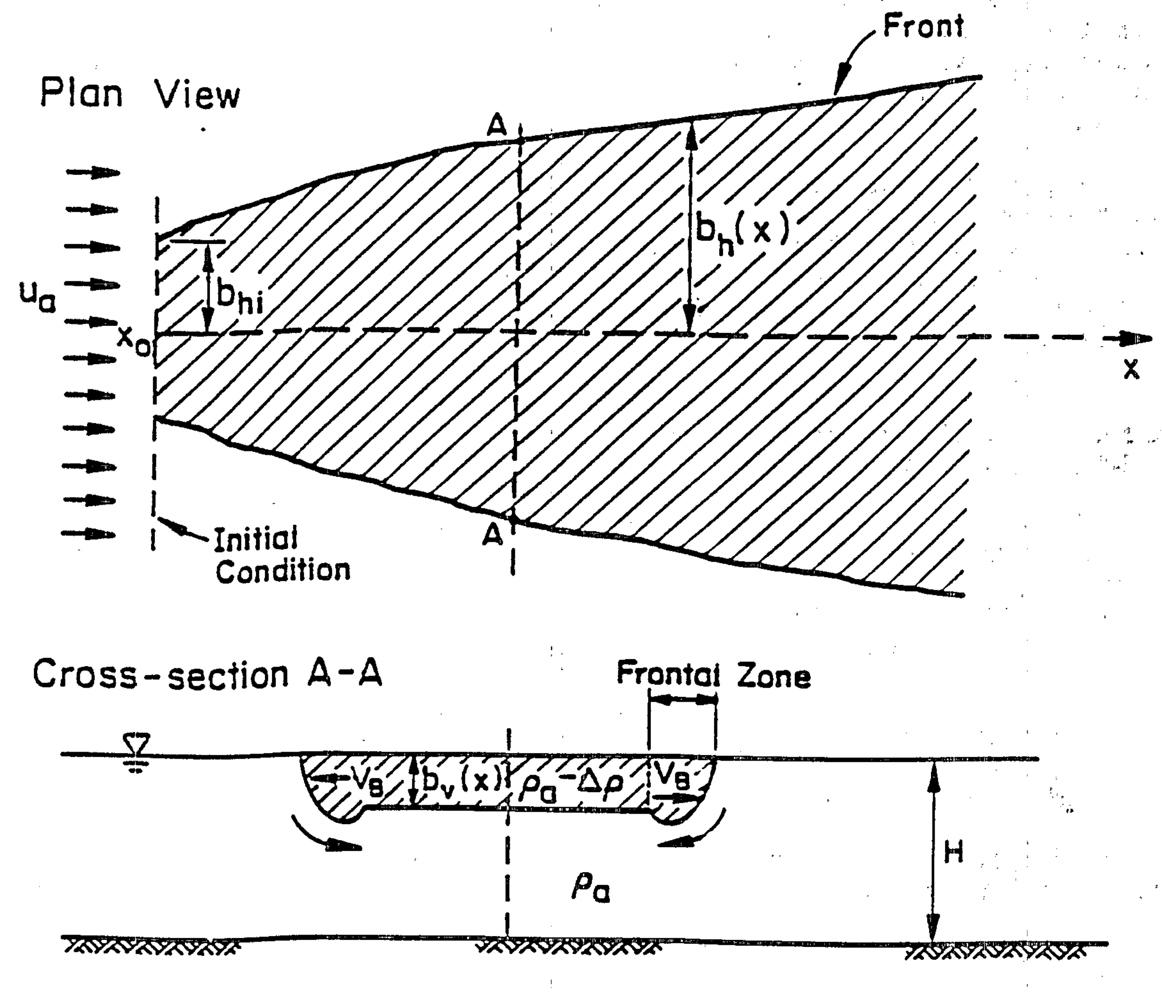


Figure 2.18 Buoyant Surface Spreading (Ref. Doneker and Jirka, 1989).

(i) spreading at the water surface, (ii) spreading at the bottom, (iii) spreading at a sharp internal interface (pycnocline) with a density jump, or (iv) spreading at the terminal level in continuously (e.g. linearly) stratified ambient.

To a major extent the buoyant spreading processes in the far-field of multiport diffusers are entirely similar to those for single port discharges. The reader is referred to Doneker and Jirka (1989) for a complete treatment of these.

Separate buoyant spreading processes can occur for multiport diffusers with parallel alignment when the continuous buoyant inflow along a long diffuser line gives a different source condition. This is discussed in the following section for unstratified and linearly stratified ambients, respectively.

2.6.3.1 Surface Density Current Developing Along Diffuser Line in Parallel Alignment

In contrast to Figure 2.18, a source condition of a continuous inflow exists along the diffuser line whose starting point is at $x = x_i$. The source flow for one side of the density current is $q_N = 0.5 S_f q_o$ where S_f is the final dilution for the near-field mixing.

The buoyancy conservation equation for the mixed flow is adapted from Doneker and Jirka (1989) as

$$u_a d(g' b_v b_h)/dx = q_e(x) + q_N \qquad (2.65)$$

where $q_e(x)$ is the localized head entrainment at the density current front, and b_h is the lateral half-width.

Neglecting the head entrainment q_e relative to the inflow q_N, and integrating Eq. (2.65)

$$u_a g' b_h b_v = j_o x/2 \qquad (2.66)$$

For constant dilution along the diffuser line, independent of x, g' will be replaced by g'_o/S_f. Benjamin (1967) has derived an equation for the spreading velocity v_B

$$v_B^2/(g' b_v) = 1/C_D \qquad (2.67)$$

where C_D is a drag coefficient that depends on the relative depth b_v/H and is in the range of 1/2 to 2. Combining the boundary condition for the streamline ($v_B = u_a db_h/dx$) and Eq. (2.67), yields

$$u_a db_h/dx = (g'_o b_v/C_D)^{1/2} \qquad (2.68)$$

Substituting Eq. (2.66) into (2.68), and integrating, the flow half-width b_h is

$$b_h = [(b_{hi}^{3/2} + (l_m/l_M)^{3/2}/(2C_D)\ (x^{3/2} - x_i^{3/2}))]^{2/3} \qquad (2.69)$$

where x_i is the downstream distance at the beginning of the buoyant spreading region, and b_{hi} is the initial density current half-width. A qualitatively similar result for the width b_h has first been obtained by Roberts (1977).

The vertical b_v is given by combining Eqs. (2.69) and (2.65), to obtain, with appropriate initial conditions at x_i,

$$b_v = S_f(l_q\ l_m)^{1/2}x/2b_h + (b_{hi}b_{vi}/b_h - S_f(l_q\ l_m)^{1/2}x_i/2b_h) \qquad (2.70)$$

2.6.3.2 Internal Density Current Developing Along Diffuser Line in Parallel Alignment

In an ambient stratification with a linear density gradient, a near-field mixing process may lead to a layer formation at a terminal level Z_t, i.e. a mixed current is produced whose density is equal to the ambient density at the terminal level. The mixed zone perturbs the ambient stratification and leads to a lateral spreading while the flow is being advected downstream.

The spreading velocity v_B for the stratified case is expressed as

$$v_B^2/(\varepsilon b_v^2) = 1/(2C_D) \qquad (2.71)$$

where C_D is the drag coefficient for the stratified case.

Proceeding in the same fashion as in Section 2.5.3.1, one obtains the following result, for horizontal half-width b_h

$$b_h = [b_{hi}^2 + (2/C_D)^{1/2}(S_f(l_q\ l_m)^{1/2}(x^2-x_i^2)/4l_a + k(x-x_i))]^{1/2} \qquad (2.72)$$

and for the vertical thickness b_v is

$$b_v = (S_f(l_q\ l_m)^{1/2}(x-x_i)/2 + k)/b_h \qquad (2.73)$$

where

$$k = (b_{hi}b_{vi} - S_f(l_q\ l_m)^{1/2})x_i/2) \qquad (2.74)$$

2.6.3.3 Upstream Intruding Density Wedges Formed in Bounded Channels

Multiport diffusers are frequently installed in narrow channels (rivers or estuaries) in which the diffuser spans a good fraction of the channel width, W, or else the diffuser mixing capacity is controlled by the available ambient flow. In either case, upon completion of the near-field mixing processes, the diffuser plume will interact with the lateral boundaries of the channel. Under certain low ambient velocity conditios (characterized by a densimetric Froude number) a laterally uniform density wedge may intrude upstream along the bottom, surface/pycnocline, or in a terminal layer. These possibilities are indicated in Figure 2.19. The degree of wedge intrusion is controlled by interfacial friction along the density wedge.

Two dynamic possibilities for wedge intrusion exist: a) wedges with a critical boundary condition, and b) wedges with a subcritical boundary condition.

2.6.3.3.1 Density Wedges with Critical Boundary Condition

Referring to Figure 2.19a and b, assume the maximum possible near-field dilution is controlled by the ambient/discharge flow ratio

$$S_n = \frac{u_a W H}{Q_o} + 1 \qquad (2.75)$$

By the mass conservation principle, this dilution cannot be exceeded in a steady-state mixing process. Thus, if this predicted dilution within the hydrodynamic mixing zone (near-field processes) - which do not account for a laterally limited ambient water body - indicates a final dilution value S_f that is in excess of S_n, then local recirculation processes will take place in the limited channel, resulting in a fully mixed downstream flow with dilution equal to S_n and a density $\rho_n = \rho_a + \Delta\rho_o/S_n$.

Upstream density wedge intrusion will occur whenever the channel densitimetric Froude number

$$F_{ch} = \frac{u_a}{\sqrt{|g'_n| H}} \qquad (2.76a)$$

is less than a critical value of about 0.7 (Arita and Jirka, 1987) in which $g'_n = (\Delta\rho_n/\rho_a)g$ and $\Delta\rho_n = \Delta\rho_o/S_n$. Under these conditions the root of the wedge (at the edge of near-field mixing zone) will be characterized by a critical depth

$$h_c = (1 - F_{ch}^{2/3})H \qquad (2.76b)$$

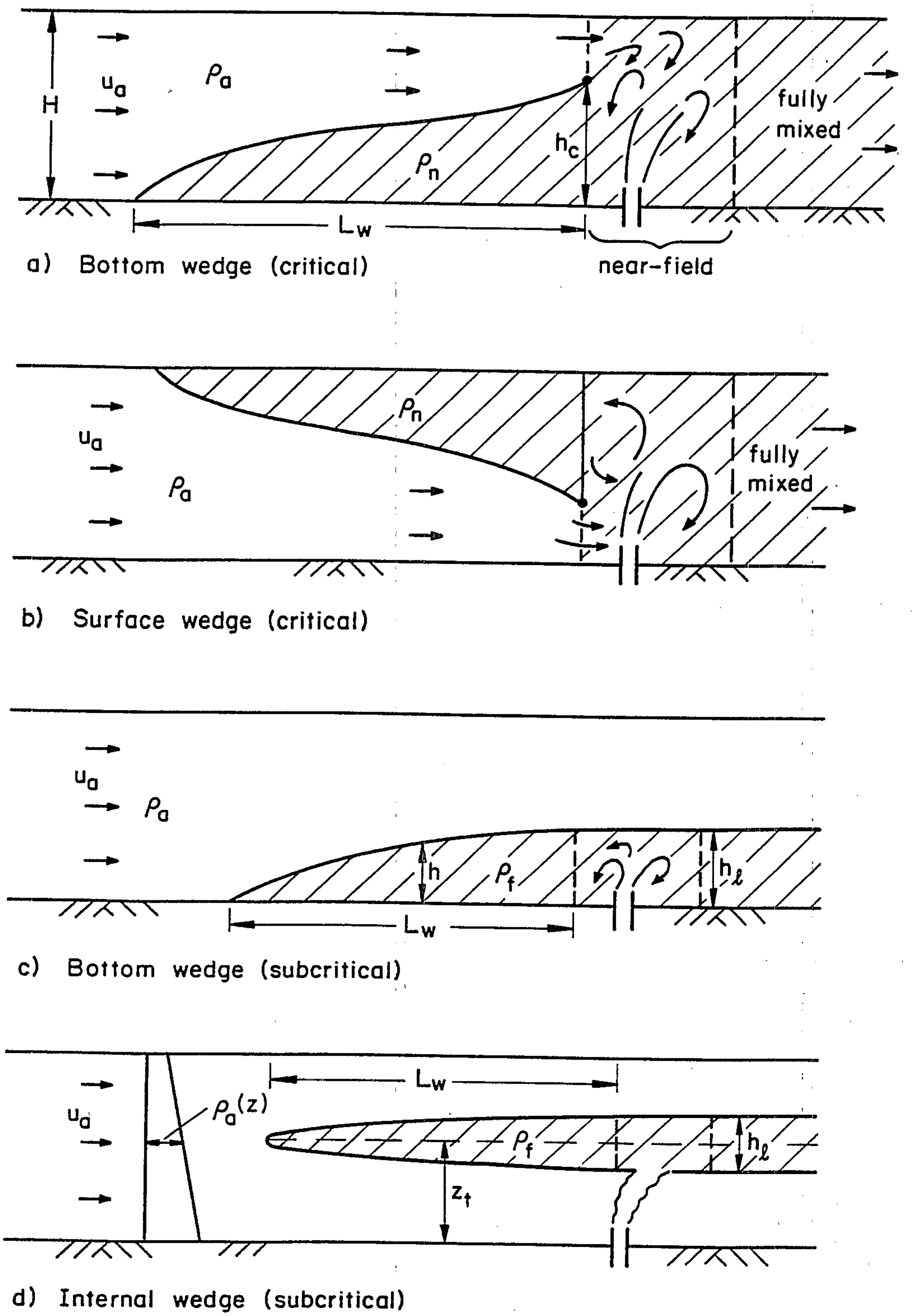


Figure 2.19 Different Upstream Wedge Intrusion in a Bounded Channel

The wedge length L_w is given for the bottom wedge (see Arita and Jirka, 1987) as

$$L_w = \frac{8}{f_i} H \left(\frac{1}{20 F_{ch}^2} - \frac{3}{10} F_{ch}^{4/3} + \frac{3}{4} F_{ch}^{2/3} - \frac{1}{2}\right) \tag{2.77}$$

and for the surface wedge (Bata, 1957) as

$$L_w = \frac{1}{f F_{ch}^2} H \left[2(1 - F_{ch}^{8/3}) + \frac{8a}{3}(1 - F_{ch}^{5/3}) + 4a(1 + a)(1 - F_{ch}^{4/3}) + 8(a(1+a)^2 - F_{ch}^2)(1 - F_{ch}^{2/3}) - 8a((1+a)^3 - F_{ch}^2)(\log a - \log(1 - a - F_{ch}^{2/3}))\right] \tag{2.78}$$

in which f = Darcy-Wesbach friction factor, f_i = interfacial friction factor, and $a = f_i/f \approx 0.5$.

2.6.3.3 Density Wedges with Subcritical Boundary Conditions

If the diffuser plume (with predicted near-field dilution $S_t < S_n$) is interacting with both lateral boundaries, then a flow away zone is formed with a layer thickness

$$h_1 = \frac{S_t Q_o}{u_a W} \tag{2.79}$$

a) For a bottom or surface layer in uniform ambient density flow, upstream intrusion takes place if the Froude number

$$F_{h1} = \frac{u_a}{\sqrt{|g'_t| h_1}} \tag{2.80}$$

in which $g'_t = (\Delta\rho_t/\rho_a) g$ and $\Delta\rho_t = \Delta\rho_o/S_t$, is less than about unity.

Assuming the layer is sufficiently thin relative to the water depth, so that the ambient velocity over the wedge is constant, a simple force balance governs the flow

$$\tau_i \, dx = |g'_t| \; h_2 \, dh_2 \tag{2.81}$$

in which τ_i = interfacial friction = $(f_i/8)\,u_a^2$. Integration of Eq. (2.80) gives the wedge length for subcritical conditions, $h_1<h_c$, as

$$L_w = \frac{4}{f_i} \frac{h_1}{F_{h1}^2} \tag{2.82}$$

b) For a linearly stratified ambient (buoyancy gradient ϵ) the upstream intrusion of an internal wedge that is of uniform internal density is controlled by the Froude number

$$F_{h2} = \frac{u_a}{\sqrt{\epsilon h2_1}} \tag{2.83}$$

The intrusion is blocked (prevented) for $F_{h2} \geq 1$ and occurs for $F_{h2} \leq 1$. The governing force balance

$$\tau_i \, dx = \epsilon \, h^2 \, dh \tag{2.84}$$

gives, upon integration, the wedge length

$$L_w = \frac{8}{3f_i} \frac{h_1}{F_{h2}{}^2} \tag{2.85}$$

2.6.4 Passive Diffusion Processes

The existing turbulence in the ambient environment becomes the dominating mixing mechanism at sufficiently large distances from the discharge point. The intensity of this passive diffusion process depends upon the geometry of the ambient shear flow as well as any existing stratification. In general, the passively diffusing flow is growing in width and in thickness (see Figure 2.20). Furthermore, it may interact with the channel bottom and/or banks. For further details on these processes, the reader is referred to Doneker and Jirka (1989), as they are independent of initial source conditions.

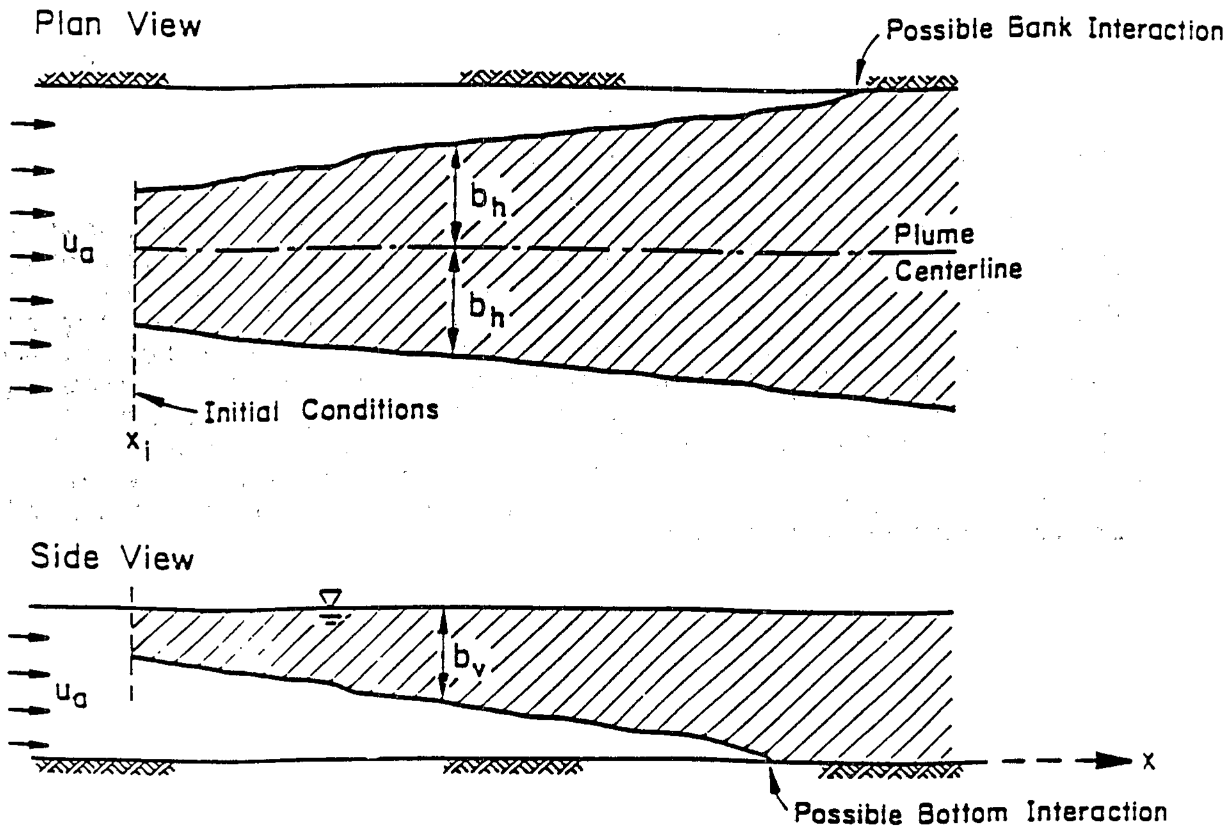


Figure 2.20 Passive Diffusion Mixing Process (Ref. Doneker and Jirka, 1989).

Chapter III

CORMIX2: System Structure and Program Elements

The Cornell Mixing Zone Expert System, Subsystem 2, (CORMIX2) is a series of software elements for the analysis and design of conventional or toxic multiport submerged buoyant, nonbuoyant, or negatively buoyant pollutant discharges into unstratified or stratified watercourses, with emphasis on the geometry and dilution properties of the initial mixing zone. The cases of both stagnant and flowing environment are included. This expert system is constructed and designed as an analysis tool for dischargers and regulators.

The user provides CORMIX2 with all the necessary information concerning the ambient environment, and the discharge characteristics. In response to this data input, CORMIX2 supplies detailed information related to the hydrodynamic mechanisms controlling the flow, dilution, geometric information concerning the pollutant plume shape in the ambient flow, and design recommendations and advice permitting the actual user to improve the effluent mixing characteristics. Information related to legal mixing zone dimensions and toxic mixing zone requirements are provided by CORMIX2 when they are requested by the user. CORMIX2 executes on a MS-DOS computer using an IBM-PC/XT along with a printer, and a hard disk drive.

The obectives of CORMIX2 is to give the user an understanding in the hydrodynamics of flows. Through repeated interactive use of the software system, the user can ultimately gain some knowledge of hydrodynamic mixing processes.

3.1 Background on Expert Systems and Logic Programming

CORMIX2 is written in two programming languages: VP-Expert, an expert systems "shell", and Fortran.

VP-Expert is an expert systems programming language, or a "shell". A shell is a self-contained inference engine that does not contain the knowledge base, but has facilities for both forward and backward reasoning, debugging aids, consistency checking, input and output menus, and explanation facilities.

The reason for using the two programming languages lies in the fact that one is powerful in knowledge representation and the other in mathematical computations. The knowledge base language VP-Expert is very efficient in knowledge representation and symbolic reasoning; however it is less powerful in numerical computational techniques. On the other hand, Fortran is effective in mathematical computations and less efficient in symbolic reasoning. Hence VP-Expert is used to implement the knowledge acquisition, the length scale computation, model selection, and the analysis of the hydrodynamic simulation. Fortran is used to carry out computations used in the hydrodynamic simulation models.

The knowledge base of an expert system contains statements containing facts and if-then rules about facts. The VP-Expert knowledge base is built from the rules supplied by the user corresponding to a problem area.

As explained by Doneker and Jirka (1988), VP-Expert programs are driven by a "goal" which the program tries to validate by searching the knowledge base to construct a "proof" by using the facts and rules in the knowledge base needed to deduce the goal as a valid hypothesis.

All the programs in VP-Expert are constructed based on rule statements where the rules are stated as: if {expression(s) or clauses called the "premise" or "head" of the rule} - then {an expression or clause named the "conclusion" or "tail" of the rule} statements. The structure of a rule can consist of one or more than one expression linked by and/or statements. An example of a rule statement is :

```
IF      site_description <> UNKNOWN and
        ambient_conditions <> UNKNOWN and
        discharge_parameters <> UNKNOWN and
        mixing_zones <> UNKNOWN
THEN    parameters_input = known;                 [1]
```

All the conditions have to be met in order to satisfy the conclusion statement (parameters_input). In other words, VP-Expert tries to satisfy all expressions in the premise of the rule, starting in statement [1] with the first expression "site_description <> UNKNOWN" (the <> UNKNOWN in [1] stands for "not equal to"). If the value of the first clause is determined, VP-Expert tries to satisfy the next expression "ambient_conditions <> UNKNOWN". If this latter is satisfied, then VP-Expert will try to meet the remaining expressions in the rule structure. When all the expressions are satisfied, the rule succeeds, and hence the conclusion statement can be given a valuation and is added to the facts known in the knowledge base.

The way VP-Expert would know the expression of "site_description" lies in the fact that there is another rule in the knowledge base related to this subject which is:

```
IF      site_name <> UNKNOWN and
        discharger_name <> UNKNOWN and
        pollutant_name <> UNKNOWN and
        design_case <> UNKNOWN
THEN    site_description = known;                    [2]
```

The same logical pattern is followed here, but since there is no present valuation for the expression "site_description", VP-Expert will locate statements with the expression "site_description" in its conclusion. If all the expressions in [2] can be assigned valuations, then the expression site_description is a known expression.
Within the program there is another rule placed in a form of an "ASK statement" like

```
ASK site_name: " Enter a descriptive name for the
discharge location."                                 [3]
```

This rule is treated as a "fact", and VP-Expert asks the user to enter the value of "site_name" through the message within the quotes of statement [3]. The user enters the value for "site_name" and thus the value for this variable is known to VP-Expert. Next, VP-Expert tries to find the values for the remainder of statement [2] in a similar manner. More detailed explanations on the expert systems logic can be found in Doneker and Jirka (1989).

Thus the knowledge base is built from rules consisting of expressions that force VP-Expert to seek valuations from other rules. The process of seeking values for the expressions continues in a tree-like search until all values are determined or when the rule is exhausted without finding a valuation.

When all the rules have succeeded, a listing of all the expressions values are saved in a file to be loaded for the next VP-Expert element.

3.2 Structure of CORMIX2

Figure 3.1 shows the overall structure of the system elements of CORMIX2. The program elements of CORMIX2 are composed of DATIN2, PARAM2, CLASS2, HYDRO2, and SUM2. During system use the elements are loaded automatically and sequentially by the system. Table 3.1 outlines the directory structure of CORMIX2 and contains comments about program files.

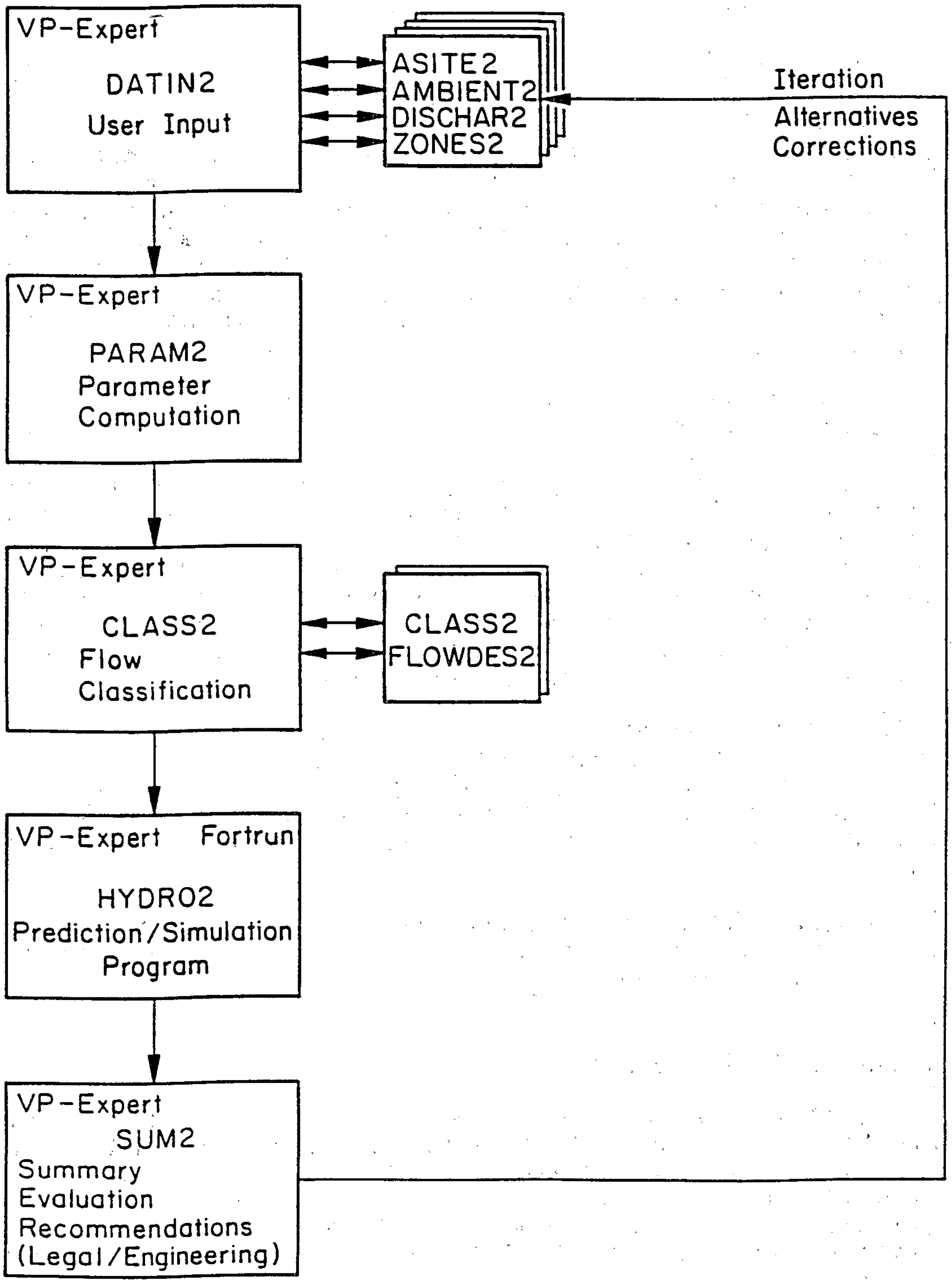


Figure 3.1 System Elements of CORMIX2

Table 3.1 CORMIX2 Program File Directories

Directory	Comments
c:\cmx2	system root directory, contains VP-Expert system files and the knowledge base program CORMIX2 (system driver)
c:\cmx2\advice2	contains all user-requested advice files
c:\cmx2\bat2	contains batch files for program execution, data file manipulation, and program control
c:\cmx2\cache2	contains cache "fact" files exported from knowledge base programs
c:\cmx2\data2	contains constants used in flow classification and other knowledge base programs
c:\cmx2\flowdes2	contains flow descriptions for each flow class
c:\cmx2\kbs2	contains all knowledge base programs
c:\cmx2\pgms2	contains Fortran hydrodynamic simulation and file manipulation programs
c:\cmx2\sim2	contains simulation results

The system runs entirely under the VP-Expert system shell. The hydrodynamic simulation Fortran program HYDRO2 is executed from the knowledge base program HYDRO2. All program elements execute sequentially. For example, when a rule in a program element DATIN2 corresponding to statement [1] fires, the "cache" of DATIN2 is written to an external DOS file. The cache is a list of all expressions within a program element that have been assigned a valuation. This cache file is read by the next sequential element in DATIN2, the knowledge base PARAM2, and so on for the remaining program elements.

3.2.1 Data Input Element: DATIN2

DATIN2 is a VP-Expert program element for the entry of relevant data and for the initialization of the other program elements. DATIN2 consist of four program segments or knowledge base sub-elements which execute sequentially. The knowledge base sub-elements are, in execution order, ASITE2, AMBIENT2, DISCHAR2, and ZONES2. DATIN2 is the first program executed, and it is invoked by entering the command "CORMIX2" at the DOS prompt.

The purpose of DATIN2 is to specify completely the physical environment of the discharge, as well as legal or regulatory specifications. The following data groups need to be entered: general site and case identifier information (knowledge base ASITE2), ambient conditions (geometry and hydrography, knowledge base AMBIENT2), discharge conditions (geometry and discharge fluxes, knowledge base DISCHAR2), and information desired including legal mixing zone definitions and toxic dilution zone criteria (knowledge base ZONES2). DATIN2 provides consistency checks, and gives advice for input parameter selection.

The system assumes a schematic rectangular cross-section bounded by two banks - or by one bank only for coastal or other laterally unlimited situations. The user receives detailed instructions on how to approximate actual cross-sections that may be quite irregular to fit the rectangular schematization. The representative schematization with all relevant hydrodynamic variables that DATIN2 gathers was given in Figure 2.1.

DATIN2 contains advice on how to enter data values and rejects inappropriate or incorrect values. The advice elements of DATIN are listed in Appendix A of this report. DATIN2 will also flag unusual design cases. For example, in the knowledge base sub-element DISCHAR2, if the users specifies a discharge horizontal angle which is directed against the ambient current the following message is displayed:

"Note that CORMIX2 will not analyse the so-called counter-flowing discharges (with horizontal angles of discharge between 135 to 225 degrees). In this case the discharge momentum opposes the ambient flow leading to complicated recirculation patterns and concentration build-ups in the near-field. This situation is difficult to analyzes and also constitutes an UNDESIRABLE DESIGN. The user is advised to re-evaluate the design or to discontinue the analysis." [4]

At its termination DATIN2 triggers the next program element PARAM2.

3.2.2 Parameter Computation: PARAM2

PARAM2 is a VP-Expert program that computes all the important and relevant physical parameters for the given discharge case. This includes the momentum flux and the buoyancy flux per unit diffuser length (m_o, and j_o), the various length scales (l_q, l_m, l_M, l'_m, l'_b, l'_a) and other values needed for the program evaluation. As PARAM2 executes, the user is notified about important characteristics of the flow. For example:

"The effluent density (1003.2 kg/m**3) is greater than the surrounding ambient water density at the discharge level (997.3 kg/m**3). Therefore, the effluent is negatively buoyant and will tend to sink towards the bottom."

At its termination PARAM2 triggers the next program element, the knowledge base CLASS2.

3.2.3 Flow Classification Element: CLASS2

CLASS2 is a VP-Expert program that <u>class</u>ifies the given discharge into one of the many possible flow configurations that have been presented in Chapter II (Figures 2.7 to 2.9). CLASS2 contains two program elements, the knowledge base sub-elements CLASS2 and FLOWDES2.

The goal of CLASS2 is to find a valuation for the expression "flow_class" in relation to the flow classification scheme. Each of the possible flow classification has an alphanumeric label(eg. MU1, MS1, MNU6, etc.). CLASS2 inputs a cache created by PARAM2 that contains the length scales and other dynamic variables needed for flow classification, and uses the knowledge base rules to assign the appropriate classification to the flow. As an example of the output from CLASS2, the following would represent some of the information presented for a discharge trapped by the pycnocline in a two layer density stratified environment:

"The near field flow configuration will have the following features:

The specified two layer ambient density stratification is dynamically important. The discharge near field flow will be confined to the lower layer by the ambient density stratification. Furthermore, it is trapped in the lower layer by the ambient density jump at the pycnocline.

The following conclusion on the flow configuration applies to the lower layer only of the specified ambient stratification condition B.

Note that the lower layer will be overlaid by the surface layer of the ambient density stratification. The surface layer will remain undisturbed by the near field discharge flow (with the exception of some possible intrusion along the pycnocline)

The flow class is MU1 for the design case represented by the DOS file name EXAMPLE."

A detailed hydrodynamic description of the flow is available to the user in the knowledge base sub-element FLOWDES2. This detailed output includes a description of the significant near field mixing processes, or the hydrodynamic mixing zone (HMZ). For an example, the description for flow class MU1 appears in Figure 3.2. The flow description of all the classes are presented in Appendix B. Typically, the HMZ is the region of strong initial mixing where the particular design of the outfall can have an effect on initial dilution. The HMZ is defined to give additional information as an aid to understanding mixing processes and to distinguish it from purely legal mixing zone definitions. CLASS2 also creates a cache output file that supplies the next CORMIX2 element HYDRO2 with instructions for running the appropriate simulation. At its termination CLASS2 triggers the next program element HYDRO2.

3.2.4 Hydrodynamic Simulation Element: HYDRO2

HYDRO2 is a Fortran program which executes the hydrodynamic simulation program for the flow classification program specified in CLASS2. The elements of the simulation program are based on the hydrodynamic theory discussed in the Chapter II and in more detail in Chapter IV.

The program HYDRO2 contains control programs or "protocols" corresponding to each hydrodynamic flow classification (MU1, MU2, MS1, etc.) as specified in CLASS2.

*** BEGINNING OF FLOW CLASS DESCRIPTION ***

FLOW CLASS MU1V

The discharge configuration is hydrodynamically "stable", that is the discharge strength (measured by its momentum flux) is weak in relation to the layer depth and in relation to the stabilizing effect of the discharge buoyancy (measured by its buoyancy flux). The buoyancy effect is very strong in the present case.

The following flow zones exist:

1) Momentum-dominated near-field slot (2-D) jet: The flow issuing from the equivalent slot diffuser is initially dominated by the effluent momentum (jet-like) and is weakly deflected by the ambient current.

2) Buoyancy-dominated (2-D) plume: After some distance the discharge buoyancy becomes the dominating factor (plume-like). The plume deflection by the ambient current is still weak.

3) Layer boundary impingement/upstream spreading: The weakly bent jet/plume impinges on the layer boundary (water surface or pycnocline) at a near-vertical angle. After impingement the flow spreads in all directions (more or less radially) along the layer boundary. In particular, the flow spreads some distance upstream against the ambient flow, and laterally across the ambient flow. This spreading is dominated by the strong buoyancy of the discharge in which strong initial mixing takes place.

*** The zones listed above constitute the HYDRODYNAMIC MIXING ZONE ***

4) Buoyant spreading at layer boundary: The plume spreads laterally along the layer boundary (surface or pycnocline) while it is being advected by the ambient current. The plume thickness may decrease during this phase. The mixing rate is relatively small. The plume may interact with a nearby bank or shoreline.

5) Passive ambient mixing: After some distance the background turbulence in the ambient shear flow becomes the dominating mixing mechanism. The passive plume is growing in depth and in width. The plume may interact with the channel bottom and/or banks.

Figure 3.2 Example of Flow Description

*** Predictions will be terminated in zone 4 or 5 depending on the definitions of the LEGAL MIXING ZONE or the REGION OF INTEREST. ***

SPECIAL CASE: If the ambient is stagnant, then advection and diffusion by the ambient flow (zones 4 and 5) cannot be considered. The mixing is limited to the hydrodynamic mixing zone (zones 1 to 3) and the predictions will be terminated at this stage.

Such stagnant water predictions may be a useful initial mixing indicator for a given site and discharge design.

For practical final predictions, however, the advection and diffusion of the ambient flow - no matter how small in magnitude- should be considered.

*** END OF FLOW CLASS DESCRIPTION FILE ***

Figure 3.2 (Continued)

Each protocol executes a series of subroutines or "modules" corresponding to the flow phenomena (e.g. weakly deflected jet in crossflow, buoyant spreading, unidirectional diffuser acceleration zone, surface interaction modules, buoyant spreading, etc.) which may occur in that flow configuration. Hence transition rules are needed to give the spacial expressions as to where each flow region ends. Each subsequent flow region is given by the initial values corresponding to the final values of the preceding flow zone. More detailed explanations on protocols and transition rules are discussed in Chapter IV.

HYDRO2 creates a tabular output file of the simulation containing information on geometry (trajectory, width, etc.) and mixing (dilution, concentration). The user has the option to view the tabular output file.

At its termination HYDRO2 triggers the final program element SUM2.

3.2.5 Summary Element: SUM2

SUM2 is a VP-Expert program that summarizes the hydrodynamic simulation results for the case under consideration. SUM2 discusses the mixing properties, determines the applicability of the legal mixing zone, and suggests the possible design alternatives to improve the mixing characteristics. Thus, SUM2 may be used as an interactive loop to guide the user back to DATIN2 to alter the design variables.

The output of SUM2 is divided into four parts which are: the site description summary, the hydrodynamic simulation summary, the analysis of the data, and finally the design advices and recommendations. All the information related to the site identifier, the ambient and discharge characteristics data, and the various discharge length scales are listed in the site description summary.

The hydrodynamic simulation summary includes the conditions related to the hydrodynamic mixing zone, legal mixing zone conditions, toxic dilution zone conditions, region of interest criteria, information about upstream intrusion, bank attachment locations, and a passive diffusion mixing summary, depending if the preceding properties occur. The data analysis part includes detailed information about the toxic dilution zone criteria, the legal mixing zone criteria, and the region of interest criteria. The last part deals with design recommendations where design suggestions and advice are given for improving the mixing properties. The design recommendation information is listed in Appendix C.

At the completion of SUM2, the user is given the option to exit to DOS, start a new design example, or modify the discharge and mixing zone data for the design case under consideration using the same general ambient data base.

Depending on the computer configuration, a typical CORMIX2 session for one discharge/environment condition may take about 5 minutes for an advanced 80386-based computer to 20 minutes for an IBM-PC/XT, if all necessary input data is at hand.

Chapter IV

CORMIX2: Flow Protocols and Simulation Modules

This chapter covers the hydrodynamic details of the effluent flow predictions and mixing zone analysis as performed in program element HYDRO2 of the expert system CORMIX2.

This chapter begins by presenting the detailed flow protocols for each of the 32 flow classes defined in program element CLASS2 (see Section 2.5). The actual prediction modules for each flow zone, including near-field, intermediate-field, and far-field processes are discussed in Section 4.2. Finally, in Section 4.3 the appropriate transition criteria that define spatial extent of each flow zone (module) are presented, along with constants used in the flow classification and simulation modules.

4.1 Flow Protocols

The prediction of effluent flow and the related mixing zone in the program element HYDRO2 is carried out by appropriate flow modules that are executed according to a protocol that pertains to each distinct flow configuration as determined by the classification scheme CLASS2.

CORMIX2 contains 32 separate flow modules that apply to each of the diverse mixing processes that occur in the near- and far-field of an effluent discharge. The physical background of these mixing processes has been discussed in Chapter II. Table 4.1 summarizes the flow modules. A detailed description of each module is given in Section 4.2.

The sequence of module execution is governed by a flow protocol for each flow class. These flow protocols have been constructed on the basis of the same arguments that have been presented in Chapter II to develop the flow classification. Detailed flow protocols for each flow class are presented in the following sub-section with extended explanations on their formulation.

The spatial extent of each flow module is governed by transition rules. These determine transitions between different near-field, and far-field mixing regions, and distances to boundary interaction. Section 4.3 gives a detailed summary of the transition rules.

Table 4.1 Flow Prediction Modules of CORMIX2

Module (MOD)	Description
	<u>Simulation Modules for Buoyant Multiport Diffusers: Subsurface Near-Field Flows</u>
201	discharge module
202	discharge (staged diffuser)
211	weakly deflected plane jet in crossflow
212	weakly deflected (3-D) wall jet in crossflow
213	near-vertical plane jet in linear stratification
214	near-horizontal plane jet in linear stratification
216	strongly deflected plane jet in crossflow
218	weakly deflected (2-D) wall jet in crossflow
221	weakly deflected plane plume in crosssflow
222	strongly deflected plane plume in crossflow
224	negatively buoyant line plume
	<u>Simulation Modules for Unstable Multiport Diffusers: Mixed Near-Field Flows</u>
271	acceleration zone for unidirectional co-flowing diffuser
272	acceleration zone for unidirectional cross-flowing diffuser (tee)
273	unidirectional cross-flowing diffuser (tee) in strong current
274	acceleration zone for staged diffuser
275	staged perpendicular diffuser in strong current

Table 4.1 (continued)

Module (MOD)	Description
277	alternating perpendicular diffuser in unstable near-field zone
279	negatively buoyant staged acceleration zone
	<u>Simulation Modules for Boundary Interaction Processes for Stable Multiport Diffusers</u>
232	near-vertical surface/bottom impingement with buoyant upstream spreading
234	near-vertical surface/bottom impingement, upstream spreading, vertical mixing, and buoyant restratification
235	near-horizontal surface/bottom/pycnocline approach
236	terminal layer stratified impingement/upstream spreading
237	terminal layer injection/upstream spreading
238	negatively buoyant diffuser (3-D) in strong current
	<u>Simulation Modules for Unstable Multiport Diffusers: Intermediate Field Flows</u>
251	diffuser plume in co-flow
252	diffuser plume in weak crossflow
	<u>Simulation Modules for Buoyant Spreading Processes</u>
241	buoyant layer spreading in uniform ambient
242	buoyant spreading in linearly stratified ambient
243	density current developing along parallel diffuser line
244	internal density current developing along parallel diffuser line
245	diffuser induced bottom density current

Table 4.1 (continued)

Module (MOD)	Description
	<u>Simulation Modules for Ambient Diffusion Processes</u>
261	passive diffusion in uniform ambient
262	passive diffusion in linearly stratified ambient
	<u>Simulation Module for Density Wedges in Bounded Channel</u>
281	Bottom/surface/internal density wedge

4.1.1 Flow Protocols for Buoyant Discharges into Uniform Ambient Layers (Flow Class MU)

The classification scheme discussed in Section 2.5.1.3 with its associated criteria (see Figure 2.9) already gives an indication of which flow processes will occur for each of the flow classes, and hence which sequence of flow modules is necessary for simulation.

In some cases, some of the modules present in the protocol will not be used due to special circumstances related to discharge or ambient characteristics. For example, for a non-buoyant discharge, the buoyant spreading regime (MOD241) will be absent in the applicable flow classes (MU2 to MU9), or in the case of a stagnant ambient environment, the buoyant spreading regime (MOD241) and the passive diffusion zone (MOD261) will be absent in the applicable flow classes (MU1, MU2, MU3, MU5, MU7, MU8, and MU9). The flow protocols for the buoyant discharge cases are listed in Table 4.2.

4.1.2 Flow Protocols for Negatively Buoyant Discharges into Uniform Ambient Layers (Flow Classes MNU)

The flow protocols for negatively buoyant discharges into uniform ambient layers, corresponding to the flow classes MNU as discussed in Section 2.5.1.4 and illustrated in Figure 2.10, are listed in Table 4.3. Some of the unstable discharge protocols bear some resemblance to those for positively buoyant discharges except for bottom re-stratification and buoyant spreading in the far-field. This is reflected in different transition criteria.

In the cases of stable discharges, boundary interaction interrupts the sequence of flow regions. When boundary interaction occurs, the sequence will change to include the appropriate boundary interaction effect and then continue as a surface far-field flow.

4.1.3 Flow Protocols for Discharges Trapped in Linearly Stratified Ambients (Flow Class MS)

Table 4.4 summarizes the protocols for the eight flow classes MS (refer to Section 2.5.1.2 and Figure 2.8) in which the ambient stratification causes an internal trapping of the effluent flow leading to a terminal layer formation and subsequent far-field processes. All stratification dominated flows (see Fig. 2.8) use special modules that account for the ambient stratification in the initial jet or plume phases of the flow.

Table 4.2 Flow Protocols (MU) for Buoyant Discharges into Uniform Ambient Layers

Flow Class	Module	Transition
MU1V	201	
		0
	211	
		1
	221	
		6
	232	
	HMZ - - -	0
	241	
		7
	261	
MU1H	201	
		0
	211	
		1
	222	
		6
	235 or 243	
	- - - - - -	0 or 38
	241	
		7
	261	
MU2	201	
		0
	271	
		21
	251	
	- - -	31
	241	
		7
	261	
MU3	201	
		0
	272	
		21
	252	
	- - -	32
	241	
		7
	261	

Table 4.2 (Continued)

Flow Class	Module	Transition
MU4	201	
		0
	273	
	- - -	0
	241	
		7
	261	
MU5	202	
		0
	274	
		22
	252	
	- - -	32
	241	
		7
	261	
MU6	202	
		0
	275	
	- - -	0
	241	
		7
	261	
MU7	202	
		0
	274	
		22
	251	
	- - -	31
	241	
		7
	261	
MU8	201	
		0
	277 or 234	
	- - - - - -	0
	241	
		7
	261	

Table 4.2 (Continued)

Flow Class	Module	Transition
MU9	201	
		0
	243 or 234	
	- - - - - -	38 or 0
	241	
		7
	261	

Table 4.3 Flow Protocols (MNU) for Negatively Buoyant Discharges into Uniform Ambient Layers

Flow Class	Module	Transition
MNU1	201	
		0
	224	
		0
	232	
	HMZ - - -	0
	241	
		7
	261	
MNU2	201	
		0
	211	
		2
	216	
		3
	222	
		15
	235 or 243	
	- - - - - -	0 or 38
	241	
		7
	261	
MNU3	201	
		0
	218	
		43
	245	
	- - -	51
	241	
		7
	261	
MNU4	201	
		0
	238	
	- - -	0
	241	
		7
	261	

Table 4.3 (Continued)

Flow Class	Module	Transition
MNU5	202	
		0
	279	
		22
	212	
		45
	245	
	- - -	51
	241	
		7
	261	
MNU6	202	
		0
	238	
	- - -	0
	241	
		7
	261	
MNU7	201	
		0
	271	
		21
	251	
	- - -	31
	241	
		7
	261	
MNU8	201	
		0
	272	
		21
	252	
	- - -	32
	241	
		7
	261	

Table 4.3 (Continued)

Flow Class	Module	Transition
MNU9	201	
		0
	273	
	- - -	0
	241	
		7
	261	
MNU10	202	
		0
	274	
		22
	252	
	- - -	32
	241	
		7
	261	
MNU11	202	
		0
	275	
	- - -	0
	241	
		7
	261	
MNU12	202	
		0
	274	
		22
	251	
	- - -	31
	241	
		7
	261	
MNU13	201	
		0
	277 or 234	
	- - - - - -	0
	241	
		7
	261	

Table 4.3 (Continued)

Flow Class	Module	Transition
MNU14	201	
		0
	243 or 234	
		38 or 0
	241	
		7
	261	

Table 4.4 Flow Protocols (MS) for Discharges Trapped in Linearly Stratified Ambients

Flow Class		Module	Transition
MS1		201	
			0
		211	
			2
		216	
			10
		235	
	HMZ	- - -	0
		242	
			11
		262	
MS2		201	
			0
		211	
			2
		216	
			0
		244	
		- - -	39
		242	
			11
		262	
MS3		201	
			0
		213	
			12
		236	
		- - -	10
		242	
			11
		262	
MS4		201	
			0
		214	
			13
		237	
		- - -	0
		242	
			11
		262	

Table 4.4 (Continued)

Flow Class	Module	Transition
MS5	201	
		0
	222	
		14
	235	
	- - -	0
	242	
		11
	262	
MS6	201	
		0
	222	
		14
	244	
	- - -	39
	242	
		11
	262	
MS7	201	
		0
	221	
		16
	236	
	- - -	0
	242	
		11
	262	
MS8	201	
		0
	211	
		1
	221	
		16
	236	
	- - -	0
	242	
		11
	262	

For instance, in stratification dominated flows (classes MS3 and MS4), the weakly deflected module (MOD211) will be replaced by its stratified counterpart, MOD213, before terminal layer interaction.

When terminal layer interaction occurs the normal sequence of flow regions is interrupted, and the sequence will change to include the appropriate terminal layer interaction in Section 2.5.1.2 and then continue as an internal layer far-field flow.

4.2 Hydrodynamic Simulation Modules

This section presents all the details related for each of the modules listed in Table 4.1 which provide the predictive element for a particular mixing process. The modules are grouped in the different flow phases (from near-field to far-field) as indicated in Table 4.1

There are two types of flow modules:

i) The continuous types describe the evolution of a flow process along a trajectory. Depending on user input, a small or large step interval can be used to obtain flow and mixing information along that trajectory.

ii) The control volume type uses a control volume approach to describe outflow values as a function of inflow values and based on conservation principles. For either type, the beginning values are denoted by the subscript "i" (e.g. S_i is beginning dilution) and final values are denoted by the subscript "f" (e.g. b_f is the final flow half-width).

4.2.1 Simulation Modules for Buoyant Multiport Diffusers: Subsurface Near-Field Flows

4.2.1.1 Introductory Comments

The flow equations in this module group describe the trajectory (x,y,z) of the jet/plume centerline and provide values along that trajectory for the flow half-width b, the local concentration c, and the local dilution S.

If a cross-section is made through the subsurface multiport diffuser plume, it will exhibit an approximately rectangular shape. The length of the rectangle is given by the diffuser length (neglecting diffusion at both "edges" of the plume). The width of the rectangle is measured by twice its transverse half-width b. The half-width b is defined here as the "1/e width" as a typical convention for Gaussian jet-like profiles (see for example, Holley and Jirka, 1986). Thus, b is the half-width of the jet/plume flow where the local concentration is 1/e, or 37%, of the centerline concentration. Since alternate width definitions are sometimes used in pollution analysis, the width definition when multiplied by 0.83 gives the 50% width, by $1/2^{1/2} = 0.71$ gives the standard deviation (61% width), and by $2^{1/2} = 1.41$ gives the 14% width, respectively.

The local concentration in this group of modules refers to the maximum centerline concentration c_c at the jet/plume centerline. Thus, the corresponding dilution refers to the minimum dilution c_0/c_c in which c_0 is the initial discharge concentration. It is important to keep in mind these flow definitions since they <u>differ</u>, in general, from those found in modules for subsequent flow zones. These differences are unavoidable due to different profile shapes for the effluent flow distribution governed by the various mixing processes.

In CORMIX2 a global Cartesian coordinate system (x,y,z) is placed at the bottom of the water body with the origin (0,0,0) at the half-way point and directly below the center of the multiport diffuser discharge. The height of the discharge orifices above the bottom is h_o. The positive x-axis is located at the bottom and directed in the downstream direction following the ambient flow. The positive y-axis is located at the bottom and points to the left, normal to the ambient flow direction (x-axis). The positive z-axis points vertically upward. The angle between the discharge axis y* and its projection on the horizontal plane (y**) (i.e. the discharge angle above horizontal) is θ. The discharge-crossflow angle σ is the angle between y** and the x-axis ($\sigma = 0$ for co-flowing discharges, $\sigma = 180$ for counter-flowing discharges) measured counter-clockwise from the x-axis. The alignment angle γ is the angle between the diffuser axis in the x-y plane and the x-axis ($\gamma = 0°$ for parallel alignment, $\gamma = 90°$ for perpendicular alignment) measured counter-clockwise from the x-axis. The orientation angle of the diffuser discharge β is the angle between the y** and the diffuser axis ($\beta = 0°$ for a staged diffuser, $\beta = 90°$ for a unidirectional diffuser).

A primed coordinate system, (x',y',z'), within a given flow region is specified with respect to the virtual source for that flow region. A virtual source is needed for each flow region because the perturbation analyses used in each module assume a point discharge source, which is physically unrealistic. The primed coordinate system is related to the global coordinate by

$$(x,y,z) = (x',y',z') + (x_v,y_v,z_v) \tag{4.1}$$

where (x_v,y_v,z_v) is the global position of the virtual source for that flow region. The position of the virtual source (x_v,y_v,z_v) is computed by taking the known flow solution at the transition, as given from the previous flow region, and back calculating the source position using the dilution equation for the given flow region.

In general, the analysis is extended to non-vertical three-dimensional trajectories within the ambient crossflow. A supplementary transverse coordinate η is defined here in a plane given by the z-axis and the projection of y* onto the z-y plane. Any vertical motion of the jet flow is controlled by the vertical component of the discharge momentum flux per diffuser length as well as the buoyancy flux per diffuser length (which always acts vertically). The transverse (horizontal) motion of the jet flow is solely controlled by the horizontal component of the discharge momentum flux per diffuser length.

Defining α as the angle between the discharge axis y* and the crossflow (x-axis), and the angle δ between the projection of y* on the vertical yz-plane (transverse coordinate η) and the x-axis the relationships are

$$\alpha = \sin^{-1}(1 - \cos^2\theta\cos^2\sigma)^{1/2} \qquad (4.2)$$

$$\delta = \tan^{-1}(\tan\theta/\sin\sigma) \qquad (4.3)$$

where θ and σ are the discharge angles.

4.2.1.2 Discharge Module (MOD201)

This module begins every flow sequence. In the module the flow is converted from a uniform velocity distribution to a Gaussian profile, with equivalent momentum flux. The representative final flow width b_f, from the discharge module

$$b_f = B(2/\pi)^{1/2} \qquad (4.4)$$

where B is the slot jet width defined earlier. No dilution is assumed to occur, so that $S_f = 1.0$ and $c_f = c_0$, where S_f is final dilution and c_f and c_0 are the final and discharge concentrations, respectively. The final x- and y-coordinate are 0, but $z_f = h_o$.

4.2.1.3 Weakly Deflected Plane Jet In Crossflow (MOD211)

The results for the mdnf presented in Section 2.6.1.1.3 are extended to include the general 3-D trajectory. For a cross-flowing discharge ($\alpha > 45°$) the trajectory is a function of η as the independent variable. Writing the trajectory equations in the virtual coordinate system in terms of the supplemental coordinate η gives the crossflow induced deflection

$$x' = \eta' \cot\alpha + \eta'^{3/2} \sin^{1/2}\alpha / (T_{11}^{3/2} l_m^{1/2}) \quad (4.5)$$

where T_{11} is the trajectory constant for the weakly deflected jet. The expression for the transverse coordinate y is simply

$$y' = \eta' \cos\delta \quad (4.6)$$

The vertical coordinate, however, experiences an additional perturbation due to buoyant deflection, or

$$z' = \eta' \sin\delta + TT_{11} \eta'^{5/2} \mathrm{sign} J_0 / (l_M^{3/2} \sin^{5/2}\alpha) \quad (4.7)$$

where TT_{11} is a constant for the buoyancy correction, and $\mathrm{sign}J_0$ is equal to +1 for a positively buoyant discharge and is equal to -1 for a negatively buoyant discharge.

The flow width is

$$b = B_{11} \eta' / \sin\alpha \quad (4.8)$$

where B_{11} is a width constant. The dilution is expressed as

$$S = S_{11} \eta'^{1/2} / (l_q^{1/2} \sin^{1/2}\alpha) \quad (4.9)$$

where S_{11} is the dilution constant.

If the discharge is co-flowing ($\alpha \leq 45°$), the simulation should step in x as the primary independent coordinate and the trajectory, width and dilution relationships are

$$z' = \eta' \sin\delta + TT_{11} x'^{5/2} \mathrm{sign} J_0 (l_M^{3/2} \cos^{5/2}\alpha) \quad (4.10)$$

$$\eta' = x' \tan\alpha - x'^{3/2} \sin\alpha / (T_{11}^{3/2} l_m^{1/2} \cos^{1/2}\alpha \quad (4.11)$$

$$b = B_{11} x' / \cos\alpha \quad (4.12)$$

$$S = S_{11} x'^{1/2} / (l_q^{1/2} \cos^{1/2}\alpha) \quad (4.13)$$

<u>4.2.1.4 Weakly Deflected (3-D) Wall Jet in Crossflow (MOD212)</u>

In this flow region unequal entrainment and spreading will be neglected in directions parallel and normal to the boundary wall. The attached flow has a horizontal momentum flux M_w two times the discharge momentum flux M_o to account for the mirror image of the attached flow with the bottom symmetry plane, so the horizontal wall momentum flux $M_w = 2M_o \cos\theta$. This assumption also results in $Q_w = 2Q_o$.

For a cross-flowing discharge ($\sigma > 45°$), the trajectory equations for y' in terms of x' (z = 0 for the attached case) becomes

$$y' = T_{12}(2\cos\theta)^{1/4} L_m^{1/2} (x' - y'\cot\sigma)^{1/2} \qquad (4.14)$$

where T_{12} is a trajectory constant. The width and dilution are given by

$$b = B_{12} y'/\sin\sigma \qquad (4.15)$$

$$S = S_{12} y' (\cos\theta/2)^{1/2} / (L_q \sin\sigma) \qquad (4.16)$$

respectively, where B_{12} a width constant, S_{12} is a dilution constant, and L_q is the three-dimensional discharge/jet length scale (Table 2.1). A similar equation system holds for the co-flowing wall jet (3-D) ($\sigma < 45°$) in analogy to the free jet (see Section 5.2.1.2, Doneker and Jirka, 1989).

4.2.1.5 Weakly Deflected (2-D) Wall Jet in Crossflow (MOD218)

Similar behavior as for the 3-D jet (MOD212) is considered here. The attached flow has a horizontal momentum flux m_w two times the discharge momentum flux m_o to account for the half width of the attached flow with the bottom symmetry plane, so the horizontal wall momentum flux $m_w = 2m_o\cos\theta$. This assumption also results in $q_w = 2q_o$.

For a cross-flowing discharge ($\sigma > 45°$), the trajectory equation for y' in terms of x' ($z = 0$ for the attached case) becomes

$$y' = T_{18}(2\cos\theta/\sin\sigma)^{1/2} l_m^{1/3} (x' - y'\cot\sigma)^{2/3} \qquad (4.17)$$

where T_{18} is a trajectory constant. The width and dilution are given by

$$b = B_{18} y'/\sin\sigma \qquad (4.18)$$

$$S = S_{18} y'^{1/2} (2\cos\theta/\sin\sigma)^{1/2} / l_q^{1/2} \qquad (4.19)$$

respectively, where B_{18} is a width constant, and S_{18} is a dilution constant. A similar equation system holds for the co-flowing wall jet (2-D) ($\sigma < 45°$) in analogy to the mdnf ($\alpha \le 45°$) jet (see Section 4.2.1.3).

4.2.1.6 Near-Vertical Plane Jet in Linear Stratification (MOD213)

For jets issued near-vertically into a density stratified environment, α is greater than 45° so the coordinates of the flow in the virtual coordinate system are given in first order by a straight line trajectory

$$x' = \eta' \cot\alpha \tag{4.20}$$

$$y' = \eta' \cos\delta \tag{4.21}$$

$$z' = \eta' \sin\delta \tag{4.22}$$

respectively. The width and dilution are expressed as

$$b = B_{13}\eta'/\sin\alpha \tag{4.23}$$

$$S = S_{13}\eta'^{1/2}(1-S_{13A}\sin^2\theta\eta'^3/l'^3_m\sin^3\alpha)^{1/2}/l_q^{1/2} \tag{4.24}$$

respectively, where B_{13} is a width constant, and S_{13} and S_{13A} are dilution constants. For the physical background, see Section 2.6.1.2.1.

4.2.1.7 Near-Horizontal Plane Jet in Linear Stratification (MOD214)

The simulation of this module (occurring in flow class MS4) is limited to the co-flowing design, with α less than 45°. The coordinates of the flow in the virtual coordinate system are given by

$$z' = \eta' \sin\delta \tag{4.25}$$

$$y' = \eta' \cos\delta \tag{4.26}$$

The width and dilution are given by

$$b = B_{14}x'/\cos\alpha \tag{4.27}$$

$$S = S_{14}x'^{1/2}/l_q^{1/2}\cos^{1/2}\alpha \tag{4.28}$$

where B_{14} and S_{14} are the width and dilution constants respectively.

4.2.1.8 Strongly Deflected Plane Jet in Crossflow (MOD216)

In the mdff the primary variable is x' due to the crossflow advection. The trajectory equations are

$$z' = \eta' \sin\delta \tag{4.29}$$

$$\eta' = T_{16}l_m^{1/2}\sin^{1/2}\alpha x'^{1/2} \tag{4.30}$$

where T_{16} is the trajectory constant. The y-coordinate is similar to that for a weakly deflected jet in a crossflow.

The width and dilution of the flow are given by

$$b = B_{16}\eta' \tag{4.31}$$

$$S = S_{16}\eta'/(l_m l_q)^{1/2} \tag{4.32}$$

where B_{16} and S_{16} are the width and dilution constants respectively.

4.2.1.9 Weakly and Strongly Deflected Plane Plume in Crossflow (MOD221 and MOD222)

As mentioned in Section 2.6.1.1.5, in order to decide if the flow has a flat or steep linear trajectory, one can use a criterion j_o/u_a^3 > or < C_{21} where C_{21} is a constant.

For a weakly deflected plume (MOD221, $j_o/u_a^3 > C_{21}$) the trajectory coordinates are a generalization of the perturbation solutions presented in Section 2.6.1.1.5. With z' as the primary coordinate the trajectory equations are

$$x' = z' l_M^{1/2}/T_{21} l_m^{1/2} +$$

$$(TT_{21A} l_M \cos\theta + TT_{21B} l_M \cos\theta \ln(z'/2l_M)\cos\sigma \tag{4.33}$$

$$y' = T_{21} l_m^{1/2} \cos^{1/2}\theta \sin^{1/2}\sigma x'^{1/2} +$$

$$(TT_{21A} l_M \cos\theta + TT_{21B} l_M \cos\theta \ln(z'/2l_M)\sin\sigma \tag{4.34}$$

where T_{21} is a trajectory constant, TT_{21A} and TT_{21B} are momentum correction coefficients. Width and dilution are given by

$$b = B_{21} z' \tag{4.35}$$

$$S = S_{21} z'/(l_m l_q)^{1/2} \tag{4.36}$$

respectively, where B_{21} is a width constant and S_{21} is a dilution constant.

The strongly deflected plume (MOD222, $j_o/u_a^3 < C_{21}$) trajectory coordinates, written in the virtual coordinate system as a function of z', are

$$x' = z' l_M^{3/4}/T_{22} l_m^{3/4} +$$

$$(TT_{21A} l_M \cos\theta + TT_{21B} l_M \cos\theta \ln(z'/TT21_C 2l_M)\cos\sigma \tag{4.37}$$

$$y' = T_{22} l_m^{1/2} \cos^{1/2}\theta \sin^{1/2}\sigma x'^{1/2} +$$

$$(TT_{21A} l_M \cos\theta + TT_{21B} l_M \cos\theta \ln(z'/TT21_C 2l_M)\sin\sigma \tag{4.38}$$

where T_{22} is a constant.

Width is given by

$$b = B_{22}z'$$ (4.39)

where B_{22} is a constant, and the dilution by

$$S = S_{22}z'/(l_m l_q)^{1/2}$$ (4.40)

where S_{22} is a constant

4.2.1.10 Negatively Buoyant Line Plume (MOD224)

In this module, a control volume approach is used. Assuming that the line plume will travel up to a distance l_M vertically, and assuming the same dilution S as in MOD221 (Eq. 2.32) with z' replaced by l_M, the final dilution is

$$S_f = S_{24}l_M^{1/2}/l_q^{1/2}$$ (4.43)

Similarly the final width becomes

$$b_f = B_{24}l_M$$ (4.44)

where S_{24} differs from S_{21} by a recirculation factor R, $S_{24} = S_{21}/R$, with $R \approx 2$, and $B_{24} \approx B_{21}$.

Here the final distance x- coordinate for the plume is

$$x_f = l_M \cos\gamma/2$$ (4.45)

and both y_f and z_f are zero due to the fall-back of the plume to the bottom.

4.2.2 Simulation Modules for Unstable Multiport Diffusers: Mixed Near-Field Flows

The flow equations in this module group describe vertically fully mixed (over the applicable layer depth H_s) diffuser plumes. The horizontal trajectory position (x,y) of the plume centerline is calculated as well as the horizontal half-width b_h, the minimum centerline concentration c_c and the corresponding centerline dilution S. Except where noted, the local half-width is defined by the "1/e width" of a Gaussian plume (for width conventions see Section 4.2.1.1). The vertical thickness b_v of the plume is, of course, equal to the layer height H_s. The z-coordinate of the flow is arbitrarily placed at the top of the layer H_s, with the exception of MOD279.

4.2.2.1 Acceleration Zone for Unidirectional Co-Flowing Diffuser (MOD271)

This region begins after MOD101 (see Section 4.2.1.2) with an initial value of b_h equal to $L_D/2$. The flow is analysed in the x-y plane, with y'' as the independent variable. The straight line trajectory equations in the virtual coordinate system are

$$y' = y'' \sin\sigma \tag{4.46}$$

$$x' = y'' \cos\sigma \tag{4.47}$$

The dilution is constant throughout the acceleration zone and is

$$S = H_s \sin\gamma / 2 (l_m l_q)^{1/2} + ((H_s^2 \sin^2\gamma + 2 H_s l_m) / l_m l_q)^{1/2} \tag{4.48}$$

and the horizontal half-width b_h as a function of y'' is

$$b_h = L_D/2 \; [\sigma_1 + (1 - \sigma_1) \; \exp(-3x^* \; (1 + x^{*3}))] \tag{4.49}$$

where:

$$x^* = 2x/L_D \tag{4.50}$$

and

$$\sigma_1 = (S(l_m/l_q)^{1/2} \sin\gamma + 0.5)/(S(l_m/l_q)^{1/2} \sin\gamma + 1) \tag{4.51}$$

Strictly speaking, the lateral flow profile gradually evolves in the acceleration zone of the unidirectional diffuser from an initial top-hat profile just downstream from the diffuser line to a final Gaussian profile (see Lee and Jirka, 1980).

4.2.2.2 Acceleration Zone for Unidirectional Cross-Flowing Diffuser (Tee) (MOD272)

The same procedure as the previous section is followed, and hence the equations used in MOD271 are used here, with an additional shoreline proximity influence (see Section 2.6.2.1.2). Thus, in case of having a discharge location x_s less than the actual diffuser length L_D, the dilution is reduced by an exponential influence factor as follows

$$S_t = S^*_t \; (1 - \exp(-S_{72} x_s / L_D)) \tag{4.52}$$

where S_{72} is a constant and S^*_t represents the dilution value given by Eq. (4.48).

4.2.2.3 Unidirectional Cross-Flowing Diffuser (Tee) in Strong Current (MOD273)

A control volume approach is used in this module. The dilution S of Eq. (4.48) is reduced by the factor r_s (see Eq. 2.51) to obtain S_f for MOD273

$$S_f = (H_s \sin\gamma/2(l_m l_q)^{1/2} + ((H_s^2 \sin^2\gamma + 2H_s l_m)/l_m l_q)^{1/2})$$

$$(1 + 5H_s \sin^2\gamma/l_m)^{-1/2} \quad (4.53)$$

Again the same procedure as before is used for shoreline interaction, where Eq. (4.53) is reduced by an exponential influence factor if $x_s < L_D$.

The horizontal half-width, based on d_m (see Section 2.6.2.4), is

$$b_h = d_m \sin\sigma/2 \quad (4.54)$$

and the final x-, and y- coordinates are

$$x_f = L_D \cos\sigma/2 \quad (4.55)$$

$$y_f = d_m \sin\sigma/2 \quad (4.56)$$

4.2.2.4 Acceleration Zone for Staged Diffuser (MOD274)

This zone begins after a special discharge module MOD202 for the staged diffusers. The only difference to MOD201 is that the final x- and y- coordinates are

$$x_f = -L_D \cos\sigma/2 \quad (4.57)$$

$$y_f = -L_D \sin\sigma/2 \quad (4.58)$$

in order to adapt to the staged geometry.

Hence, the equations for the trajectory are

$$y = y_i + y'' \sin\sigma \quad (4.59)$$

$$x = x_i + y'' \cos\sigma \quad (4.60)$$

The dilution S is constant in this region

$$S = S_{74} ((l_m \ l_q)^{1/2} - \cos\gamma)H_s/(l_m \ l_q)^{1/2} \quad (4.61)$$

and the horizontal half-width is

$$b_h = (B_{74} + 0.5 \tan \beta)y'' \quad (4.62)$$

where both S_{74} and B_{74} are constants.

4.2.2.5 Staged Perpendicular Diffuser in Strong Current (MOD275)

A control volume approach is used in this mode similar to MOD273. The same equations are used as in MOD273 with the exception of having the angle σ replaced by γ in Eqs. (4.54 to 4.56). The final dilution equation is

$$S = S_{75}(H_s/l_q)^{1/2}(1 + 2.23H_s\sin^2\gamma/l_m)^{1/2} \tag{4.63}$$

Shoreline proximity does not apply in this case.

4.2.2.6 Alternating Perpendicular Diffuser in Unstable Near-Field Zone (MOD277)

A control volume approach is used in this module, where the final y- coordinate is zero, and the final x_f coordinate is as follows

$$x_f = (L_D\cos\gamma + 5H_s)/2 \tag{4.64}$$

The final dilution is

$$S = H_s((0.25l_m + l_M\sin^2\gamma)/l_M l_m l_q)^{1/2} \tag{4.65}$$

and the final horizontal width is

$$b_h = (L_D\sin\gamma + 5H_s)/2 \tag{4.66}$$

4.2.2.7 Negatively Buoyant Staged Acceleration Zone (MOD279)

A three-dimensional diffuser plume develops along the staged diffuser axis.

The following module equations are similar to those developed by Lee (1980).

The dilution increases along the diffuser axis as

$$S = S_{79}(y''/l_q)^{1/2} \tag{4.67}$$

the thickness as

$$b_v = B_{79}\, y'' \tag{4.68}$$

and the horizontal width as

$$b_h = (B_{79} + 0.5\tan\beta)y'' \tag{4.69}$$

The trajectory coordinates are similar to those of MOD274.

4.2.3 Simulation Modules for Boundary Interaction Processes for Stable Multiport Diffusers

When the flow interacts with a boundary such as the surface, bottom, or pycnocline density jump, an appropriate interaction module will be used to describe the process. The only difference is the centerline height of the flow as well as any hydrostatic adjustment process for pycnocline flows (see Section 2.23 Doneker and Jirka, 1990).

In all of these modules a control volume approach is used. Generally, a bell-shaped jet/plume inflow is transformed to a more uniform (top-hat) outflow zone that follows the boundary (surface, bottom, pycnocline) or flows in the stratified terminal layer. Thus, after transformation the final geometric values are the trajectory (x_f, y_f, z_f), the total vertical thickness b_{vf}, and the horizontal half-width b_{hf} of the profile. Also concentration and dilution values refer to average values which, within the top hat profile, tend to be close to extreme (maximum or minimum, respectively) values.

Most of the boundary interaction modules, namely the near-vertical surface impingement with buoyant upstream spreading (MOD232), the near-vertical surface impingement with unstable recirculation (MOD234), the stratified terminal layer impingement with buoyant spreading (MOD236), and the stratified near-vertical surface injection with upstream spreading (MOD237) are identical to the ones presented by Doneker and Jirka (1989 their, MOD32, MOD34, MOD36, and MOD37 respectively). The following two modules, however, applies to the multiport diffuser alone.

4.2.3.1 Near-Horizontal Surface/Bottom/Pycnocline Approach (MOD235)

In this simplest approach condition, the bent over flow approaches the interface near-horizontally with an impingement angle $\theta_i < 45°$.

The final x-coordinate is given by a geometric shift due to the size of the in-flowing jet/plume

$$x_f = x_i + 2b_i \tag{4.70}$$

y_f is set equal to y_i, and z_f equal to z_i. The final bulk dilution is

$$S_f = SB_{35}S_i \tag{4.71}$$

where SB_{35} is a bulk mixing conversion factor.

The final horizontal half-width is calculated (see Section 2.6.1.3) to be

$$b_{hf} = L_D \sin\gamma/2 \tag{4.72}$$

and the vertical width is

$$b_{vf} = S_f Q_o/u_a b_{hf} \tag{4.73}$$

4.2.3.2 Negatively Buoyant Diffuser (3-D) in Strong Current (MOD238)

The diffuser plume will occupy a thin layer only near the bottom of the ambient flow.

For a parallel diffuser, the thickness is given by

$$b_{vf} = B_{38A}\ L_M \tag{4.74}$$

with a lateral width

$$b_{hf} = \frac{L_D}{2} \cos\gamma + b_{vf} \tag{4.75}$$

The lateral coordinate is shifted

$$y_f = L_m \sin\sigma \tag{4.76}$$

and the downstream final position is

$$x_f = \frac{L_D}{2} \sin\gamma + L_M \tag{4.77}$$

For a perpendicular diffuser the corresponding equations are

$$b_{vf} = B_{38B}\ l_M \tag{4.78}$$

$$b_{hf} = \frac{L_D}{2} \cos\gamma + b_{vf} \tag{4.79}$$

$$y_f = l_m \sin\sigma \tag{4.80}$$

$$x_f = \frac{L_D}{2} \sin\gamma + l_M \tag{4.81}$$

In either case, $z_f = 0$ and the final dilution is cross-flow controlled

$$S_t = 2 \frac{b_{vt}\, b_{ht}}{L_D} \frac{1}{(l_q\, l_m)^{1/2}} \qquad (4.82)$$

4.2.4 Simulation Modules for Unstable Multiport Diffusers: Intermediate-Field Flows

As mentioned in Section 2.6.2.4, the intermediate-field plume for the unidirectional or staged diffuser is divided into two regions. Region 1 starts immediately after the acceleration zone, and extends up to a distance where restratification occurs. This distance (Eq. 2.59) is determined by a critical densimetric Froude number ($F_c = u_c/(g'_c H_s)^{1/2}$, $g'_c = g'_o/S$), where F_c depends on the diffuser type. For the unidirectional diffuser, F_c will be indicated by F_{c50u}, and for the staged by F_{c50s} (see Table 4.8).

Region 2 starts when the flow restratifies. In that region the flow has a superimposed surface spreading (Section 2.6.2.4).

In this module group, the conventions for horizontal half-width b_h, the minimum centerline concentration c_c, and the corresponding dilution S are identical to those defined in Section 4.2.2.

4.2.4.1 Diffuser Plume in Co-Flow (MOD251)

In Region 1: Because the discharge is approximately co-flowing, the simulation steps in x' as the primary independent coordinate. Thus,

$$y' = x'\tan\sigma - x'^{3/2}\sin\sigma/T_5^{3/2} d_m^{1/2}\cos^{1/2}\sigma \qquad (4.83)$$

and the dilution is

$$S = S_{50} x'^{1/2}/d_q^{1/2}\cos^{1/2}\sigma \qquad (4.84)$$

and the horizontal half-width b_h is

$$b_h = B_{50} x'/\cos\sigma \qquad (4.85)$$

where T_5, S_5, and B_5 are constants. Because the flow is vertically completely mixed, the vertical thickness b_v is set equal to H_s.

Region 2: The same trajectory and dilution equations are used as in the first region, but both vertical and horizontal widths are changed, hence

$$b_h = BB_{50}\,(H_s^{1/2}/l_M^{1/2} L_D^{1/6})\,(x^{7/4} - x'^{7/4}_t)^{2/3} + b_{hi} \qquad (4.86)$$

and

$$b_v = S_i b_{hi} H_s / b_h S \quad (4.87)$$

where BB_5 is a constant, S_i and S are the initial and local dilution, respectively, and b_{hi} the final horizontal width at the end of region 1.

4.2.4.2 Diffuser Plume in Weak Cross-Flow (MOD252)

A procedure analogous to MOD151 is used here for both regions. The only difference is that instead of stepping in x′, the primary coordinate is y′ because the discharge is cross-flowing. The equations are modified accordingly. For example, the trajectory relation is

$$x' = y'^{3/2} \sin^{1/2}\sigma / T_{50}^{3/2} d_m^{1/2} + y' \cot\sigma \quad (4.88)$$

4.2.5 Simulation Modules for Buoyant Spreading Processes

The flow distribution inherent in the two buoyant spreading modules is mostly uniform (top-hat). Hence, the same interpretations on geometric (width) and dilution (or concentration) values apply (see introductory comments to Section 4.2.3).

4.2.5.1 Buoyant Surface/Bottom Spreading (MOD241) and Buoyant Terminal Layer Spreading (MOD242)

The equations for MOD241 and MOD242 are the same equations used in Doneker and Jirka (1990), MOD41 and MOD42 respectively.

4.2.5.2 Density Current Developing Along Parallel Diffuser Line (MOD243)

The physical background for the cumulative density current along the diffuser line was presented in Section 2.6.3.1. The flow equations are

$$b_h = [(b_{hi}^{3/2} + (l_m/l_M)^{3/2}/(2\ C_{D43})\ (x^{3/2} - x_i^{3/2}))]^{2/3} \quad (4.89)$$

$$b_v = S_f(l_q\ l_m)^{1/2}\ x/2b_h + (b_{hi}b_{vi}/b_h - S_f(l_q\ l_m)^{1/2} x_i/2b_h) \quad (4.90)$$

where B_{43} is a constant and

$$b_{hi} = (L_D \cos\gamma + 5H_s)/2 \quad (4.91)$$

and

$$b_{vi} = H_s/2 \quad (4.92)$$

The position x is defined as

$$x = (L_D\cos\gamma + 5H_s)/2 \quad (4.93)$$

and the dilution is as follows

$$S_t = H_s(S_{43}/l_M l_q + S_{43A}\sin^2\gamma/l_m l_q)^{1/2} \quad (4.94)$$

where S_{43} and S_{43A} are both dilution constants.

4.2.5.3 Internal Density Current Developing Along Parallel Diffuser Line (MOD244)

Referring to Section 2.6.3.2, the flow equations are

$$b_h = [(b_{hi}^2 + (2/C_D)^{1/2}(S_t(l_q l_m)^{1/2}(x^2-x_i^2)/4l_a + k(x - x_i))]^{1/2} \quad (4.95)$$

$$b_v = (S_t(l_q\ l_m)^{1/2}(x - x_i)/2 + k)/b_h \quad (4.96)$$

where

$$k = (b_{hi}b_{vi}u_a - S_t(l_q\ l_m)^{1/2})x_i/2) \quad (4.97)$$

4.2.5.4 Diffuser Induced Bottom Density Current (MOD245)

MOD245 represents a bottom density current that is greatly affected, however, by the momentum flux of the diffuser thus leading to a trajectory that is similar to a two-dimensional wall jet (MOD218). Thus, the module equations are similar to those for MOD218 with superimposed spreading (MOD241).

4.2.6 Simulation Modules for Ambient Diffusion Processes

The physical processes underlying the two ambient diffusion modules (MOD261 and MOD262) have ben presented in Section 2.5.4. The equations for MOD261 and MOD262 are identical to those used by Doneker and Jirka (1989, their MOD61 and MOD62, respectively).

4.2.7 Simulation Module for Density Wedge in Bounded Channel

4.2.7.1 Bottom/Surface/Internal Density Wedge (MOD281)

Note that MOD281 does not occupy a fixed position in the predictive protocols. However, MOD281 will be executed at the end of the HMZ for any flow class (see Tables 4.2, 4.3, or 4.4) if two conditions hold: a) the channel is bounded, and b) examination of the HMZ final results indicates that lateral interaction of the plume with both banks does occur. This is usually the case for strongly buoyant discharges into a low velocity ambient environment.

The governing equations have been presented in Section 2.6.3.3. These are the limiting dilution S_n, Eq. (2.75) for wedges with critical boundary control, the channel Froude number, Eq. (2.76a), the critical depth h_c, Eq. (2.76b), and the wedge lengths L_w for bottom (Eq. 2.77) and surface (Eq. 2.78), respectively.

For subcritical wedges, the corresponding equations on the layer depth h_l, Eq. (2.79), the Froude numbers, Eq. (2.80) and (2.83), and the wedge lengths, Eq. (2.82) and (2.85), for bottom or surface and internal wedges, respectively.

4.3 Transition Rules, Flow Criteria and Coefficient Values

This section provides the detailed equations for the transition rules listed in the flow protocols that control the spatial extent of each flow module. It also provides the complete functional form for the criteria, including terminal height evaluations that have been used in the flow classification presented in Chapter III. Furthermore, a listing and justification of all numerical coefficients is supplied.

4.3.1 Transition Rules

Transition rules are needed to give the spatial expressions as to where each flow region ends. Each subsequent flow region is assigned initial values that corresponding to the final values of the preceding flow region. Transition rules used in the simulation appear in Table 4.5, and the constant values for the transition rules appear in Table 4.9.

For example, Transition Rule 2 gives the final value of a weakly deflected plane jet coordinate when it is followed by a strongly deflected plane jet in crossflow. The transition from one region to the other is characterized by the plane jet/crossflow length scale l_m. If the horizontal discharge angle is α, the final supplementary coordinate η'_t, and the final x-coordinate x'_t, transition rule 1 yields

Table 4.5 Transition Rules

Transition Rule	From MOD	To MOD	Equation
1	211	221	$\alpha > 45°,\ \eta'_f = T_{C1} l_M \sin \alpha$
	211	222	$\alpha < 45°,\ x'_f = T_{C1} l_M \cos \alpha$
2	211	216	$\alpha > 45°,\ \eta'_f = T_{C2} l_m \sin \alpha$
			$\alpha < 45°,\ x'_f = T_{C2} l_m \cos \alpha$
3	216	222	$x'_f = T_{C3} l_M$
6	221	232	$z_f = 0.75H_s + 0.25h_o$
	222	235	
	222	243	
7	241	261	$x_f = x_i + (2^{3/2}/3) CD_{41}^{1/2} (b_{hi}^{3/2}/L_b^{1/2}) \{[(8L_b b_{vi})/(S_i f L_m L_q R_{fc41})]^{3/2} - 1\}$
10	216	235	$z'_f = T_{C10} l_m^{1/4}\ l_m'^{3/4} \sin^{1/2}\theta$
	216	244	
11	242	262	$x_f = x_i + (2CD_{42})^{1/2}/(2-\beta)(L_m'^2 b_{hi}/L_m/b_{vi}) \{[(8/f/R_{fc42})^{1/2} L_m b_{vi}/L_m'^2]^{(2-\beta)/(1-\beta)} - 1\}$
12	213	236	$z_f' = T_{C12}\ l_m' \sin^{1/3}\theta + T_{c12B}(l_b'^3/l_m'^2) \cos^{2/3}\theta$
13	214	237	$z_f' = T_{C13} l_m' \sin^{1/3}\theta + [T_{c13B}\ (l_b'^3/l_m'^2) \cos^{2/3}\theta$
			$\alpha > 45^0,\ y_f' = T_{c13P}\ l_m' \sin \alpha$
			$\alpha < 45^0,\ x_f' = T_{c13P}\ l_m' \cos \alpha$
14	222	244	$z_f = T_{C14} l_b^{3/2}/l_a^{1/2}$
15	222	235	$z_f = \max(0.25h_o, 0.25z_i)$
	222	243	
16	221	236	$z'_f = T_{C16} l_b'$
21	271	251	$y''_f = T_{C21} L_D$
	272	252	

Table 4.5 (Continued)

Transition Rule	From MOD	To MOD	Equation
22	274	251	$y''_t = L_D \cos\beta$
	274	252	
	279	212	
31	251	241	$x'_t = T_{c31} L_M^4 / F_c^4 H_s^3$
32	252	241	$y'_t = T_{c32} L_M^4 / F_c^4 H_s^3$
38	243	241	$x_t = (L_D \cos\gamma + 5H_s)/2$
39	244	242	$x_t' = L_D \cos\gamma /2$
43	218	245	$\sigma > 45°$, $y'_t = T_{C43} l_M \sin\sigma$ $\sigma < 45°$, $x'_t = T_{C43} l_M \cos\sigma$
45	212	245	$\sigma > 45°$, $y'_t = T_{C45} L_M \sin\sigma$ $\sigma < 45°$, $x'_t = T_{C45} L_M \cos\sigma$
51	245	241	$\sigma > 45°$, $y'_t = T_{C51} L_m \sin\sigma$ $\sigma < 45°$, $x'_t = T_{C51} L_m \cos\sigma$

$$\eta'_t = T_{C2} l_m \qquad \alpha > 45° \tag{4.98}$$

$$x'_t = T_{C2} l_m \qquad \alpha \leq 45° \tag{4.99}$$

where T_{C2} is a constant (Transition rule Constant 2).

As shown in Tables 4.2 to 4.4 the proper transition rule depends on the sequence of current flow module to next flow module. In general, flow transition between flow regimes are smooth due to matching volumetric dilutions. There may occasionally be slight discontinuities in the predicted flow width.

4.3.2 Flow Classification Criteria

A summary of the detailed classification criteria that have been shown in "order of magnitude" form on Figures 2.8 to 2.10 is provided in Table 4.6. The labels C1, C2, etc. correspond to the labels used on those figures. The values of the numerical constants are also included in the first column of Table 4.6 with reference or comments on how they were obtained.

4.3.3 Terminal Layer Expressions

Table 4.7 lists the detailed terminal height equations used in Figure 2.8 of the flow classification scheme. The equations may differ from the usual equations available in the literature through geometric factors that measure the vertical or horizontal momentum strengths and through factors measuring the direction of the buoyancy force. The first column also gives the adopted numerical values with the appropriate reference.

4.3.4 Model Coefficient Values

Any predictive model describing turbulent flow processed contains a number of constants that must be determined from experimental data. The predictive flow modules and transition rules of CORMIX2 are listed in Table 4.8 and 4.9, respectively. A large number of constants appear as required by the different physical processes in the various flow zones. The reader is referred to Doneker and Jirka (1990) regarding the procedure for adopting numerical constants with consistency checks among different types of constants.

Table 4.6 Flow Classification Criteria

Criterion Value	Equation Used in CLASS2	Data Sources, and References, or Comments
$C_1 = 0.75$	l_m'/l_b'	From List (1982), Wright (1979, 1982), and Roberts (1989)
$C_2 = 0.90$	l_m/l_m'	From Abdelwahed and Chu (1982)
$C_3 = 2.2$	l_b'/l_a	From Roberts (1977)
$C_4 = 0.54$ $C_{4A} = 0.1$	$l_M(1 + \cos^2\theta)^2/H_s$ $+ (l_M - C_{4A}*h_o)/l_m$	From Jirka (1973, 1982)
$C_4' = 0.22$	l_M/l_m	From Jirka (1982)
$C_5 = 10$	l_m/H_s	From Jirka (1982)
$C_6 = 10$	l_m/H_s	From Jirka (1982)
$C_7 = 0.54$	$\|l_M\|(1 - \cos^2\theta)^2/H_s$ $- \|l_M\|/l_m$	From Jirka (1973, 1982)
$C_8 = 0.54$	$\|l_M\|/H_s$	From Jirka (1973, 1982)
$C_9 = 0.4$	l_m/H_s	From Abdelwahed and Chu (1982)
$C_{10} = 0.17$	$\|l_M\|/L_m$	From Jirka (1982), Wright (1977), List (1982), and Holley and Jirka (1986)
$C_{11} = 0.6$	$\|L_M\|/L_m$	From Jirka (1982), Wright (1977), List (1982), and Holley and Jirka (1986)

Table 4.7 Stratified Terminal Height Expressions

Constant and Value	Equation Used in CLASS2	Reference, or Comments
$C_{T1} = 2.4$	$C_{T1} l_m^{1/4} l_m'^{3/4} \sin^{1/2}\theta$	From List (1982), and Abdelwahed and Chu (1982)
$C_{T2} = 2.4$	$C_{T2} l_m^{1/4} l_m'^{3/4} \sin^{1/2}\theta$	From List (1982), and Abdelwahed and Chu (1982)
$C_{T3} = 2.3$	$C_{T3} l_m' \sin^{1/3}\theta$	From List (1982)
$C_{T4} = 2.3$	$C_{T4} l_m' \sin^{1/3}\theta$	From List (1982)
$C_{T5} = 2.5$	$C_{T5} l_b'^{3/2} / l_a^{1/2}$	From Roberts (1977, and 1989)
$C_{T6} = 2.5$	$C_{T6} l_b'^{3/2} / l_a^{1/2}$	From Roberts (1977, and 1989)
$C_{T7} = 1.7$	$C_{T7} l_b'$	From Roberts (1977)
$C_{T8} = 1.7$	$C_{T8} l_b'$	From Roberts (1977)

Table 4.8 Module Constants

Coefficient	Value	Data Source, Summary Reference, or Comment
T_{11}, T_{18}	2.7	From Holley and Jirka (1986)
S_{11}, S_{13}, S_{14}, S_{18}	0.58	"
B_{11}, B_{13}, B_{14}, B_{18}	0.13	"
TT_{11}	0.20	"
T_{12}	2.3	From Doneker and Jirka (1990)
S_{12}	0.18	"
B_{12}	0.11	"
S_{13A}	0.011	"
T_{16}	1.6	"
S_{16}	0.30	"
B_{16}	0.25	"
T_{21}	0.36	From Holley and Jirka (1986)
S_{21}	0.54	"
B_{21}, B_{24}	0.15	"
TT_{21A}	2.5	"
TT_{21B}	0.79	"
TT_{21C}	2.0	"
T_{22}	0.25	From Davidson (1989)
S_{22}	1.16	From Doneker and Jirka (1990)
B_{22}	0.60	"
S_{24}	0.27	From Holley and Jirka (1986)
B_{38A}, B_{38B}	0.15	Doneker and Jirka (1990)

Table 4.8 (Continued)

Coefficient	Value	Data Source, Summary Reference, or Comment
S_{43}	0.25	From Jirka (1982)
S_{43A}	0.64	"
CD_{43}	0.8	From Simpson (1982), and Jirka and Arita (1987)
CD_{44}	1.2	"
S_{50}	0.58	From Holley and Jirka (1986)
T_{50}	1.0	From Brocard (1977), and Stolzenbach et. al (1976)
B_{50}	0.21	From Brocard (1977), and Stolzenbach et. al (1976)
TT_{50}	0.48	"
BB_{50}	0.25	"
F_{c50u}	2.5	"
F_{c50s}	1.5	"
$SNBR_{70}$	3.22	After Lee (1984)
S_{74}	0.50	From Lee (1981), and Stolzenbach & Almquist (1981)
B_{74}, B_{79}	0.15	From Holley and Jirka (1986)
S_{75}	0.67	From Jirka (1982)
S_{75A}	2.23	"

The rest of the constants for MOD232, MOD234, MOD236, MOD237, MOD241, MOD242, MOD261, and MOD262, are identical to MOD32, MOD34, MOD36, MOD37, MOD41, MOD42, MOD61, and MOD62, presented by Doneker and Jirka (1990) respectively.

Table 4.9 Coefficients In Transition Rules

Coefficient	Value	Data Source, Summary Reference, or Comment
T_{C1}	2.0	From Holley and Jirka (1986)
T_{C2}	2.6	From Wright (1977), List (1982), Wong (1982), and Holley and Jirka (1986)
T_{C3}	2.0	"
T_{C10}	2.4	"
T_{C12}	2.3	From Holley and Jirka (1986)
T_{C12B}	2.0	"
T_{C13}	2.3	From Wright (1977), List (1982), Wong (1982), and Holley and Jirka (1986)
T_{C13B}	2.0	
T_{C13P}	10.0	
T_{C14}	2.3	From Roberts (1989)
T_{C16}	1.7	"
T_{C21}	0.5	From Jirka (1982)
T_{C31u}	2.0	"
T_{C31s}	0.65	"
T_{C32u}	1.55	"
T_{C32s}	0.4	"
T_{C43}	2.5	From Holley and Jirka (1986)
T_{C45}	5.0	From Wright (1977), List (1982), Wong (1982), and Holley and Jirka (1986)
T_{C51}	3.0	"

Chapter V

System Validation and Application

5.1 Comparison with Laboratory and Field Data

In this section the predictions of CORMIX2 will be compared with laboratory and field data. This section is not meant to be an exhaustive validation of all possible CORMIX2 flow classes and associated predictions, but rather to test the key CORMIX2 modules that are common to many flow protocols (flow classes) and to illustrate the flexibility of the system in handling complex environment and discharge conditions.

While CORMIX2 can accommodate many possible flow configurations, actual available laboratory or field data are quite limited. In Section 5.1.1 comparisons are made with data for diffusers discharging in deep receiving water in the absence of any boundary effects. Section 5.1.2 addresses flows related to diffusers discharging in shallow receiving water in which different forms of boundary interaction processes play a significant role.

In all of the comparisons shown below the numerical constants and coefficient values have been consistently set to the values summarized in Chapter IV.

To facilitate comparison with the non-dimensionalization that is frequently used in the available literature the following parameters are introduced:

Densimetric Froude Number based on port diameter

$$F_o = u_o/(g'_o D)^{1/2} \qquad (5.1)$$

Densimetric Froude Number based on slot width

$$F_{ro} = u_o/(g'_o B)^{1/2} = (l_M/l_q)^{3/4} \qquad (5.2)$$

Jet/Crossflow Ratio

$$R = u_o/u_a = (l_m/l_q)^{1/2} \qquad (5.3)$$

5.1.1 Diffuser Discharges in Deep Receiving Water

This sub-section presents analyses of near-field flows, starting with buoyant multiport diffuser in a stagnant uniform ambient, followed by positively and negatively buoyant multiport diffuser in uniform co-flowing currents, and, finally, flows in stratified stagnant ambient. To validate these buoyant jet near-field flows, CORMIX2 predictions are compared with laboratory data from Cederwall (1963), Davidson (1989), Isaacson et. al. (1983), and Tong and Stolzenbach (1979).

5.1.1.1 Unstratified Ambient

5.1.1.1.1 Stagnant Ambient

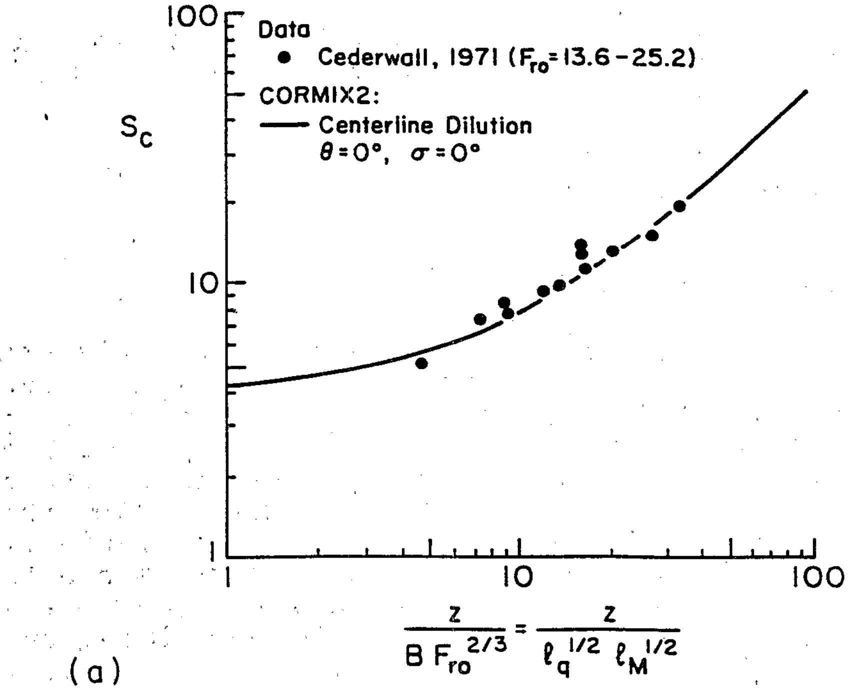
Figure 5.1a and 5.1b show one case of Cederwall's (1963) centerline dilution and trajectory data, adapted from Davidson (1989), for a two-dimensional (slot) buoyant jet in a stagnant uniform ambient water compared with CORMIX2 projections. The buoyant jets were discharged horizontally (θ = 0°) into a uniform ambient density tank. For this stagnant environment (for which l_m tends to infinity) CORMIX2 classifies the flow as MU1V (mdnf, bd-v), since the flow is hydrodynamically stable (previously discussed in Chapter II). Figure 5.1a shows Cederwall's two-dimensional buoyant jet dilution data plotted against the vertical z-coordinate (normalized by both the slot width B and the densimetric Froude number based on slot width F_{ro}). Figure 5.1b shows the corresponding trajectory data (both x- and z-coordinates normalized by both the slot width B and the densimetric Froude number based on slot width F_{ro}). Note that $l_M = BF_{ro}^{4/3}$ is indeed the appropriate normalization length. The flow travels horizontally at first, after some distance the buoyancy force deflects the flow vertically. For this stagnant condition the predicted dilution and trajectory seem to be in excellent agreement with the observed plume data.

5.1.1.1.2 Co-Flowing Ambient

Figure 5.2 and 5.3 show the trajectory data from an experiment of Davidson (1989) for a multiport buoyant discharge in a co-flowing unstratified ambient (θ = 0°, and σ = 0°) with velocity ratio R = 5 and R = 8.33 ($R = u_o/u_a$), respectively. The experiment with R = 5 (Figure 5.2) possesses more discharge momentum (F_o = 8.3) than the one with R = 8.33 (F_o = 5.6) (Figure 5.3). Here CORMIX2 (flow class MU1H, mdnf, bd-h) predicts a slightly stronger deflected plume than shown by the experimental data.

Note that this comparison is only valid for the particular diffuser spacing to port diameter ratio (s/D = 27.3) as used in Davidson's experiment.

Furthermore, it must be stressed that in Davidson's experiments the diffuser nozzles were well elevated above the bottom (h_o/D = 83.33) so that the diffuser plume was able to rise away from the bottom and ambient flow could



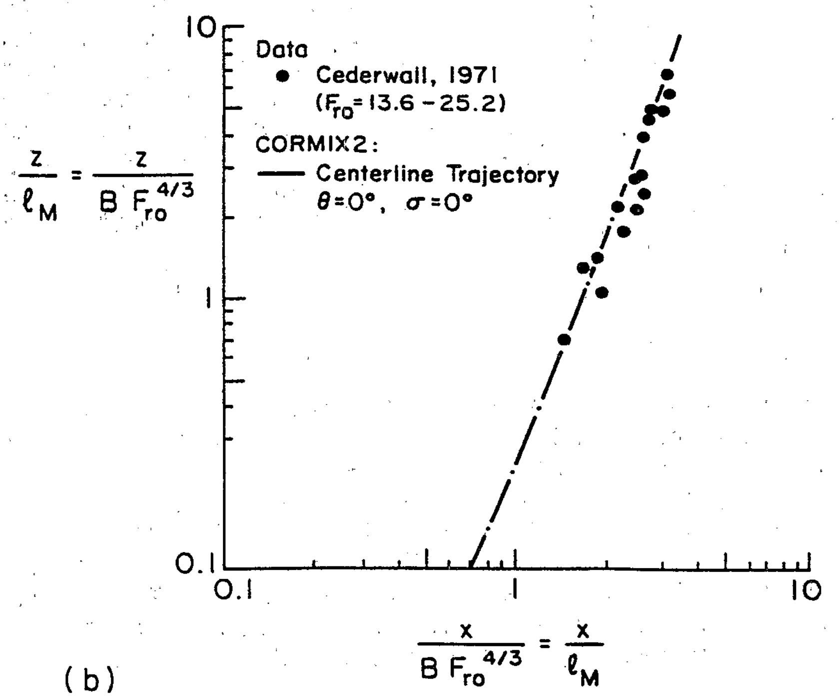


Figure 5.1 Horizontal Buoyant Two-Dimensional Jet in Stagnant Ambient: (a) Dilution and (b) Trajectory

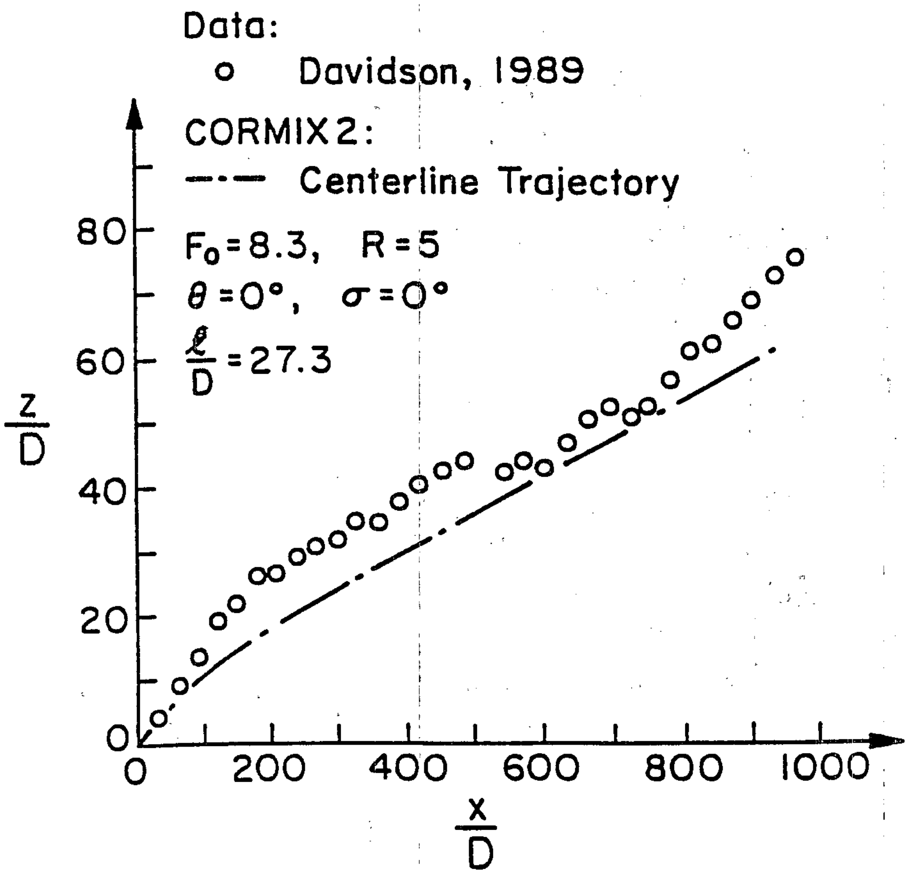


Figure 5.2 Horizontal Multiport Buoyant Jet Trajectory in a Co-Flowing Ambient (Relative Spacing s/D = 27.3)

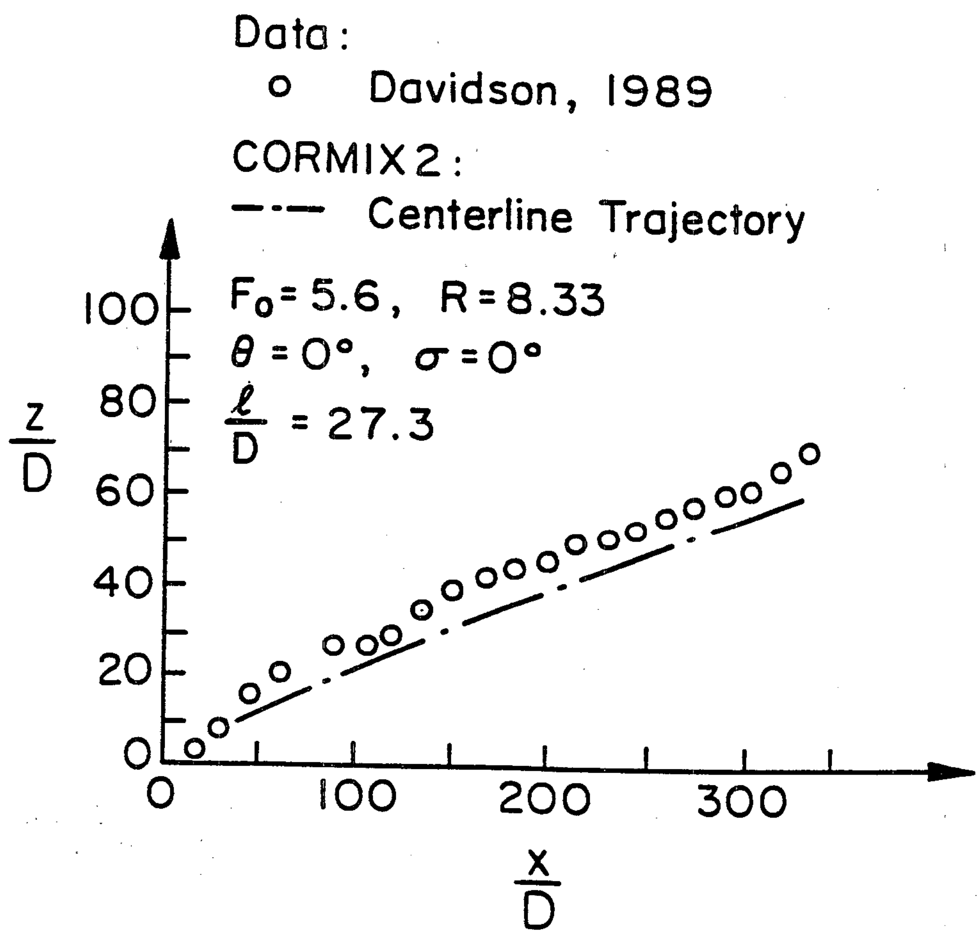


Figure 5.3 Horizontal Multiport Buoyant Jet Trajectory in a Co-Flowing Ambient (Relative Spacing s/D = 27.3)

pass below the plume. For lesser elevations the diffuser plume could stay trapped to the bottom and CORMIX2 (see criterion C_7) would predict such attachment (leading to a flow class MNU2).

CORMIX2 assumes Gaussian distribution profiles for velocity and concentration. In Davidson's experiment, the concentration profiles show considerable irregularity which may explain some disagreement in the trajectories. Other explanations are related to the exact method of determining the centerline position, experimental setup, and unsteadiness of the flow.

Figure 5.4 shows the dilution data for two different experiments by Davidson (1989), each having a different R and F_o. Both dilution and the vertical z-coordinate are normalized as shown in the figure. Note that s/D is fixed and equal to 27.3 as in the previous figures. CORMIX2 somewhat underpredicts the centerline dilution. Again, this disagreement is related to the method of determining the centerline position, and to the assumption of having a Gaussian concentration profile.

5.1.1.1.3 Negatively Buoyant Discharges

Figure 5.5 shows the centerline trajectory and plume boundaries of an experiment by Tong and Stolzenbach (1979) for a negatively buoyant unidirectional diffuser discharging vertically (θ = 90°) into a co-flowing crossflow (σ = 0°, and γ = 90°) with R = 9.36. In this case CORMIX2 predicts an MNU2 (mdnf, mdff, bd-h, bottom approach) flow class with numerical results that are in good agreement with the visually observed plume boundaries (the dilution predicted by CORMIX2 at different locations agree with the experimental ones), however, the flow becomes attached at a distance greater than the observed one. This difference is due to the initial three dimensional flow of the individual diffuser jets near the discharge location. This aspect can be better predicted by using CORMIX1 (using same nozzle diameter and spacing length as channel width).

5.1.1.2 Stratified Stagnant Ambient

Laboratory measurements on a multiport diffuser discharging into a stratified ambient were performed by Isaacson (1983). The data presented in Table 5.1 is for a hydraulic model study of a sanitary wastewater diffuser discharge into the ocean under dry weather flow conditions. An alternating diffuser with three nozzles per riser discharging into a stratified crossflowing ambient current (γ = 90°) was used in the model. The ocean density profiles for the dry weather case were fitted by a type D (see Figure

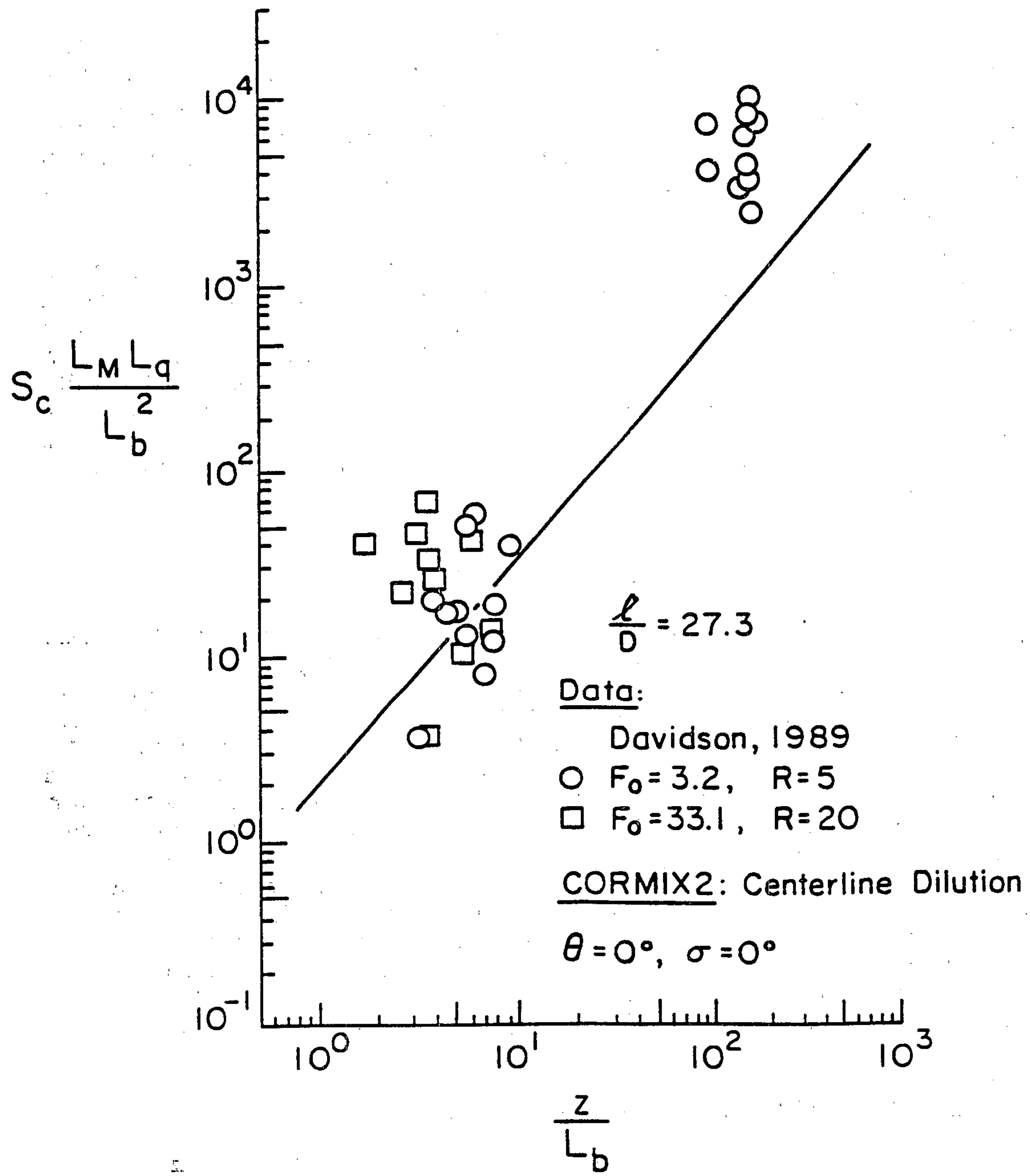


Figure 5.4 Dilution for Buoyant Multiport Discharge in a Co-Flowing Ambient (Relative Spacing s/D = 27.3)

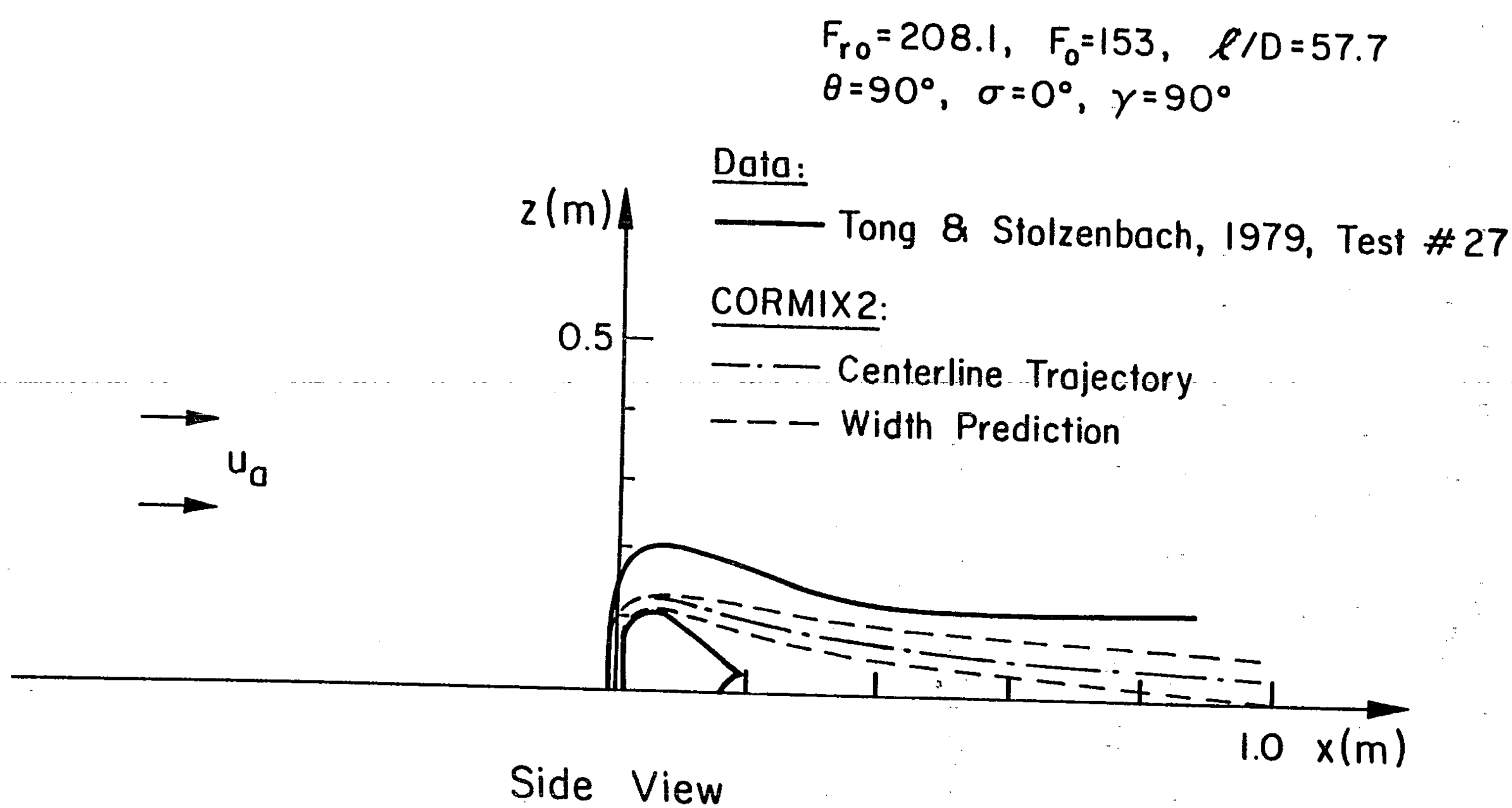


Figure 5.5 Negatively Buoyant Multiport Diffuser Discharging Vertically Upward in a Co-Flowing Uniform Ambient

Table 5.1 Comparison Between Laboratory Test Results (Isaason et. al., 1983) and CORMIX2

D_o (cm)	s (m)	H (m)	q_o (m^2/s)	Test #	S_m (1)	S_a (2)	S_p (3)
8.2	10.97	22.86	0.0052	DW-1	103	105	106.8
8.2	10.97	22.86	0.0092	DW-5	68	80	86.9

(1) S_m = Measured minimum dilution.

(2) S_a = Measured average dilution.

(3) S_p = CORMIX2 centerline dilution.

2.1) profile. In both dry weather cases (DW-1 and DW-5), CORMIX2 predicts an MS7 (bd-v, terminal layer impingement with upstream spreading) flow class with numerical results that are in good agreement (7%-14% difference) with the average and minimum measured dilution. The comparison between the minimum dilution predicted by CORMIX2 and the measured average and minimum dilutions as reported by Isaacson is given in Table 5.1. Although details (e.g. height of terminal levels) on these model results are not reported, the comparison give good support to CORMIX2.

5.1.2 Diffuser Discharges in Shallow Receiving Water

This section is intended to illustrate the ability of CORMIX2 to predict flow dynamics of different shallow diffuser types discharging into either a stagnant or a flowing unstratified ambient in the presence of various boundary interaction processes. CORMIX2 predictions are compared with experimental data from Brocard (1977), Jirka (1973), Roberts (1977), and Stolzenbach et. al. (1976).

5.1.2.1 Unidirectional Diffuser

Figures 5.6 and 5.7 present surface isotherms for hydraulic model results from the experimental study of Stolzenbach et. al. (1976) for the thermal diffuser discharge from the Cayuga Station located at the Somerset site. Figure 5.6 (Run #31) shows a positively buoyant unidirectional diffuser discharging into a stagnant ambient ($\theta = 0°$, $\sigma = 90°$, and $\gamma = 0°$), and Figure 5.7 (Run #35) a positively buoyant unidirectional diffuser discharging into a predominantly crossflowing ambient ($\theta = 0°$, $\sigma = 120°$, and $\gamma = 30°$). CORMIX2 predicts an unstable (shallow water) flow class MU3 (tee acceleration zone, diffuser plume in cross-flow) for Run #31. For the stagnant case (Figure 5.6) the predicted plume shape is in good agreement with the observed plume surface isotherms. Also the centerline concentrations closely agree with observations. However, CORMIX2 is unable to predict some temperature build-up ("hot spots") at the plume periphery. This is essentially an unsteady phenomenon (probably exaggerated by the limited laboratory basin) and outside the capabilities of CORMIX2.

The experimental data for Run #5 show a slightly smaller deflection than the one indicated by CORMIX2. The centerline concentrations (temperature rises) are in good agreement with the experimental observations for the surface isotherms. Note the far-field region is absent because the ambient is stagnant (see Chapter II). The same flow class (MU3) is obtained for Run #35 but with the additional presence of the far-field region.

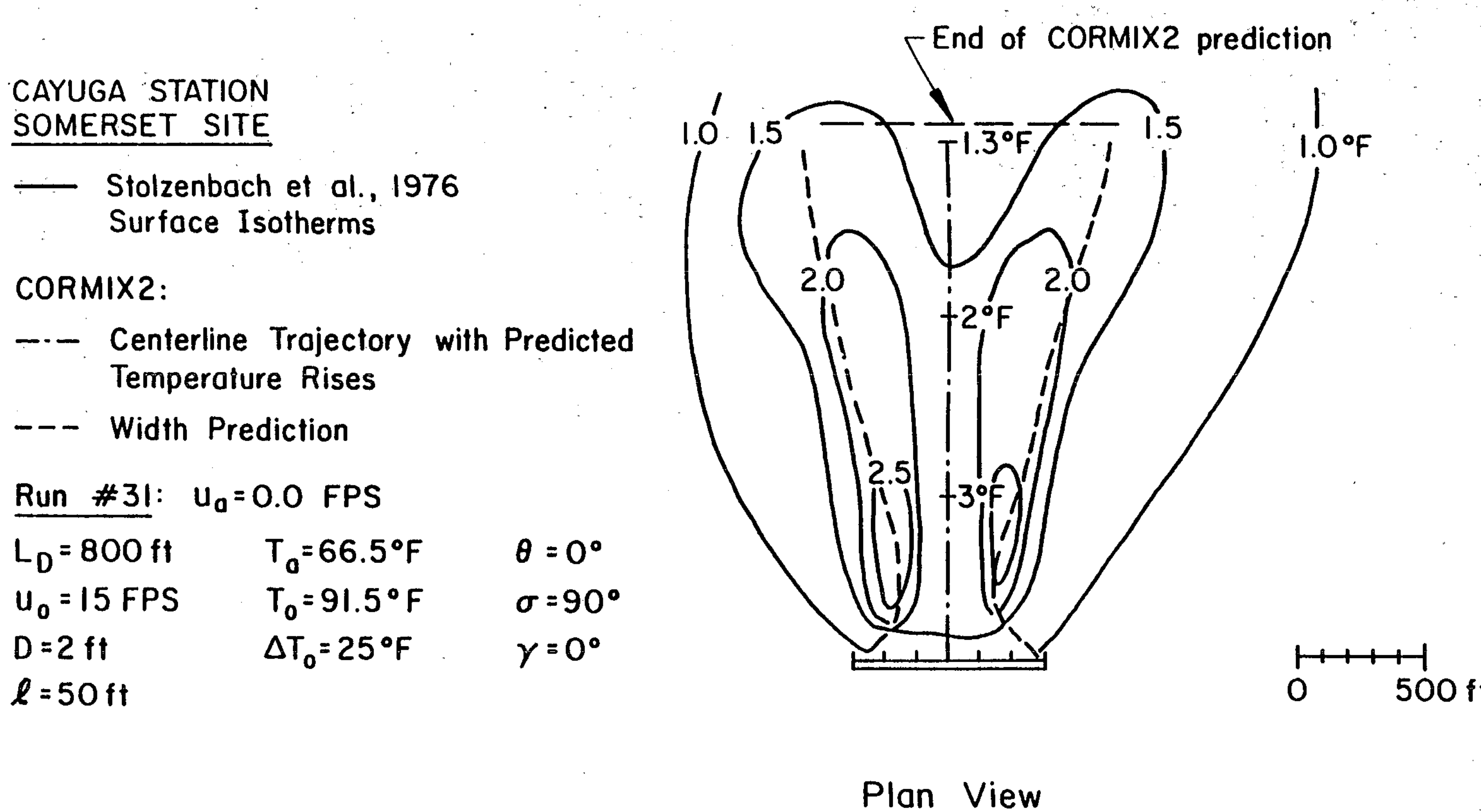


Figure 5.6 Unidirectional Diffuser Discharging in a Stagnant Shallow Ambient

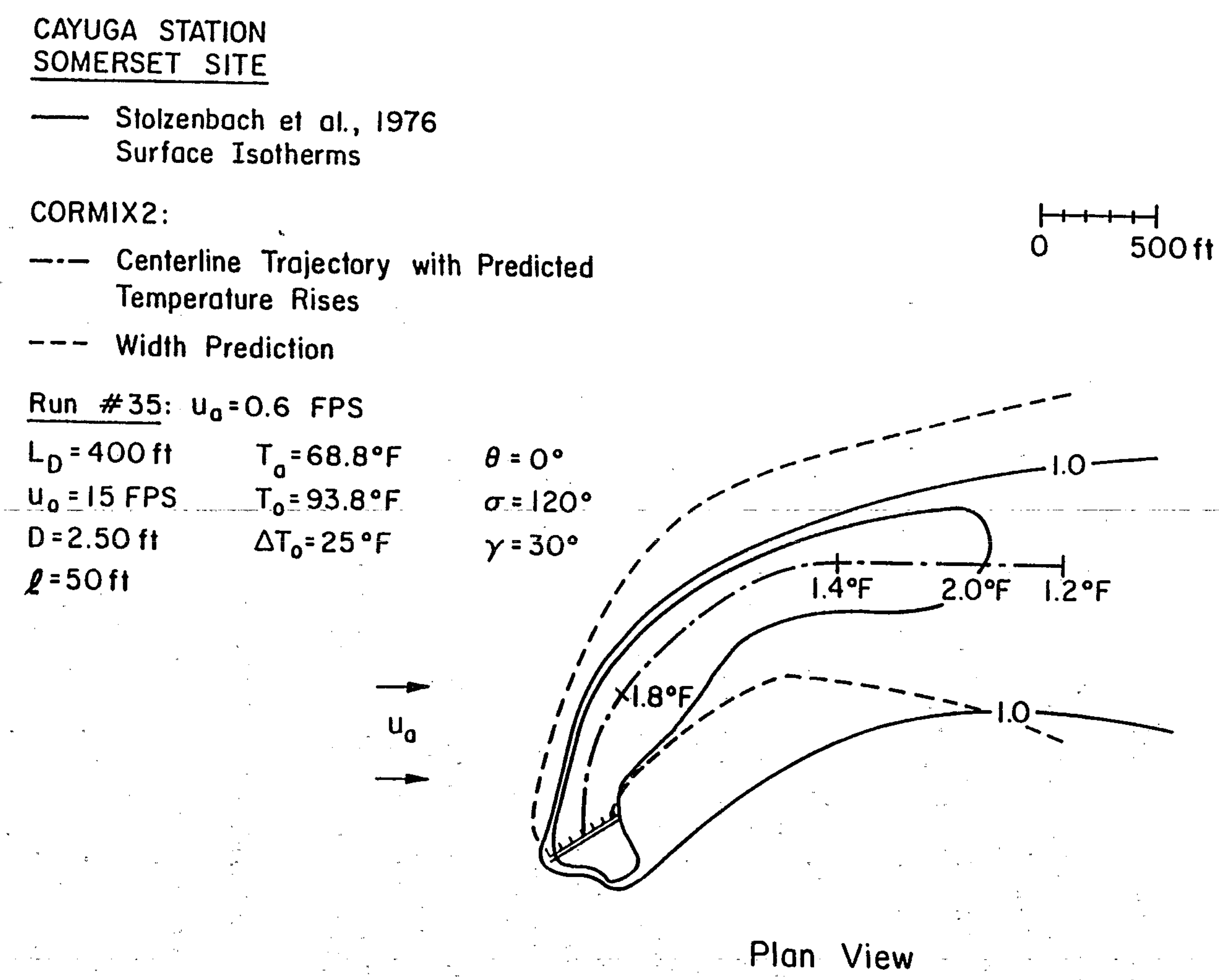


Figure 5.7 Unidirectional Diffuser Discharging in Shallow Ambient with Crossflow

Once an ambient crossflow is present (Figure 5.7) the unsteady build-up zones are prevented and CORMIX2 predictions are in good agreement with the isotherm observations.

5.1.2.2 Staged Diffuser

Figures 5.8 and 5.9 present surface isotherms from the laboratory model of Brocard et. al. (1977) for the thermal diffuser discharge at the Charlestown site. Figure 5.8 (Test #5) shows a positively buoyant staged diffuser discharging into a stagnant ambient (θ = 20°, σ = 90°, and γ = 90°), and Figure 5.9 (Test #6) a similar diffuser discharging into a crossflow ambient (θ = 20°, σ = 90°, and γ = 90°).

CORMIX2 predicts a shallow water flow class MU5 (staged acceleration zone, diffuser plume in cross-flow) for Test #5 (Figure 5.8). Again, unsteady recirculation effects are present in the laboratory data (limited basin size) for the stagnant case. If those effects are excluded, the near- and intermediate field predictions of CORMIX2 give satisfactory results. The same flow class (MU5) is obtained for Test #6, with the additional presence of the far-field zone. As for the staged diffuser in the presence of crossflow, a much better agreement with predictions is obtained due to the minimization of unsteady and/or boundary effects.

Figure 5.10 shows another staged diffuser in a shallow crossflowing ambient (θ = 0°, σ = 90°, and γ = 90°) for the model study of Stolzenbach et al. (1976). Agreement appears satisfactory even though some recirculation may be present in this somewhat weak crossflow situation.

5.1.2.3 Alternating Diffuser

Figure 5.11a and 5.11b show surface isotherms from the study by Jirka and Harleman (1973) for an alternating diffuser (θ = 45°) in a perpendicular (γ = 90°) unstratified crossflow (Run #BC-3) and an alternating diffuser (θ = 45°) into a parallel (γ = 0°) unstratified crossflow (Run #BC-13). For Run #BC-3 (Figure 5.11a), CORMIX2 predicts an unstable flow class MU8 with a buoyant upstream intrusion. The plume shape and extent of upstream intrusion is in good agreement with the experiment. For Run #BC-13, CORMIX2 predicts an unstable flow class MU9 with upstream intrusion. Once again, good agreement in plume shape , intrusion distance, and dilution values is evident.

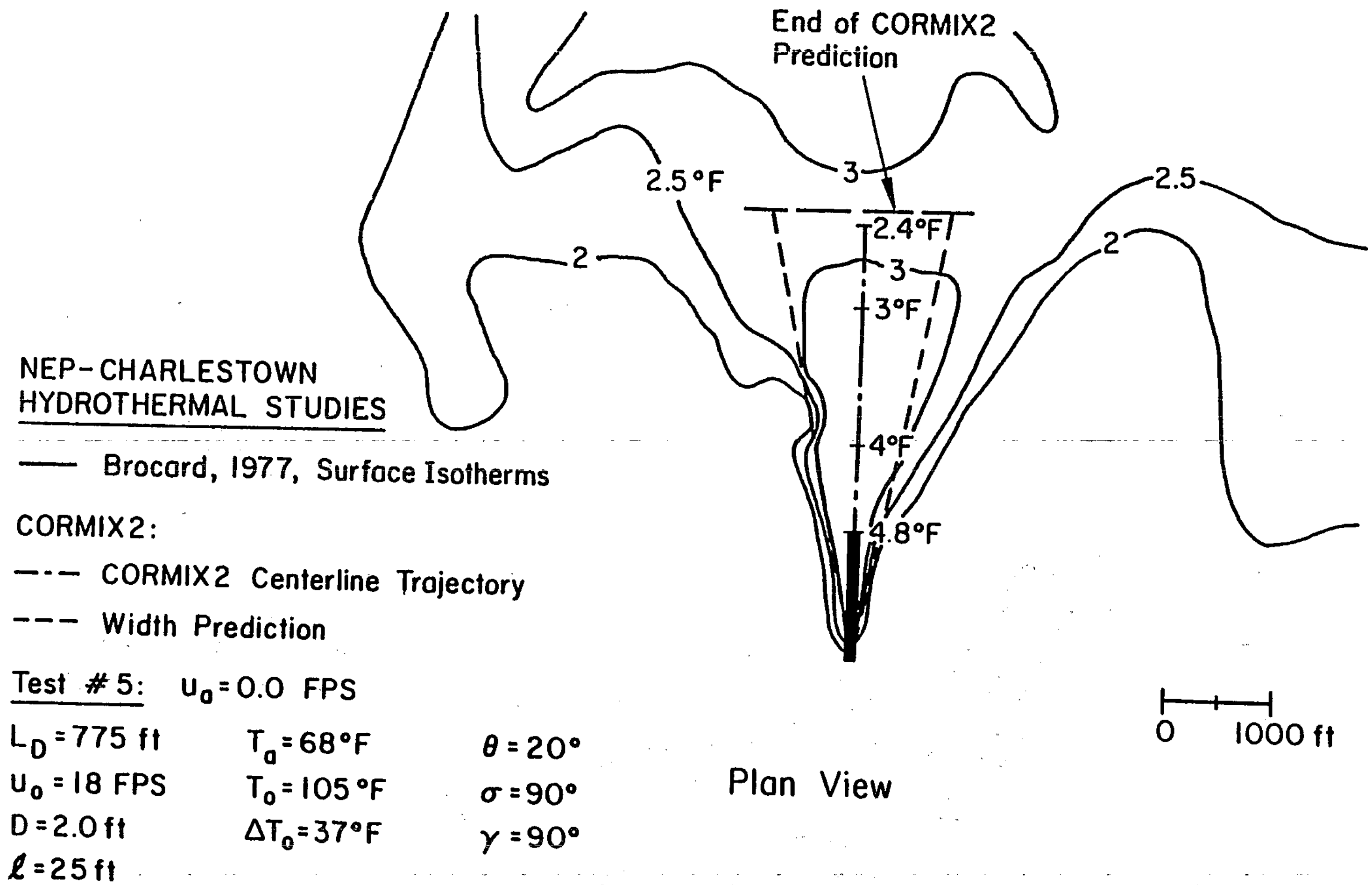


Figure 5.8 Staged Diffuser Discharging in a Stagnant Shallow Ambient

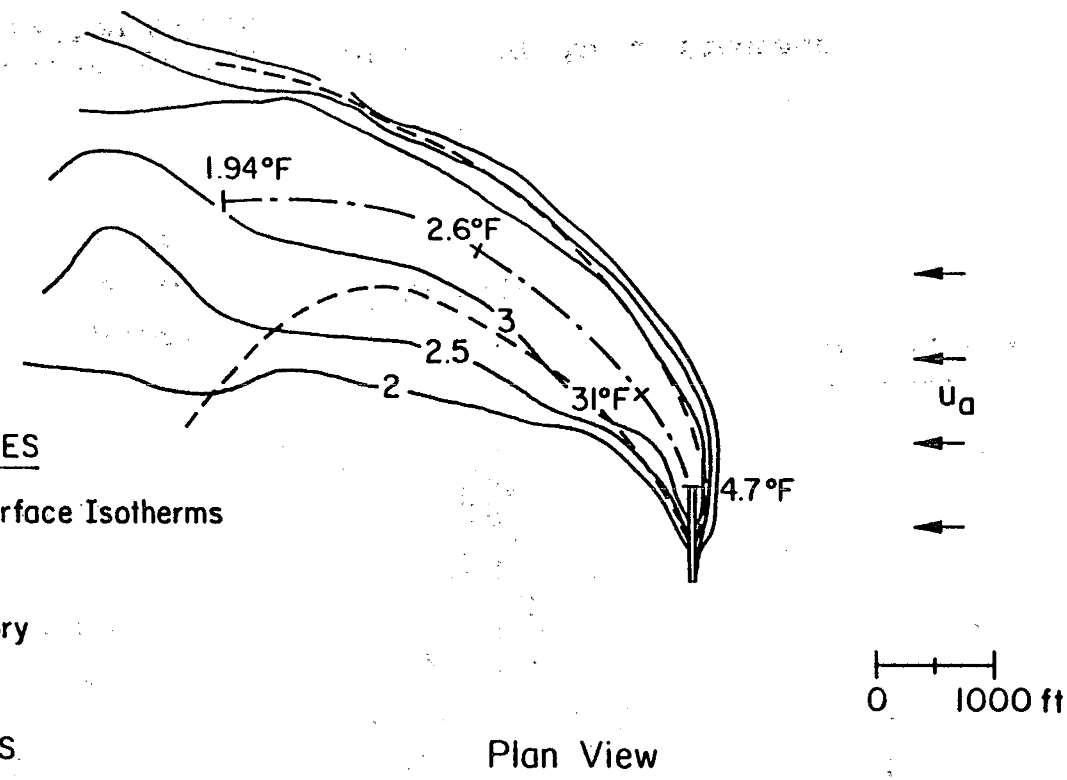


Figure 5.9 Staged Diffuser Discharging in a Cross-Flowing Shallow Ambient

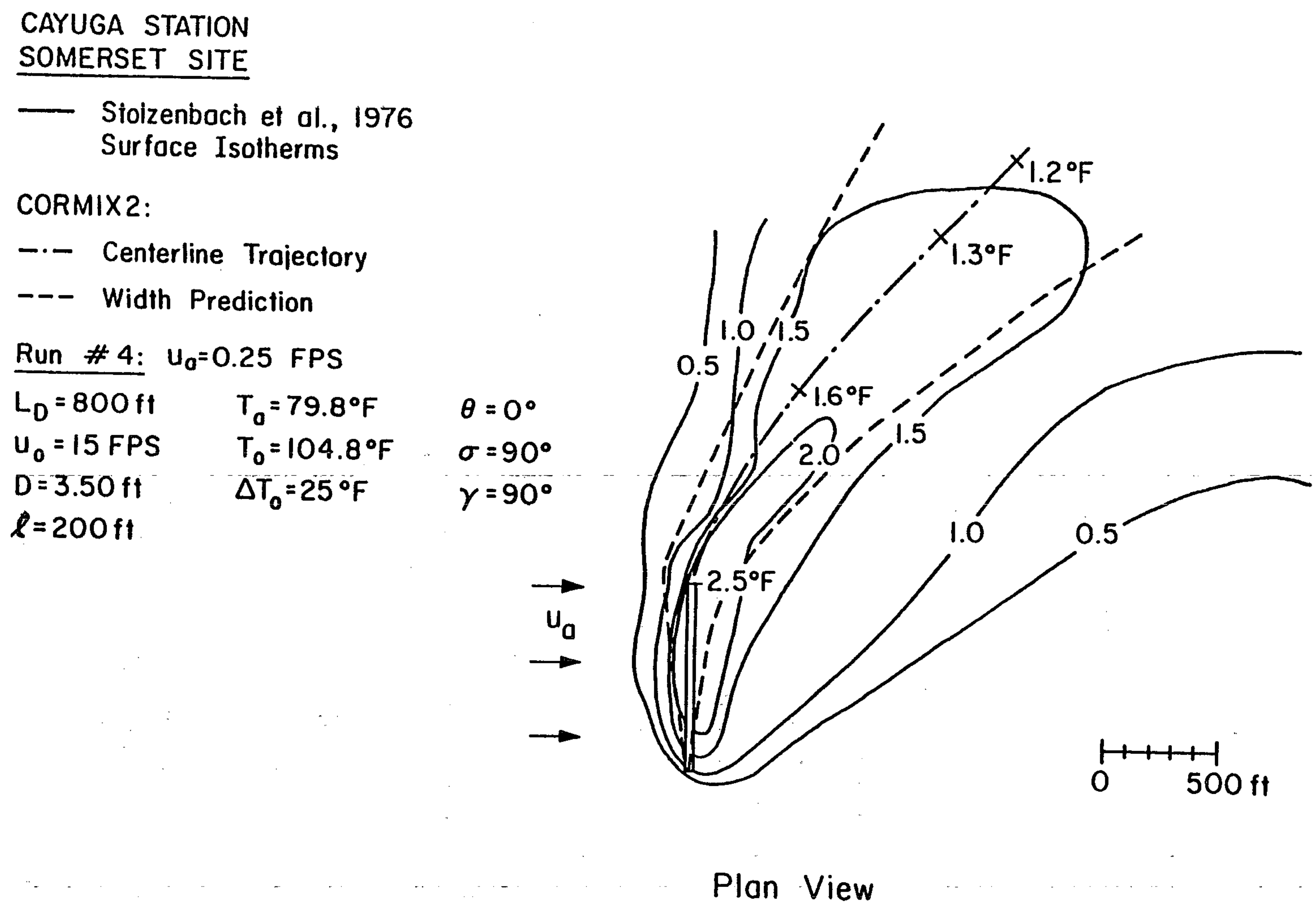
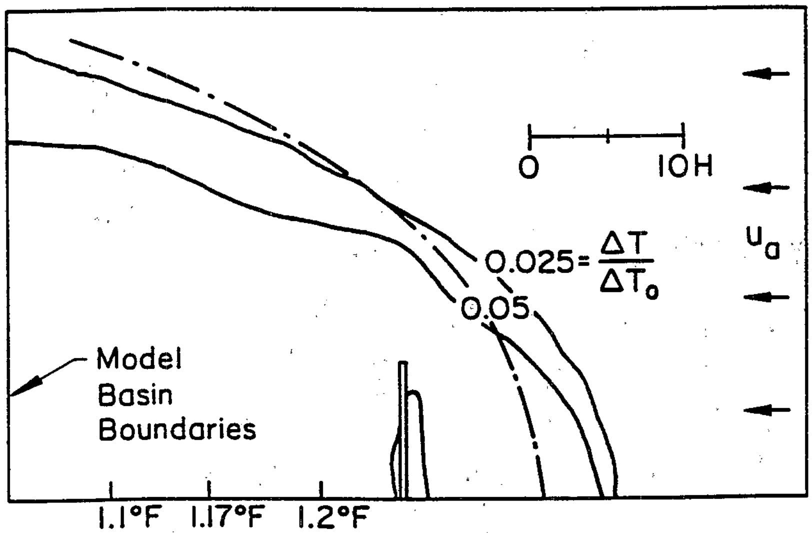


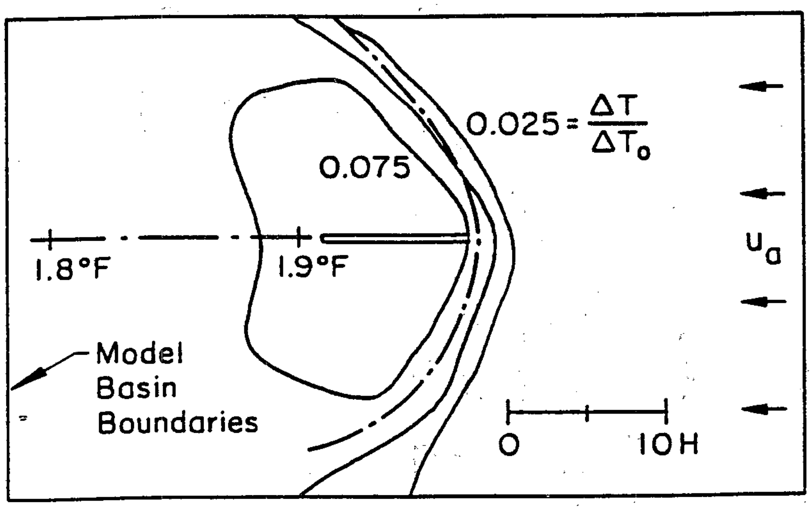
Figure 5.10 Staged Diffuser Discharging in a Cross-Flowing Shallow Ambient

(a)



—— Jirka, 1973 Isotherms, Run # BC-3
—·— CORMIX2 Width
$\theta = 45°$, $\gamma = 90°$

(b)



—— Jirka, 1973 Isotherms, Run # BC-13
—·— CORMIX2 Front Prediction
$\theta = 45°$, $\gamma = 0°$

Figure 5.11 Surface Plume from Buoyant Alternating Diffuser Discharging a) Perpendicular and b) Parallel Alignment

Another comparison can be made with the experimental data of Roberts (1977) for a situation in which the flow is hydrodynamically stable (deep water). The objective here is to test once again the prediction of CORMIX2 for upstream intrusion and surface spreading. Figure 5.12 shows a photograph of a surface plume generated by an alternating diffuser discharging into a crossflowing ($F = u_a^3/j_o \simeq 0.1$, $\gamma = 90°$) unstratified ambient. CORMIX2 assigned an MU1V flow class with an upstream intrusion of 0.16 m with a half-width of 0.42 m at surface impingement. The photograph shows an upstream intrusion of 0.22 m and a half-width of 0.47 m at surface impingement. CORMIX2 overpredicts the surface spreading for the same reasons as before.

As mentioned earlier, laboratory experiments are always conducted in model basins of limited size and the somewhat weaker frontal spreading observed by Jirka and Harleman (1973) and Roberts (1977) than that predicted by CORMIX2 is, in part, related to boundary effects in the model studies.

5.1.3 Summary and Appraisal

Despite the limited availability of laboratory and field data for the wide range of discharge/ambient characteristics that is embodied in the 32 flow classes (and their additional sub-classes) contained in CORMIX2, the preceding comparison indicates satisfactory system performance under quite diverse conditions. Thus CORMIX2 has been demonstrated to have adequate flexibility and accuracy in predicting diffuser discharging under deep water conditions, in ambient stratification, in shallow fully mixed environments and with negative discharge buoyancy. For additional comments on data/system comparisons see Doneker and Jirka (1989).

5.2 Application: Case Studies

The purpose of this section is to give an overview of the significant features of CORMIX2 in discharge mixing zone evaluation and design, and to illustrate the flexibility of CORMIX2 in highly divergent design conditions. The first case presented represents a hypothetical example of a discharge from a small municipal treatment plant into the ocean illustrating the effects of density stratification, and the second example is a discharge from a power plant discharging heated effluent into a large lake under varying ambient currents.

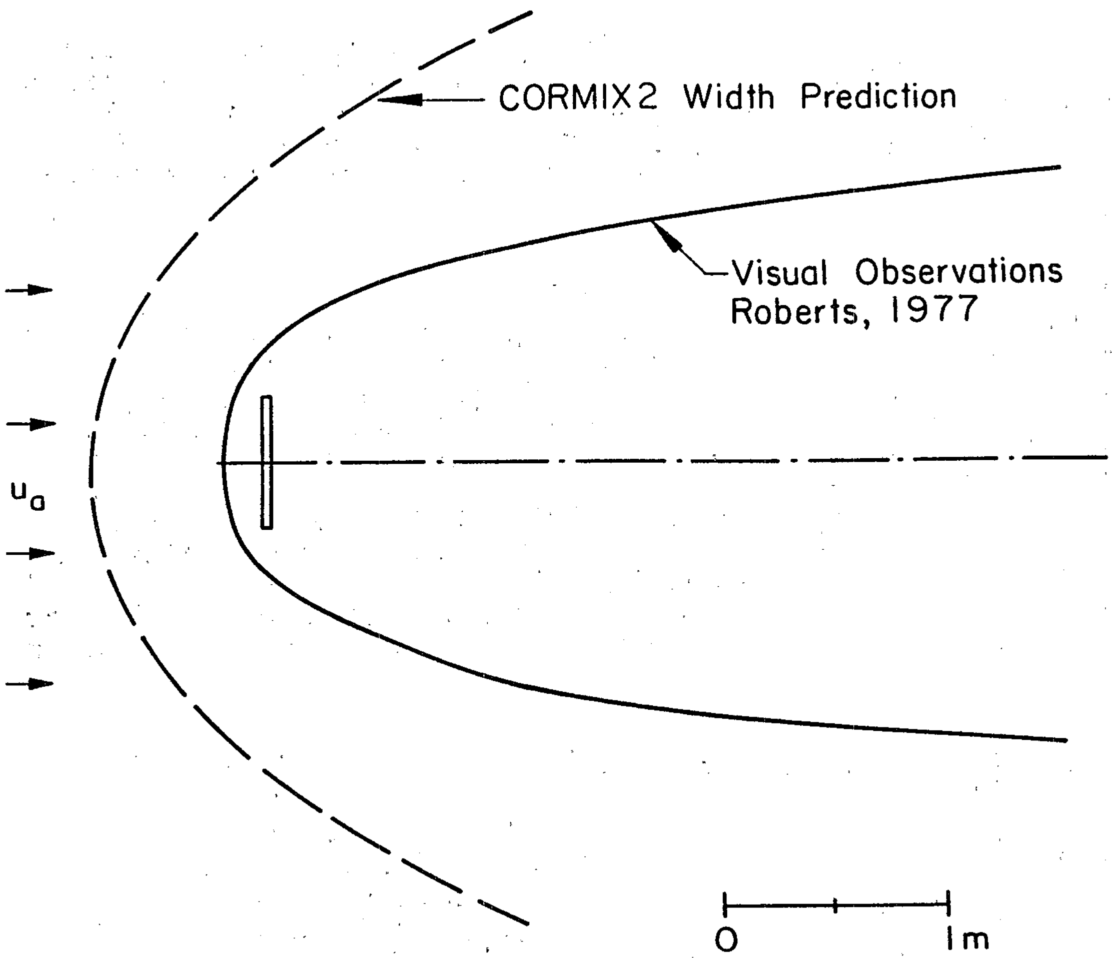


Figure 5.12 Buoyant Alternating Diffuser in Perpendicular Crossflow: Plan View of Surface Fronts

5.2.1 AAA Municipal Treatment Plant

This example will illustrate the effect of ambient density stratification in a coastal environment on the mixing of a buoyant effluent flow containing toxic substances. The discharge is subject to three mixing criteria: a toxic dilution zone, a plume width criteria on a legal mixing zone, and a downstream region of interest. The analyst seeks pollutant concentrations at these locations. The analyst will use CORMIX2 to try to study the effect of typical winter and summer ambient density profiles on the mixing behavior of the discharge.

5.2.1.1 The Problem Statement

The discharge from the AAA municipal treatment plant into coastal waters contains some toxic substances. The mixing characteristics for typical winter and summer profiles are to be considered (see Figure 5.13). The discharge is to be located 3000 m from shore at a local water depth of 24.2 m. The bathymetry is sloping approximately linearly from the shoreline.

A 100 m long unidirectional diffuser is used with 41 ports openings. The ports are round with a diameter of 0.3 m and extend about 0.3 m above the surrounding bottom with a vertical angle θ = 30 . The diffuser is discharging in the direction of the prevailing ambient current (co-flow) (σ = 0°, and γ = 90°) which has a velocity of 0.09 m/s. The total design discharge flowrate is 3.0 m^3/s and contains 100 mg/l of a toxic substance with a CMC of 5 mg/l. The discharge density is 994.0 kg/m^3. A public beach is located 3000 m down-current from the discharge with a legal mixing zone (LMZ) width set at 400 m. The plume characteristics at this distance are of interest.

5.2.1.2 CORMIX2 Analysis

The first step in the analysis would be to choose one of the four ambient stratification types to represent the actual density profiles as seen in Figure 5.13. An ambient profile of Type D is chosen to represent the August data, with surface density ρ_s = 1022.7 kg/m^3, bottom density ρ_b = 1024.9 kg/m^3, and a pycnocline height h_{int} = 12.50 m. The representative cross-section case places the discharge 3000 m from shore in 24.2 m of water. A weak linear ambient density stratification (Type A) is chosen to represent the March data, with surface density ρ_s = 1025.59 kg/m^3 and bottom density ρ_b = 1025.82 kg/m^3.

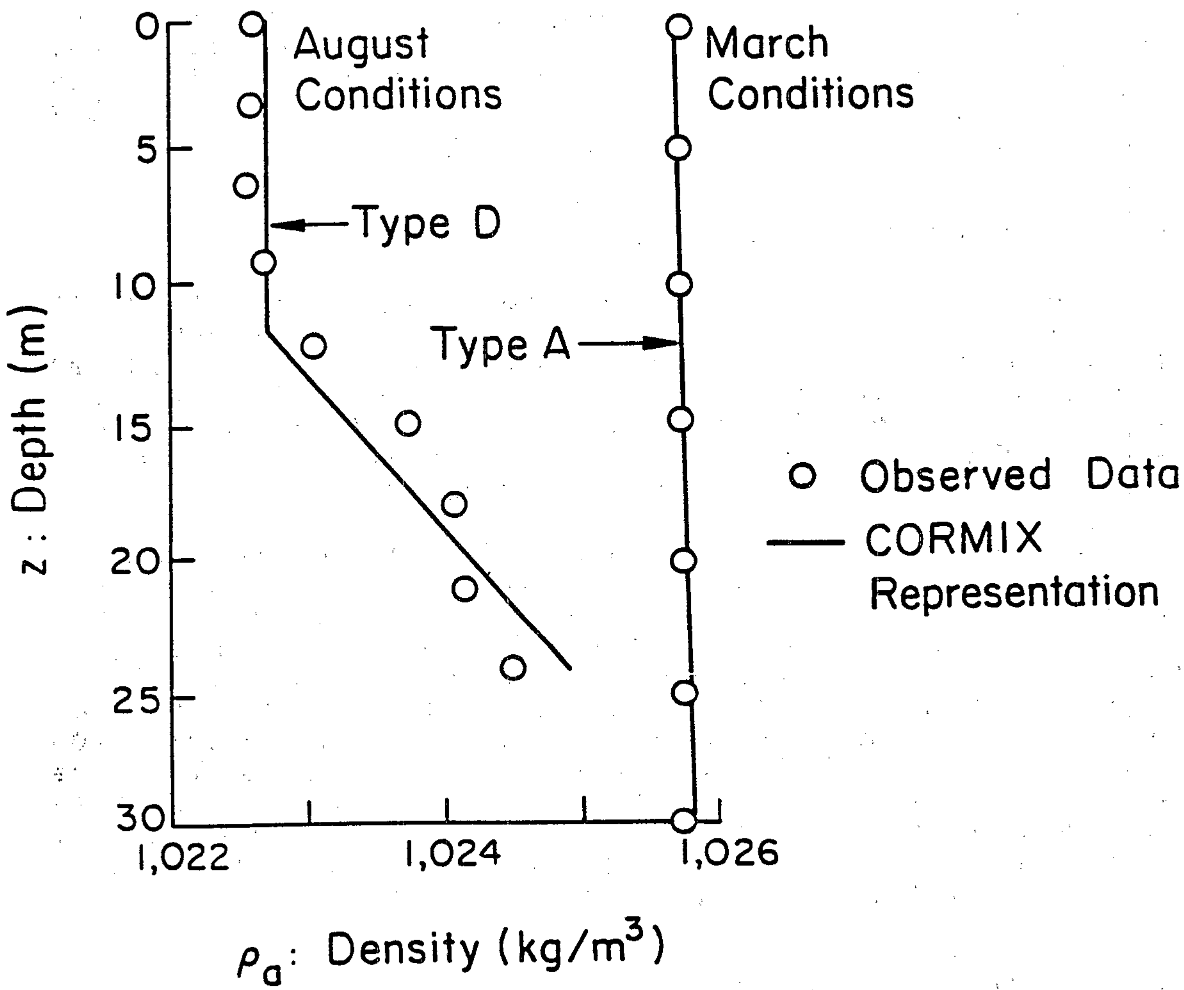


Figure 5.13 AAA Municipal Outfall: Typical Density Profiles in Coastal Ocean

For the August design conditions, CORMIX2 concludes the flow will be confined to the lower stratified layer only of the specified ambient stratification condition D, and assigns a flow class MS8 (mdnf, bd-v, terminal layer impingement with upstream spreading, buoyant spreading, passive diffusion). The simulation results are shown in Figure 5.14 indicating an upstream buoyant intrusion at the terminal height. CORMIX2 indicates an upstream intrusion length of about 176 m. SUM2 notifies the user that both the hydrodynamic mixing zone (HMZ) and the legal mixing zone (LMZ) occurs at x = 188 m downstream from the discharge point with plume centerline z = 9.52 m, dilution value S = 44.6, and the plume half-width b_h and thickness b_v are equal to 353 m and 2.11 m, respectively.

The CMC value occurs at x = 7 m from the discharge point. SUM2 notifies the user on the criteria checked for a TDZ; i) the discharge velocity was not equal to or greater than the minimum value of 3.0 m/s, ii) the downstream distance of the TDZ (1.33 m) did not exceed the maximum distance of 50 times the discharge length scale L_q = 1.73 m, iii) the downstream distance of the TDZ was met within the maximum distance of 5 times the water depth of 24.16 m, and finally iv) the downstream distance of the TDZ was within 10 % of the distance to the LMZ.

At 3000 m from the outfall, the plume dilution S = 51.1 with plume depth b_v = 1.23 m and flow half-width b_h = 681 m.

For the March design conditions, CORMIX2 concludes the linear ambient density stratification is dynamically unimportant and unstable, and a uniform ambient density is set equal to the layer average of 1025.588 kg/m^3. CORMIX2 assigns a flow class MU1V for the full water depth. The simulation results are shown in Figure 5.15 indicating an upstream intrusion at the surface with an intrusion length of about 188 m.

SUM2 notifies the user that both the hydrodynamic mixing zone (HMZ) and the legal mixing zone (LMZ) occurs at x = 266 m downstream from the discharge point with plume centerline at the surface (z = 24.16 m), dilution value S = 556.1, and the plume half-width b_h and thickness b_v are equal to 488 m and 19 m, respectively.

The CMC value occurs at x = 6.9 m from the discharge point.

At 3000 m from the outfall, the plume dilution S = 768, the plume depth b_v = 7.2 m, and the flow half-width b_h = 1775 m, indicating the flow does not contact the shoreline near the public beach.

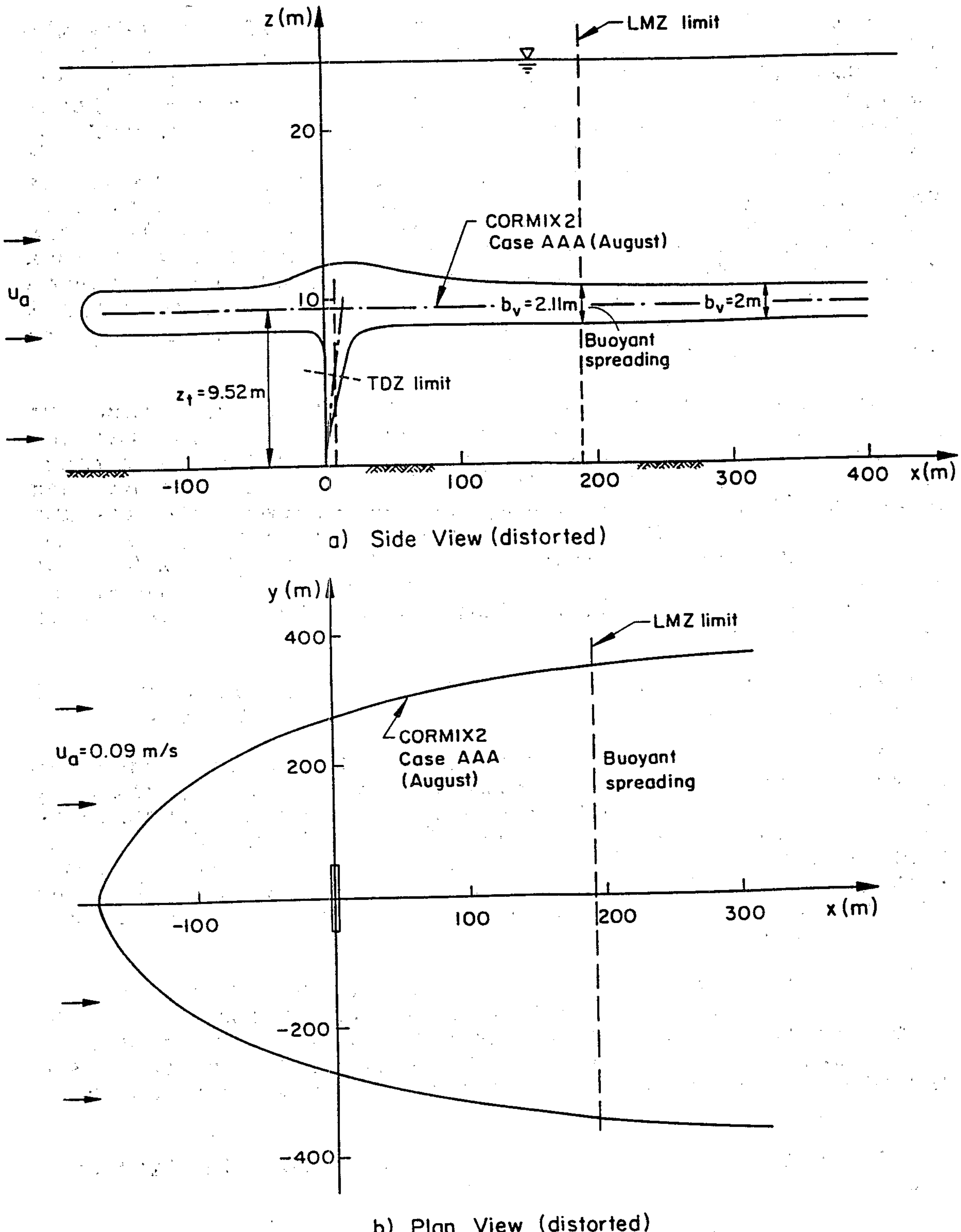


Figure 5.14 AAA Municipal Outfall: August Design Case with Internal Flow Trapping

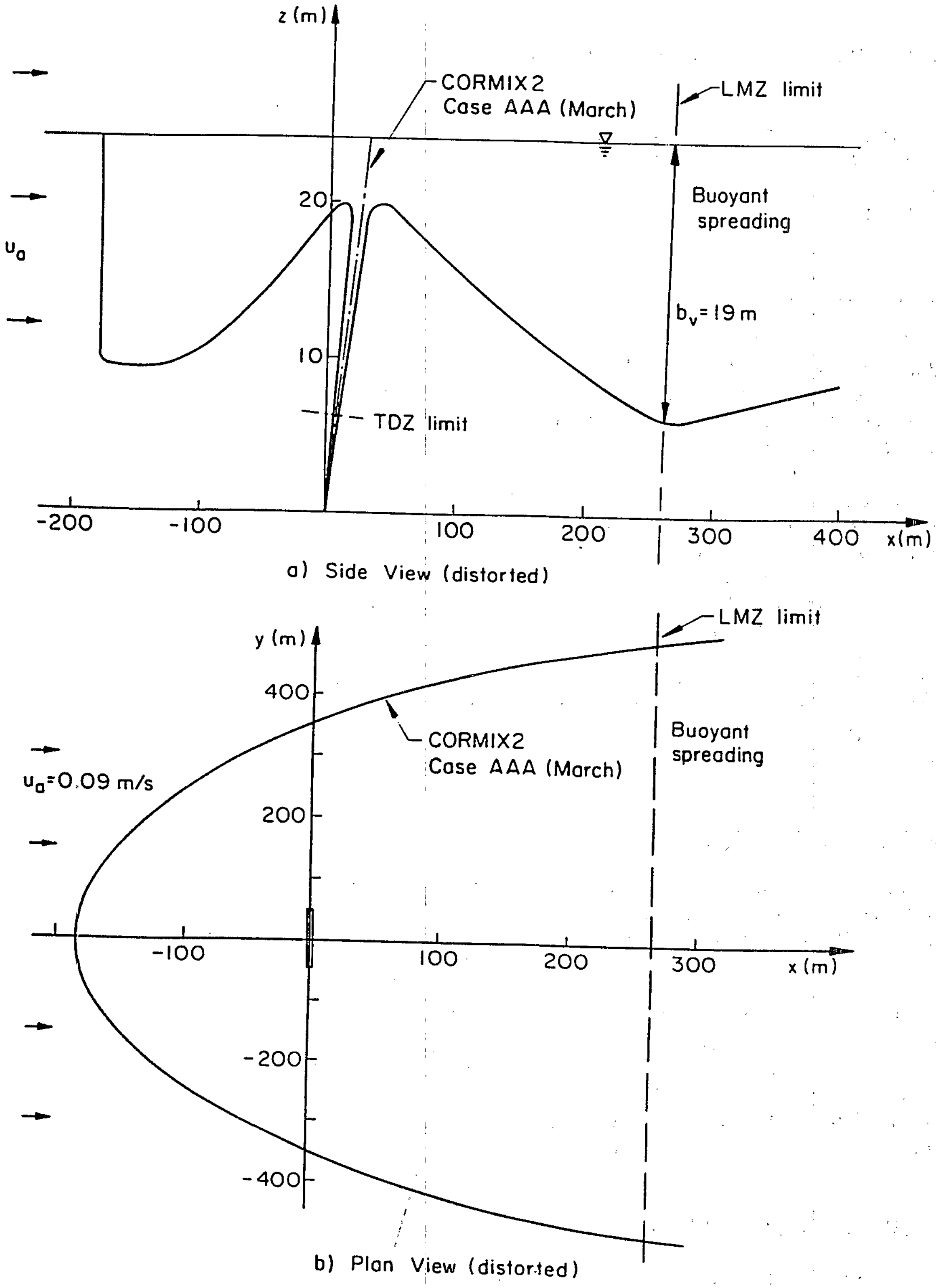


Figure 5.15 AAA Municipal Outfall: March Design Case with Surface Interaction

5.2.2 PPP Electric Power Company

This design example represents a heated discharge effluent into a large lake from an electric power company in relatively shallow water with various ambient currents under a weak ambient stratification. There is no toxic effluent in the discharge.

5.2.2.1 The Problem Statement

The lake is 8000 m wide, and the outfall is located at a distance of 1000 m from the left side of the lake at a local water depth of 10.0 m. Available site data indicate a uniform ambient density profile with an average temperature of 15 C.

A 300 m long staged diffuser is used with 31 ports giving a spacing of 30 m. The ports issue about 0.5 m above the surrounding bottom. The ports are round with a diameter of 0.9 m. The diffuser is discharging horizontally ($\theta = 0°$) and perpendicular to the direction of the prevailing ambient current (cross-flow) ($\sigma = 90°$, and $\gamma = 90°$). The total design discharge flowrate is 30 m^3/s with a design effluent temperature of 35 C. The discharge site is characterized by wind-induced currents varying between 0.03 m/s and 0.15 m/s. The diffuser is subject to a legal mixing zone (LMZ) requirement with a local plume width of 400 m.

5.2.2.2 CORMIX2 Analysis

For the minimum ambient current speed of $u_a = 0.03$ m/s, and the maximum current speed, CORMIX2 assigns flow classes MU5 and MU6, respectively. The simulation results are shown in Figure 5.16 and 5.17 respectively.

When the current is weak, the analysis shows that the legal mixing zone (LMZ) is reached at a distance of about 340 m downstream where the dilution S = 12 with a plume depth $b_v = 1.25$ m. However, with a strong ambient current, the latter occurs within 100 m from the discharge point with a dilution S = 17.1 and plume depth $b_v = 10$ m.

5.3 Additional Comments on CORMIX2

As mentioned in Chapter III it is expected that CORMIX2 will be a general predictive system applicable to the majority (better than 80%) of all multiport diffuser discharge/environmental conditions. It is impossible, however, to devise a system that will analyze all conceivable submerged discharges. For this reason, CORMIX2

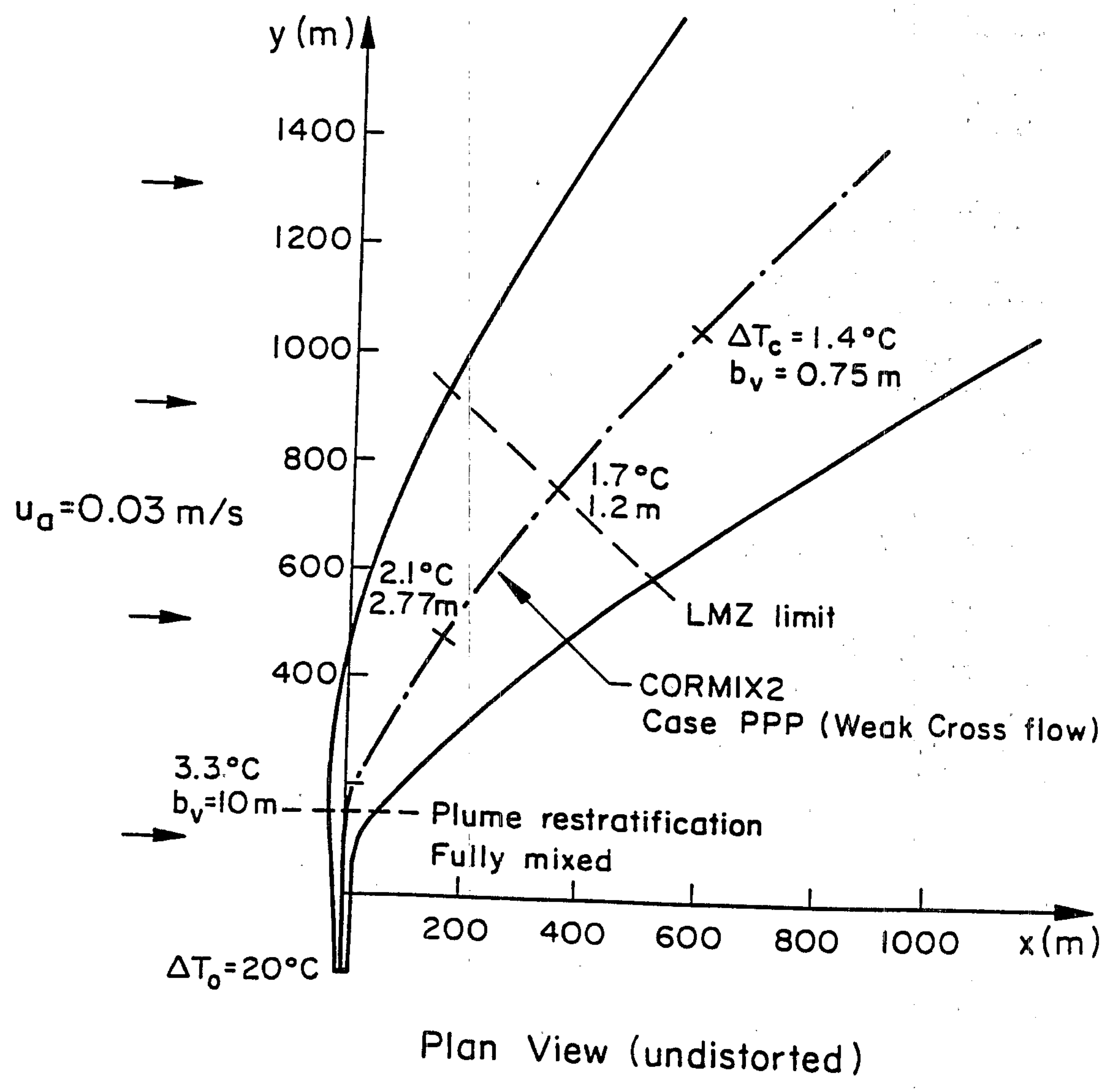


Figure 5.16 PPP Electric Company Outfall in Low Ambient Current

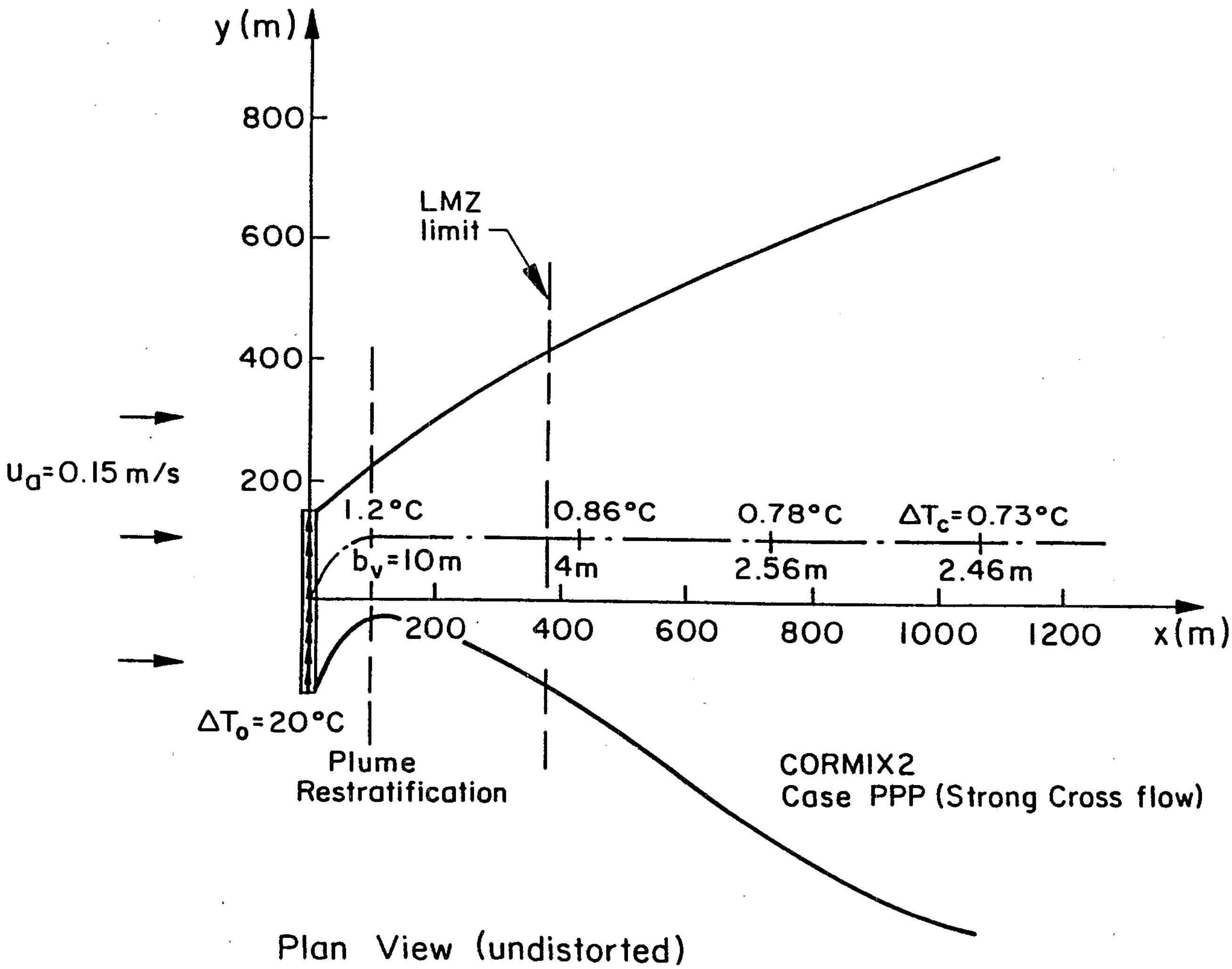


Figure 5.17 PPP Electric Company Outfall in Strong Ambient Current

contains several internal criteria (limitations) designed to avoid system misuse for such extreme conditions.

CORMIX2 is devised for deeply submerged multiport discharges in water of variable depth H. The discharge is assumed to be located near the bottom of the water body. CORMIX2 uses the applicability criterion for the height of the discharge port h_o

$$h_o \leq 0.33H \tag{5.4}$$

Eq. 5.4 is needed to assure a valid test for deep/shallow discharge stability in the flow classification scheme.

Also the diameter D for each port or nozzle must not exceed 20% of the water depth,

$$D \leq 0.2\ H \tag{5.5}$$

Finally, the height of the pycnocline (i.e. thickness of the lower layer) h_{int} must be in the range between 40% to 90% of the water depth

$$0.4H \leq h_{int} \leq 0.5H \tag{5.6}$$

It is pointed out, however, that an experienced user can modify the data input to allow for CORMIX2 analyses that are seemingly outside this normal range of system applicability. Hints for those system applications can be found in Doneker and Jirka (1989).

Furthermore, CORMIX2 assumes a conservative discharge which is a reasonable assumption since its emphasis is on initial mixing mechanisms with short time scales (for further discussion, see Doneker and Jirka, 1989).

Chapter VI
Conclusions and Recommendations

U.S water quality regulations contain the concept of a mixing zone, a limited area or volume of water where initial discharge dilution occurs. Water quality standards are applicable at the border of, and outside, the mixing zone. Toxic discharges are subject to additional regulatory limitations. This water quality policy is implemented through the National Pollution Discharge Elimination System (NPEDS) which requires, among other factors, an estimate of the initial mixing characteristics. There exist many possible combinations of discharge conditions and ambient environments, hence a considerable amount of skill and training is required to pursue reliable mixing zone analysis. For the purpose of facilitating this task, an expert system methodology has been developed, the Cornell Mixing Zone Expert System (CORMIX).

Subsystem CORMIX2 predicts trajectory and mixing characteristics of a multiport diffuser, discharging buoyant (positively, negatively, or neutrally) effluents discharges into uniform or stratified ambient environments with or without the presence of ambient current. Knowledge gathered from hydrodynamic expertise is used in CORMIX2 for mixing analysis. CORMIX2 collects all input data, verifies for data consistency, groups and executes the suitable hydrodynamic simulation models, summarizes the simulation results in accordance with legal requirements including criteria for toxic substances, and finally recommends alternatives for improving mixing characteristics. CORMIX2, with its emphasis on rapid initial mixing, assumes a conservative pollutant discharge neglecting any physical, chemical, biological reaction, or decay processes. However, the predictive results can be readily converted to adjust for first-order reaction processes.

The results obtained for the hydrodynamic simulation are in good agreement with laboratory and field data. CORMIX2 correctly predicts highly complex discharge situations involving deep or shallow water environments, ambient stratification, plume intrusions, and boundary interactions. Many of these processes are absent in currently available mixing models.

Further work should be accomplished in order to refine the hydrodynamic flow protocols in the flow classification, and to substantiate various constants in the system. This task will require additional field and laboratory data. Also, computer generated graphics should be developed to plot simulation and to help the user in better understanding the mixing processes.

References

Abdelwahed, S. T., and Vincent H. Chu. (1978), "Bifurcation of Buoyant Jets in Cross Flow", Technical Rept. No 78-1, Department of Civil Engineering and Applied Mechanics, McGill University, Montreal, Canada.

Alam, A. M. Z., D. R. F. Harleman, and J. M Colonell (1982), "Evaluation of Selected Initial Dilution Models". Journal of the Environmental Engineering Division, ASCE, Vol 108, No. EE1, February. pp 159-185.

Allan Hancock Foundation, University of Southern California (1964), "Final Report on an Investigation on the Fate of Organic and Inorganic Wastes Discharge into the Marine Environment and Their Effects of Biological Productivity", September 15.

Almquist, C. W., and Stolzenbach, K. D. (1976), "Staged Diffusers in Shallow Water", M.I.T., Ralph M. Parsons Laboratory for Water Resources and Hydrodynamics, Tech. Rep No. 213.

Almquist, C. W., and Stolzenbach, K. D. (1980), "Staged Multiport Diffusers", J. Hydraulics Division, Vol. 106, No. HY2.

Anderson, J. L., Parker, F.L. and Bennedict, B.A. (1973) "Negatively Buoyant Jets in a Crossflow", Environmental Protection Technology Series, U.S.E.P.A., Washington, D.C.

Arita, M. and G.H. Jirka, (1987), "Two-Layer Model of Saline Wedge II: Prediction of Mean Properties", J. Hydraulic Engineering, Vol. 113, No. 10.

Barnwell, T. O.,Brown L. C., and Marek, W. (1985), "Development of a prototype expert advisor for the enhanced stream water quality model QUAL2E", Internal Report, Environmental Research Laboratory, Office of Research and Development, U.S.E.P.A., Athens, Georgia, September, 1985.

Bata, G. L. (1957), "Recirculation of Cooling Water in Rivers and Canals", J. Hydraulics Division, Vol. 83, No. HY3.

Benjamin, T. B. (1968), "Gravity Currents and Related Phenomena", J. Fluid Mechanics, Vol. 31, pt. 2.

Briggs, G. A. (1969), Plume Rise, U.S. Atomic Energy Commission, Division of Technical Information, Oak Ridge, Tennessee.

Brocard, D. N. (1977), "Hydrothermal Studies of Staged Diffuser Discharge in the Coastal Environment, Charlestown Site", Alden Research Laboratories, Tech. Report No. 136-7/M296EF.

Cederwall, K. (1963), "The Initial Mixing of Jet Disposal into a Recipient," Tech. Rep. 14 and 15, Div. of Hydraulics, Chalmers Institute of Technology, Goteborg, Sweden.

Chen, J. C. (1980), "Studies on Gravitational Spreading Currents", Rep. KH-R-40, W.M. Keck Laboratory of Hydraulics and Water Resources, California Institute of Technology, Pasadena, Calif.

Chu, V. H., and Jirka, G. H. (1986), "Surface Buoyant Jets and Plumes", Encyclopedia of Fluid Mechanics, Chapter 25, 1986.

Clocksin, W. F. and Mellish, C. S. (1984), Programming in Prolog, 2nd ed., Springer-Verlag.

Congressional Research Service (1977), "Legislative History of the Clean Water Act 1977", Congressional Research Service, Library of Congress, October 1978, No. 95-14 p. 330.

Davidson, M. J. (1989), "The Behavior of Single and Multiple, Horizontally Discharged, Buoyant Flows in a Non-Turbulent Coflowing Ambient Fluid", Ph.D. Thesis, Department of Civil Engineering, University of Canterbury, Christchurch, New Zealand.

Doneker, R. L., and G. H Jirka (1990), "CORMIX1: An Expert System for Mixing Zone Analysis of Conventional and Toxic Single Port Aquatic Discharges", Tech. Rep. EPA/600/3-90/012, Environmental Research Lab., U.S. EPA, Athens, Georgia (also published as Tech. Rep., DeFrees Hydraulics Laboratory, Cornell University, Ithaca, New York, 1989.

Fischer, H. B. et al. (1979), Mixing in Inland and Coastal Waters, Academic Press, New York.

Gaschnig, J., Reboh, and J. Reiter (1981), "Development of a Knowledge-Based Expert System for Water Resources Problems", Palo Alto, Calif.

Holley, E. R., and Jirka, G. H. (1986), "Mixing in Rivers", Technical Report E-86-11, U.S. Army Corps of Engineers, Washington, D.C.

Isaacson, M. S., Koh, R. C.Y., and Brooks, N. H. (1983), "Plume Dilution for Diffusers with Multiport Risers", J. Hydraulic Engineering, Vol. 109, No. 2.

Jirka, G. H. and Harleman, D. R.F. (1973), "The Mechanics of Submerged Multiport Diffusers for Buoyant Discharges in Shallow Water", M.I.T., Ralph M. Parsons Laboratory for Water Resources and Hydrodynamics, Tech. Rep No. 169.

Jirka, G. H., and Harleman, D. R.F (1979), "Stability and Mixing of a Vertical Plane Buoyant Jet in Confined Depth", J. Fluid Mechanics, Vol. 94, Part 2, pp.275-304.

Jirka, G. H., J. M. Jones, and F. E. Sargent (1980), "Theoretical and Experimental intermediate Field Dynamics of Ocean Energy Conversion Plants", Progress Report, 1978-1979, School of Civil and Environmental Engineering, Cornell University.

Jirka, G. H. (1982), "Multiport Diffuser for Heat Disposal: a Summary", J. of Hydraulics Division, ASCE, 108, HY12, 1982, pp. 1425-68.

Jirka, G. H., Colonell, J. M., and Jones, D. (1985), "Outfall Mixing Design in Shallow Coastal Water Under Arctic Ice Cover", MTS Journal, Vol. 20, No. 3.

Jirka, G. H., and Joseph H.-W. Lee (1991), "Waste Disposal in the Ocean", Hydraulic Structures Design Manual, E. Naudascher, Ed., Vol 10. International Association of Hydraulic Research, (in print).

Jirka, G.H., and P.J. Akar (1991), "Hydrodynamic Classification of Submerged Multiport-Diffuser Discharges", J. Hydraulics Div., ASCE, Vol 117, No. 9, September 1991.

Jones, J. M., G. H. Jirka, and D. A. Caughey (1985), "Numerical Techniques for Steady Two-Dimensional Transcritical Stratified Flow Problems, with an Application to the Intermediate Field Dynamics of Ocean Thermal Energy Conversion Plants", Report No. ANL/EES-TM-27\1, Argonne National Laboratory, (also published as Tech. Rep. School of Civil and Environmental Engineering, Cornell University, Ithaca, New York).

Koh, R. C., and Brooks, N. H. (1975), "Fluid Mechanics of Waste Water Disposal in the Ocean", Annual review of Fluid Mechanics, Vol 7, pp. 187-211.

Lee, J. H.W., Jirka, G. H., and Harleman, D. R.F. (1977), "Modelling of Unidirectional Thermal Diffusers In Shallow Water", M.I.T., Ralph M. Parsons Laboratory for Water Resources and Hydrodynamics, Tech. Rep No. 228.

Lee, J. H.W., and Jirka, G. H. (1979), "Heat Recirculation Induced by Thermal Diffusers", J. Hydraulics Division, Vol. 105, No. HY10.

Lee, J. H.W. (1980), "Near Field of Staged Diffuser", J. Hydraulics Division, Vol. 106, No. HY8.

Lee, J. H.W., and Jirka, G. H. (1980), "Multiport Diffuser as Line Source of Momentum in Shallow Water", Water Resources Research, Vol. 16, No. 4., pp. 695-708.

Lee, J. H.W. (1984), "Boundary Effects on a Submerged Jet Group", J. Hydraulic Research, Vol. 22, No. 4.

Liseth, P. (1970), " Mixing of Merging Buoyant Jets from a Manifold in Stagnant Receiving Water of Uniform Density", Hydraulic Engineering Laboratory, University of California, Berkeley, California. Tech. Rept. HEL 23-1.

List, E. J., and Imberger J. (1973), "Turbulent Entrainment in Buoyant Jets", Proc. ASCE, J. Hydraulics Division, 99, 1461-1474.

List, E. J. (1982), "Mechanics of Turbulent Buoyant Jets and Plumes', Chapter in Turbulent Buoyant Jets and Plumes, (1982). W. Rodi, ed., Permagon Press.

Muellenhoff, W. P., et al. (1985), "Initial Mixing Characteristics of Municipal Ocean Discharges (Vol. 1&2)", U.S.E.P.A, Environmental Research Laboratory, Narragansett, R.I.

Munk, W., and Anderson, E.R. (1948), "Notes on a Theory of the Thermocline." J.Mar. Res. 7, 276-295.

Ortolano, Leonard (1984), Environmental Planning and Decision Making, John Wiley & Sons.

Roberts, P. J. W. (1977), "Dispersion of Buoyant Wastewater Discharge From Outfall Diffusers of Finite Length", Report No. KH-R-35, W. M. Keck Laboratory of Hydraulics and Water Resources, Division of Engineering and Applied Sciences, California Institute of Technology, Pasadena, Cal.

Roberts, P. J. W. (1979), "Line Plume and Ocean Outfall Dispersion", Hydraulics Division, Vol 105, No. HY4.

Roberts, P. J. W., Snyder, W. H., and Baumgartner, D. J. (1989), "Ocean Outfalls. I: Submerged Wastefield Formation, II: Spacial Evolution of Submerged Wastefield, III: Effect of Diffuser Design on Submerged Wastefield", J. Hydraulic Engineering, Vol. 115, No. 1.

Rodi, W. ed (1982), Turbulent Buoyant Jets and Plumes, Pergamon Press, New York.

Scorer, R. S. (1954), "The Behavior of Chimney Plumes," International Journal of Air Pollution, Vol 1, pp 198-220.

Shwartz, J. and Tulin, M.P. (1972), "Chimney Plumes in Neutral and Stable Surroundings", Atmospheric Environment, Vol. 6 pp. 19-36.

Stolzenbach, K. D. et. al. (1976), "Analytical and Experimental Studies of Discharge Designs for the Cayuga Station at the Somerest Alternate Site", M.I.T., Ralph M. Parsons Laboratory for Water Resources and Hydrodynamics, Tech. Rep No. 211.

Tait, H. (1984), "Section 402 Guidelines for Reviewing National Pollutant Discharge Elimination Permits", National Coastal Ecosystems Team, Rept. No. FWS/OBS-84/05, U.S. Dept. of the Interior, Washington, D.C., September.

Tennekes, H. and Lumley, J.L. (1972), A First Course in Turbulence, MIT Press, Cambridge, Mass, p. 99.

Tong, S. S., and Stolzenbach, K. D. (1979), "Submerged Discharges of Dense Effluent", Tech. Rept. 243, Ralph M. Parson Laboratory for Water Resources and Hydrodynamics, Massachusetts Institute of Technology, Cambridge, Massachusetts.

USEPA (1972), "Water Quality Criteria 1972", EPA-R3-73-003, Environmental Studies Board, Committee on Water Quality Criteria, Washington, D.C.

USEPA (1976), "Quality Criteria for Water 1976" (Red Book), Guidelines for State and Area Wide Water Quality Management Program, Washington, D.C. (Chapter 5).

USEPA, (1984), Water Quality Standards Handbook. Office of Water Regulations and Standards, Washington, D.C.

USEPA, (1984), "Technical Guidance Manual for the Regulations Promulgated Pursuant to Section 301 (g) of the Clean Water Act of 1977 (Draft) ", Washington D.C., August.

USEPA, (1985), "Technical Support Document for Water Quality-based Toxics Control", Office of Water, Washington, D.C., September (in revision, 1990).

Wright, S. J. (1977), "Effects of Ambient Crossflows and Density Stratification on the Characteristic Behavior of Round Turbulent Buoyant Jets", Rep. KH-R-36, W.M. Keck Laboratory of Hydraulics and Water Resources, California Institute of Technology, Pasadena, Calif.

Wright, S.J., and Wallace, R. B. (1979), "Two-Dimensional Buoyant Jets in Stratified Fluid", J. Hydraulic Division, Vol. 105, No. HY11.

Wright, S.J., Wong, D. R., and Zimmerman, K. E. (1982), "Outfall Diffuser Behavior in Stratified Ambient Fluid", J. Hydraulics Division, Vol. 108., No. HY4.

Wong, D. R. (1984), "Buoyant Jet Entrainment in Stratified Fluids", Ph.D. Thesis, Civil Engineering Dept., The University of Michigan, Ann Arbor MI.

Appendix A: Data Input Advices

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CORNELL MIXING ZONE EXPERT SYSTEM: GENERAL INFORMATION

The Cornell Mixing Zone Expert System (CORMIX) is a series of software subsystems for the analysis, prediction and design of aqueous discharges into watercourses, with emphasis on the geometry and dilution characteristics of the initial mixing zone.

Subsystem CORMIX2 deals with buoyant submerged discharges from MULTIPORT DIFFUSERS into flowing unstratified or stratified water environments, such as rivers, lake, estuaries, and coastal waters. It includes the limiting cases of non-buoyant and negatively buoyant discharges and of stagnant ambient conditions.

The predictive elements of CORMIX2 are based on the "equivalent slot diffuser" concept. This means the details of the individual jets emanating from the evenly spaced diffuser ports/nozzles are neglected by assuming an equivalent slot jet on the basis of equivalency of flux quantities per unit diffuser length. This concept provides a dynamically accurate representation of the actual three-dimensional diffuser if attention lies in the region after merging. (In most cases,the distance to merging is short, of the order of twice the spacing between individual jets. If further predictive details for the individual three-dimensional jets prior to merging are desired, the user is advised to use CORMIX1 with the flow parameters for the individual jets).

Please note that the time for loading of individual program elements will depend on the speed of your computer and the size of the program element. The time for these file operations may range from a few seconds (IBM PS/2 Model 70, 80386-based) to more than a minute (IBM PC/XT, 8088-based). Also DOS file manipulation information may be displayed by the system during program execution, or may be neglected by the user.

PROGRAM ELEMENTS:

The program elements of CORMIX2 are listed below. During system use the program elements are loaded sequentially and automatically in the order given below.

1) DATIN

This is a knowledge base program for the entry of relevant data about the discharge situation and for the initialization of the other program elements. DATIN consist of four subprograms that execute automatically; each subprogram assembles a data group. You are presently using DATIN. The four data groups DATIN seeks are: general identifier information, ambient conditions (geometry and hydrography), discharge conditions (geometry and fluxes), and output information desired including legal mixing zone definitions. After each subprogam executes, the values for data entered or concluded are displayed.

DATIN is a detailed program with complete explanations on data preparations, assumptions and schematizations. DATIN along with the programs PARAM and CLASS (described below) automatically creates the files fn.CXD, fn.CXC, and HYDRO2.CXE where fn is a user supplied file name. The fn.CXD contains all necessary input data for the hydrodynamic simulation model HYDRO2 described below. The file fn.CXC contains all knowledge base conclusions. The HYDRO2.CXE file instructs HYDRO2 which fn.CXD file to load as input for the current session.

2) PARAM

This is a knowledge base program that computes the relevant physical parameters for the given discharge situation. Output from PARAM is included in the fn.CXD file.

3) CLASS

This is a knowledge base program that classifies the given discharge into one of many possible hydrodynamic configurations, e.g. a boundary attached discharge, an unstable vertically mixed case, or mixing controlled by the ambient crossflow.

Each separate flow configuration has an alphanumeric label (Example MU1,MS4,..) and a detailed hydrodynamic description is available. Output from CLASS is contained in the fn.CXD file.

4) HYDRO

This is a knowledge base program that executes the external FORTRAN hydrodynamic program (HYDRO2) consisting of a number of simulations subroutines (modules) each corresponging to a particular hydrodynamic mixing process. For each flow configuration (Examples: MU4, MS5) identified in CLASS, the appropriate modules are executed sequentially according to a specific protocol.

The program prints out data on geometry (trajectory, width, etc.) and associated mixing (dilution, concentration) following the path of the effluent discharge. As mentioned above, the main predictive elements are based on the three-dimensional "equivalent slot diffuser" representation of the actual multiport diffuser.

HYDRO2 automatically creates the files fn.CXO and fn.CXS where fn is the user supplied file name. The fn.CXO contains the output file data from HYDRO2. The fn.CXS file is used as input by the final program segment SUM.

5) SUM

This is a knowledge base program that summarizes the given situation, comments on the mixing characteristics, evaluates how applicable legal requirements are satisfied, and suggests possible design alternatives and improvements.

UNITS OF MEASUREMENT:

CORMIX uses the SI system of measurement, specifically: length in m, mass in kg, time in s, and temperature in deg C. Furthermore, all pollutant concentrations are considered in arbitrary units, i.e. the user can specify these in any units he/she desires, and all output data must be interpreted accordingly in these same units.

COORDINATE SYSTEM:

All predictions in CORMIX2 are displayed using the following three-dimensional coordinate system:

---The origin is located at the half-way point of the diffuser line.

*** There is one exception: when the diffuser line starts at the shore, then the origin is located directly at the shore. ***

---The x-axis is located at the bottom of the water body and directed in the downstream direction following the ambient flow.

---The y-axis is located at the bottom and points to the left normal to the ambient flow direction (x-axis).

---The z-axis points vertically upward.

Note, if the ambient current direction is variable (e.g. due to reversing tidal flows), the x-axis and the y-axis will change depending on flow direction. Furthermore, if a stagnant situation is to be analysed, the x-axis may be defined by the direction of the prevailing currents.

****

DATA REQUIREMENTS FOR AMBIENT CONDITIONS:

Ambient conditions are defined by the hydrographic and the geometric conditions in the vicinity of the discharge. For this purpose typical cross-sections normal to the ambient flow direction at the discharge site and further downstream need to be considered:

A) Bounded cross-section: If the cross-section is bounded on both sides by banks - as in rivers, streams, narrow estuaries, and other narrow watercourses -, then the cross-section is considered "bounded".

B) Unbounded cross-section: In some cases the discharge is located close to one boundary while the other boundary is for practical purposes very far away. This would include discharges into wide lakes, estuaries and coastal areas. These situations are defined as "unbounded".

A) BOUNDED CROSS-SECTION:

Hydrographic information:

Data on the design ambient flow condition - such as average river discharge or low flow discharge - needs to be available. The user has the option of entering such data directly as the discharge or as an average velocity. The ambient density profile (i.e. the vertical distribution of the ambient water density) must be approximated. It may be specified as either uniform (within given limits) or approximated as one of four simplified profiles. An opportunitiy for obtaining more detailed information on these profiles is given later.

The ambient density can be specified directly, or -in case of freshwater- is computed after specification of the ambient temperature.

Geometric information:

CORMIX will conduct its analysis assuming a rectangular cross-section that is given by a width and a depth both of which are constant in the downstream direction following the ambient flow. This schematization may be quite evident for well-channeled and regular rivers or artificial channels. For highly irregular cross-sections, it may require more judgement and experience - perhaps combined with a repeated use of CORMIX to get a better feeling on the sensitivity of the results.

In any case, the user is advised to consider the following steps:

1) Be aware that a particular flow condition (such as a river discharge) is usually associated with a certain water surface elevation ("stage"). Data for a stage-discharge relationship is normally available from a separate hydraulic analysis or from field measurements.

2) For the given stage-discharge combination display the cross-section at the discharge location and several downstream cross-sections. Look over these. Determine a an "equivalent rectangular cross-sectional area". Very shallow bank areas or shallow floodways may be neglected. Also more weight should be given to the cross-sections at, and close to, the discharge location.

3) Determine the surface width and depth of the equivalent rectangular area. In case that ambient discharge and ambient velocity data are available, note that the continuity relation specifies that discharge = (velocity * cross-sectional area). The width and depth values thus chosen need to be specified to CORMIX which will check for any inconsistencies.

Note On Stagnant Conditions:

If zero (or a very small value) for ambient velocity is entered, CORMIX will label the discharge environment as stagnant. In this case CORMIX will predict only the near field of the discharge. Although stagnant conditions represent an extreme limiting case for dilution prediction, a more realistic assumption for natural water bodies would be to consider a finite ambient crossflow, no matter how small. It is therefore reccommended to conduct subsequent analysis with a small crossflow.

4) As a measure of geometric non-uniformity also specify the actual maximum depth of the cross-sections (again with more weight given to the near-discharge cross-sections).

5) As a measure of the roughness characteristics in the channel the value of the Manning "n", or alternatively of the Darcy-Weisbach friction factor "f", must be specified. These parameters influence the mixing process only in the final stage considered by CORMIX and are not very sensitive to the predictions. Generally, if these values are assumed known within +-30% the predictions will vary by +-10% at the most.

B) UNBOUNDED CROSS-SECTION:

Both hydrographic and geometric information are closely linked in this case:

1) Determine the water elevation (given by lake or reservoir elevation or tidal stage etc.) for which the analysis should be conducted.

2) Assemble cross-sectional profiles that plot water depth as a function of distance from the shore for the discharge location and for several positions downstream following the ambient current direction.

3) a) If detailed hydrographic data (from field surveys or from some hydraulic numerical model calculations) are available, determine the cumulative ambient discharge from the shore to the discharge location for the discharge cross-section. For each of the subsequent downstream cross-sections determine the distance from the shore at which the same cumulative ambient discharge has been attained. Mark this position on all cross-sectional profiles. Now consider the velocity (vertically averaged) and the depth at these positions. Specify to CORMIX a typical ambient velocity and a typical depth from these data by giving most weight to the conditions at, and close to, the discharge location. Specify a typical distance from the shore by dividing the cumulative ambient discharge by (ambient velocity * depth).

b) If detailed hydrographic data is not available - but at least data, or estimates, on the vertically averaged velocity at the discharge location must be available! - then determine the cumulative cross- sectional area from the shore to the discharge location for the discharge cross-section.
For each of the subsequent downstream cross-sections, mark the position where the cumulative cross-sectional area has the same value as at the discharge cross-section. Determine the typical ambient velocity and the typical ambient depth at these positions with most weight given to conditions at, or close to, the discharge location. Specify the typical distance from the shore by dividing the cumulative cross-sectional area by the ambient depth.

4) In summary, CORMIX will conduct its analysis for the unbounded case by assuming an "equivalent rectangular cross-sectional area" defined by depth, by distance from one bank to the discharge position, and by ambient velocity. Note the similarities to the bounded case discussed above. As for the bounded cross-section, the ambient density profile (i.e. the vertical distribution

of the ambient water density) must be approximated. It may be specified as either uniform (within given limits) or approximated as one of four simplified profiles. An opportunitiy for obtaining more detailed information on these profiles is given later.

The ambient density can be specified directly, or -in case of a freshwater ambient - is computed by specification of the ambient temperature.

5) As a measure of the roughness characteristics of the flow area the value of the Manning "n", or alternatively of the Darcy-Weisbach friction factor "f", must be specified. These parameters influence the mixing process only in the final stage considered by CORMIX and are not very sensitive to the predictions. Generally, if these values are assumed known within +-30% the predictions will vary by +-10% at the most.

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ADVICE FOR SPECIFYING DISCHARGE CHARACTERISTICS: MULTIPORT DIFFUSERS:

GENERAL INFORMATION AND DEFINITIONS:

A multiport diffuser is a linear structure consisting of many closely spaced ports or nozzles which inject a series of turbulent jets at high velocity into the ambient receiving water body. These ports or nozzles may be connected to vertical risers attached to an underground pipe or tunnel, or may simply be openings in a pipe lying on the bottom.

The diffuser line (or axis) is a line connecting the first port or nozzle and the last port or nozzle. Generally, the diffuser line will coincide with the connecting pipe or tunnel. CORMIX2 will assume a straight diffuser line. If the actual diffuser pipe has bends or directional changes it must be approximated by a straight diffuser line.

The diffuser length is the distance from the first to the last port or nozzle. The origin of the coordinate system used by CORMIX2 is located at the center (mid-point) of the diffuser line (there is one exception: when the diffuser line starts at the shore, then the origin is located directley at the shore.

CORMIX2 considers the three major diffuser types in common engineering practice:

1) UNIDIRECTIONAL DIFFUSER: All ports (or nozzles) are pointing to one side of the diffuser line, more or less normally to the diffuser line, and more or less

horizontally.

2) STAGED DIFFUSER: All ports are pointing in one direction following the diffuser line (or nearly so, with small deviations to either side of the diffuser line), and more or less horizontally.

3) ALTERNATING DIFFUSER: The diffuser ports do not have a preferred horizontal direction: Either they point, in an alternating fashion and more or less horizontally, to both sides of the diffuser line, or they all point upward, more or less vertically.

DIFFUSER GEOMETRY SPECIFICATION:

CORMIX2 will ask for the following data on diffuser geometry. Note, that CORMIX2 will assume uniform discharge conditions along the diffuser line. This includes a uniform ambient depth as specified earlier. If the depth is, in fact, variable (e.g. due to an offshore slope) it should be approximated by a mean depth along the diffuser line (with a possible bias to the more shallow near-shore conditions). Similarly, discharge parameters (e.g. port size or spacing or discharge per port) may vary along the diffuser line; again, they must be approximated by mean values.

1) Specify the diffuser length. Also specify the distance from the shore for both end points of the diffuser line.

2) Details on port or nozzle geometry and construction: Are the ports or nozzles connected to vertical risers from an underground pipe or tunnel? If yes, how many risers exist, and how many ports or nozzles are attached to each riser? If no, how many ports or nozzles are spaced along the diffuser line? In either case, CORMIX2 will assume a uniform spacing between risers or between nozzles or ports.

3) Specify the average diameter of the discharge ports or nozzles. CORMIX2 assumes round ports/nozzles. Also, the value for the jet contraction coefficient should be specified.

4) Specify the height of the port/nozzle centers above the ambient bottom.

5) The vertical angle of discharge (THETA) is the angle of the port/nozzle centerline measured from the horizontal plane. As examples, THETA is 0 deg for a horizontal discharge, and it is +90 deg for a vertical (upward) discharge.

6) Consider a plan view of the diffuser as seen from above. Defined for the unidirectional and staged diffusers only, the horizontal angle of discharge (SIGMA) is the angle between the port/nozzle centerline in this plan projection and the ambient current direction, measured counterclockwise from the ambient current direction (x-axis). The possible range of SIGMA is from 0 deg to 360 deg. In case of variable orientation, specify the average horizontal angle.

7) The diffuser alignment angle (GAMMA) is the angle between the diffuser axis and the ambient current, measured counterclockwise from the ambient current direction (x-axis). The possible range for the alignment angle is from 0 deg to 180 deg. As examples, special cases are the parallel diffuser (GAMMA = 0 deg or 180 deg), and the perpendicular diffuser (GAMMA = 90 deg).

8) The relative orientation angle (BETA) of the port/nozzle discharge is the nearest (clockwise or counterclockwise) angle between the horizontal projection of the port/nozzle centerline and the diffuser axis. The possible range of the BETA is between 0 deg (staged diffuser) and 90 deg (unidirectional diffuser).

DIFFUSER FLOW VARIABLES:

1) Specify the total diffuser discharge or the discharge velocity. Note, these two variables are related through the total cross-sectional area of all discharge ports/nozzles.

2) The discharge density can be specified directly, or - in case of an essentially freshwater discharge in which the addition of any pollutant or tracer has negligible effect on density - it is computed after specification of the discharge temperature.

3) The discharge concentration of the material of interest (pollutant, tracer, or temperature) is defined as the excess concentration above any ambient concentration. The user can specify this quantity in any units and the CORMIX2 results for computed excess concentrations should then be interpreted in these same units.

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SPECIFICATION OF DESIRED MIXING ZONE INFORMATION:

The user must specify data that indicates over which spatial region information will be desired, and in what detail. Legal mixing zone (LMZ) requirements may exist or not.

The user has several options for this specification:

1) LEGAL MIXING ZONE (LMZ): Options exist for specifying the legal mixing zone as a maximum distance from the discharge location, or as a maximum cross-sectional area occupied by the plume, or as the maximum width of the effluent plume. If the discharge is toxic, the criterion continuous concentration (CCC) value must be met at the boundary of the LMZ.

2) REGION OF INTEREST (ROI): When legal mixing zone restrictions do not exist or when the user is interested in information over a larger area, then a region of interest must be specified as the maximum distance in the direction of mixed effluent flow.

3) HYDRODYNAMIC MIXING ZONE (HMZ): In all cases, CORMIX will label a usually smaller initial region in which discharge-induced mixing takes place as the "hydrodynamic mixing zone". The dilution conditions in the HMZ may be a useful measure for the outfall designer when attempting to optimally design the discharge conditions.

4) TOXIC DILUTION ZONE (TDZ): For all discharges that have been designated as toxic by USEPA standards (Technical Support Document for Water Quality-Based Toxics Control, USEPA, 1985; in revision, 1990) CORMIX will automatically define the concentration values at the edge of the toxic dilution zone as defined in that document. CORMIX will indicate if the criterion maximum concentration (CMC) standard has been met.

After all applicable data have been specified on these zones, CORMIX also needs information on the level of detail for the output data within these zones and, simultaneously, within all the hydrodynamic elements (modules) that may occupy these zones.

Appendix B: Flow Descriptions for all Flow Classes

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FLOW CLASS MS1

This flow configuration is profoundly affected by the linear ambient density stratification. The predominantly jet-like flow gets trapped at some terminal (equilibrium) level. The trapping is also affected by the reasonably strong ambient crossflow. For this case, the diffuser alignment is predominantly perpendicular to the ambient flow.

Following the trapping zone, the discharge flow forms an internal layer that is further influenced by buoyant spreading and passive diffusion.

The following flow zones exist:

1) Weakly deflected plane jet in crossflow: The flow issuing from the equivalent slot width is initially dominated by the effluent momentum (jet-like) and is weakly deflected by the ambient current.

2) Strongly deflected plane jet in crossflow: The jet has become strongly deflected by the ambient current and is slowly rising toward the trapping level.

3) Terminal layer approach: The bent-over submerged jet/plume approaches the terminal level. Within a short distance the concentration distribution becomes relatively uniform across the plume width and thickness.

*** The zones listed above constitute the HYDRODYNAMIC MIXING ZONE in which strong initial mixing takes place. ***

4) Buoyant spreading in internal layer: The discharge flow within the internal layer spreads laterally while it is being advected by the ambient current. The plume thickness may decrease during this phase. The mixing rate is relatively small. The plume may interact with a nearby bank or shoreline.

5) Passive ambient mixing: After some distance the background turbulence in the ambient shear flow becomes the dominating mixing mechanism. The passive plume is growing in depth and in width. The plume may interact with the upper layer boundary, channel bottom and/or banks.

*** Predictions will be terminated in zone 4 or 5 depending on the definitions of the LEGAL MIXING ZONE or the REGION OF INTEREST. ***

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FLOW CLASS MS2

This flow configuration is profoundly affected by the linear ambient density stratification. The predominantly jet-like flow gets trapped at some terminal (equilibrium) level. The trapping is also affected by the reasonably strong ambient crossflow. For this case, the diffuser alignment is predominantly parallel to the ambient flow.

Following the trapping zone, the discharge flow forms an internal layer that is further influenced by buoyant spreading and passive diffusion.

The following flow zones exist:

1) Weakly deflected plane jet in crossflow: The flow issuing from the equivalent slot width is initially dominated by the effluent momentum (jet-like) and is weakly deflected by the ambient current.

2) Strongly deflected plane jet in crossflow: The jet has become strongly deflected by the ambient current and is slowly rising toward the trapping level.

3) Internal density current along diffuser line: The plume develops along the diffuser line due to continuous inflow of mixed buoyant water. The plume spreads laterally along the layer boundary (surface or pycnocline) which it is being advected by the ambient current. The mixing rate is relatively small.

*** The zones listed above constitute the HYDRODYNAMIC MIXING ZONE in which strong initial mixing takes place. ***

4) Buoyant spreading in internal layer: The discharge flow within the internal layer spreads laterally while it is being advected by the ambient current. The plume thickness may decrease during this phase. The mixing rate is relatively small. The plume may interact with a nearby bank or shoreline.

5) Passive ambient mixing: After some distance the background turbulence in the ambient shear flow becomes the dominating mixing mechanism. The passive plume is growing in depth and in width. The plume may interact with the upper layer boundary, channel bottom and/or banks.

*** Predictions will be terminated in zone 6 or 7 depending on the definitions of the LEGAL MIXING ZONE or the REGION OF INTEREST. ***

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FLOW CLASS MS3

This flow configuration is profoundly affected by the linear ambient density stratification. The predominantly jet-like flow issues vertically, or near-vertically, upward and gets trapped at some terminal (equilibrium) level. The crossflow is weak in the present situation.

Following the trapping zone, the discharge flow forms an internal layer that is further influenced by buoyant spreading and passive diffusion.

The following flow zones exist:

1) Near-vertical plane jet in linear stratification: The flow issuing from the equivalent slot is initially dominated by the effluent momentum (jet-like) and is weakly deflected by the ambient current and the density stratification.

2) Terminal layer impingement / upstream spreading: The weakly bent jet/plume approaches (impinges) the terminal layer at a near- vertical angle, and may overshoot that level to some extent. After impingement the flow spreads in all directions (more or less radially) at the terminal level forming an internal layer. In particular, the flow spreads some distance upstream against the ambient flow, and laterally across the ambient flow. This spreading is dominated by the buoyant collapse of the internal layer within the linear ambient stratification.

*** The zones listed above constitute the HYDRODYNAMIC MIXING ZONE in which strong initial mixing takes place. ***

3) Buoyant spreading in internal layer: The discharge flow within the internal layer spreads laterally while it is being advected by the ambient current. The plume thickness may decrease during this phase. The mixing rate is relatively small. The plume may interact with a nearby bank or shoreline.

4) Passive ambient mixing: After some distance the background turbulence in the ambient shear flow becomes the dominating mixing mechanism. The passive plume is growing in depth and in width. The plume may interact with the upper layer boundary, channel bottom and/or banks.

*** Predictions will be terminated in zone 3 or 4 depending on the definitions of the LEGAL MIXING ZONE or the REGION OF INTEREST. ***

SPECIAL CASE: If the ambient is stagnant, then advection and diffusion by the ambient flow (zones 3 and 4) cannot be considered. The mixing is limited to the hydrodynamic mixing zone (zones 1 and 2) and the predictions will be terminated at this stage.

Such stagnant water predictions may be a useful initial mixing indicator for a given site and discharge design.

For practical final predictions, however, the advection and diffusion of the ambient flow - no matter how small in magnitude - should be considered.

****

FLOW CLASS MS4

This flow configuration is profoundly affected by the linear ambient density stratification. The predominantly jet-like flow issues horizontally, or near-horizontally, into the density stratified layer and gets trapped at some terminal (equilibrium) level. The crossflow is weak in the present situation.

Following the trapping zone, the discharge flow forms an internal layer that is further influenced by buoyant spreading and passive diffusion.

The following flow zones exist:

1) Near-horizontal plane jet in linear stratification: The flow issuing from the equivalent slot width is initially dominated by the effluent momentum (jet-like) and is weakly deflected by the ambient current and the density stratification.

2) Terminal layer injection / surface spreading: The weakly bent jet/plume approaches (injects into) the terminal layer at a near- horizontal angle. After injection the flow spreads in all directions (more or less radially0 at the terminal level forming an internal layer. The residual horizontal momentum flux within the jet affects that spreading process. In particular, the flow spreads some distance upstream against the ambient flow, and laterally across the ambient flow. This spreading is dominated by the buoyant collapse of the internal layer within the linear ambient stratification.

*** The zones listed above constitute the HYDRODYNAMIC MIXING ZONE in which strong initial mixing takes place. ***

3) Buoyant spreading in internal layer: The discharge flow

within the internal layer spreads laterally while it is being advected by the ambient current. The plume thickness may decrease during this phase. The mixing rate is relatively small. The plume may interact with a nearby bank or shoreline.

4) Passive ambient mixing: After some distance the background turbulence in the ambient shear flow becomes the dominating mixing mechanism. The passive plume is growing in depth and in width. The plume may interact with the upper layer boundary, channel bottom and/or banks.

*** Predictions will be terminated in zone 3 or 4 depending on the definitions of the LEGAL MIXING ZONE or the REGION OF INTEREST. ***

SPECIAL CASE: If the ambient is stagnant, then advection and diffusion by the ambient flow (zones 3 and 4) cannot be considered. The mixing is limited to the hydrodynamic mixing zone (zones 1 and 2) and the predictions will be terminated at this stage.

Such stagnant water predictions may be a useful initial mixing indicator for a given site and discharge design.

For practical final predictions, however, the advection and diffusion of the ambient flow - no matter how small in magnitude - should be considered.

****
FLOW CLASS MS5

This flow configuration is profoundly affected by the linear ambient density stratification. The predominantly plume-like flow gets trapped at some terminal (equilibrium) level. The trapping is also affected by the reasonably strong ambient crossflow. For this case, the diffuser alignment is predominantly perpendicular to the ambient flow.

Following the trapping zone, the discharge flow forms an internal layer that is further influenced by buoyant spreading and passive diffusion.

The following flow zones exist:

1) Strongly deflected plane plume: The flow issuing from the equivalent slot width is initially dominated by the effluent buoyancy (plume-like) and the plume buoyancy starts to affect the flow. The plume is strongly deflected by the current and is slowly rising towards the terminal level.

2) Terminal layer approach: The bent-over submerged jet/plume approaches the terminal level. Within a short distance the concentration distribution becomes relatively uniform across the plume width and thickness.

*** The zones listed above constitute the HYDRODYNAMIC MIXING ZONE in which strong initial mixing takes place. ***

3) Buoyant spreading in internal layer: The discharge flow within the internal layer spreads laterally while it is being advected by the ambient current. The plume thickness may decrease during this phase. The mixing rate is relatively small. The plume may interact with a nearby bank or shoreline.

4) Passive ambient mixing: After some distance the background turbulence in the ambient shear flow becomes the dominating mixing mechanism. The passive plume is growing in depth and in width. The plume may interact with the upper layer boundary, channel bottom and/or banks.

*** Predictions will be terminated in zone 3 or 4 depending on the definitions of the LEGAL MIXING ZONE or the REGION OF INTEREST. ***

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FLOW CLASS MS6

This flow configuration is profoundly affected by the linear ambient density stratification. The predominantly plume-like flow gets trapped at some terminal (equilibrium) level. The trapping is also affected by the reasonably strong ambient crossflow. For this case, the diffuser alignment is predominantly parallel to the ambient flow.

Following the trapping zone, the discharge flow forms an internal layer that is further influenced by buoyant spreading and passive diffusion.

The following flow zones exist:

1) Strongly deflected plane plume: The flow issuing from the equivalent slot width is initially dominated by the effluent buoyancy (plume-like) and the plume buoyancy starts to affect the flow. The plume is strongly deflected by the current and is slowly rising towards the terminal level.

2) Terminal layer approach: The bent-over submerged jet/plume approaches the terminal level. Within a short distance the concentration distribution becomes relatively uniform across the plume width and thickness.

3) Internal density current along diffuser line: The plume develops along the diffuser line due to continuous inflow of mixed buoyant water. The plume spreads laterally along the layer boundary (surface or pycnocline) which it is being advected by the ambient current. The mixing rate is relatively small.

*** The zones listed above constitute the HYDRODYNAMIC MIXING ZONE in which strong initial mixing takes place. ***

4) Buoyant spreading in internal layer: The discharge flow within the internal layer spreads laterally while it is being advected by the ambient current. The plume thickness may decrease during this phase. The mixing rate is relatively small. The plume may interact with a nearby bank or shoreline.

5) Passive ambient mixing: After some distance the background turbulence in the ambient shear flow becomes the dominating mixing mechanism. The passive plume is growing in depth and in width. The plume may interact with the upper layer boundary, channel bottom and/or banks.

*** Predictions will be terminated in zone 4 or 5 depending on the definitions of the LEGAL MIXING ZONE or the REGION OF INTEREST. ***

****
FLOW CLASS MS7

This flow configuration is profoundly affected by the linear ambient density stratification. The predominantly plume-like flow issues vertically, or near-vertically, and rises vertically upward and gets trapped at some terminal equilibrium level. The crossflow is weak in the present situation.

Following the trapping zone, the discharge flow forms an internal layer that is further influenced by buoyant spreading and passive diffusion.

The following flow zones exist:

1) Weakly deflected plane plume in linear stratification: The flow issuing from the equivalent slot width is initially dominated by the effluent buoyancy (plume-like) and is weakly affected by the ambient current and the density stratification.

2) Terminal layer impingement / upstream spreading: The weakly bent jet/plume approaches (impinges) the terminal layer at a near- vertical angle, and may overshoot that level to some

extent. After impingement the flow spreads in all directions (more or less radially) at the terminal level forming an internal layer. In particular, the flow spreads some distance upstream against the ambient flow, and laterally across the ambient flow. This spreading is dominated by the buoyant collapse of the internal layer within the linear ambient stratification.

*** The zones listed above constitute the HYDRODYNAMIC MIXING ZONE in which strong initial mixing takes place. ***

3) Buoyant spreading in internal layer: The discharge flow within the internal layer spreads laterally while it is being advected by the ambient current. The plume thickness may decrease during this phase. The mixing rate is relatively small. The plume may interact with a nearby bank or shoreline.

4) Passive ambient mixing: After some distance the background turbulence in the ambient shear flow becomes the dominating mixing mechanism. The passive plume is growing in depth and in width. The plume may interact with the upper layer boundary, channel bottom and/or banks.

*** Predictions will be terminated in zone 4 or 5 depending on the definitions of the LEGAL MIXING ZONE or the REGION OF INTEREST. ***

SPECIAL CASE: If the ambient is stagnant, then advection and diffusion by the ambient flow (zones 3 and 4) cannot be considered. The mixing is limited to the hydrodynamic mixing zone (zones 1 and 2) and the predictions will be terminated at this stage.

Such stagnant water predictions may be a useful initial mixing indicator for a given site and discharge design.

For practical final predictions, however, the advection and diffusion of the ambient flow - no matter how small in magnitude - should be considered.

****
FLOW CLASS MS8

This flow configuration is profoundly affected by the linear ambient density stratification. The predominantly plume-like flow issues horizontally, or near-horizontally, into the density stratified layer and, after some distance, rises vertically upward and gets trapped at some terminal equilibrium level. The crossflow is weak in the present situation.

Following the trapping zone, the discharge flow forms an internal layer that is further influenced by buoyant spreading and passive diffusion.

The following flow zones exist:

1) Weakly deflected plane jet in crossflow: The flow issuing from the equivalent slot diffuser is initially dominated by the effluent momentum (jet-like) and is weakly deflected by the ambient current.

2) Weakly deflected plane plume in linear stratification: After some distance, the flow becomes dominated by the effluent buoyancy (plume-like) and is weakly affected by the ambient current and the density stratification.

3) Terminal layer impingement / upstream spreading: The weakly bent jet/plume approaches (impinges) the terminal layer at a near- vertical angle, and may overshoot that level to some extent. After impingement the flow spreads in all directions (more or less radially) at the terminal level forming an internal layer. In particular, the flow spreads some distance upstream against the ambient flow, and laterally across the ambient flow. This spreading is dominated by the buoyant collapse of the internal layer within the linear ambient stratification.

*** The zones listed above constitute the HYDRODYNAMIC MIXING ZONE in which strong initial mixing takes place. ***

4) Buoyant spreading in internal layer: The discharge flow within the internal layer spreads laterally while it is being advected by the ambient current. The plume thickness may decrease during this phase. The mixing rate is relatively small. The plume may interact with a nearby bank or shoreline.

5) Passive ambient mixing: After some distance the background turbulence in the ambient shear flow becomes the dominating mixing mechanism. The passive plume is growing in depth and in width. The plume may interact with the upper layer boundary, channel bottom and/or banks.

*** Predictions will be terminated in zone 4 or 5 depending on the definitions of the LEGAL MIXING ZONE or the REGION OF INTEREST. ***

SPECIAL CASE: If the ambient is stagnant, then advection and diffusion by the ambient flow (zones 4 and 5) cannot be considered. The mixing is limited to the hydrodynamic mixing zone (zones 1 to 3) and the predictions will be terminated at this stage.

Such stagnant water predictions may be a useful initial mixing indicator for a given site and discharge design.

For practical final predictions, however, the advection and diffusion of the ambient flow - no matter how small in magnitude - should be considered.

****
FLOW CLASS MU1H

The discharge configuration is hydrodynamically "stable", that is the discharge strength (measured by its momentum flux) is weak in relation to the layer depth and in relation to the stabilizing effect of the discharge buoyancy (measured by its buoyancy flux). The buoyancy effect is very strong in the present case.

The following flow zones exist:

1) Weakly deflected plane jet in crossflow: The flow issuing from the equivalent slot diffuser is initially dominated by the effluent momentum (jet-like) and is weakly deflected by the ambient current.

2) Strongly deflected plane plume: After some distance the discharge buoyancy becomes the dominating factor (plume-like). The plume is deflected by the effect of the strong ambient current.

3) Surface layer approach: The bent-over submerged jet/plume approaches the terminal level. Within a short distance the concentration distribution becomes relatively uniform across the plume width and thickness.

or

3) Density current along diffuser line: The plume develops along the diffuser line due to continuous inflow of mixed buoyant water. The plume spreads laterally along the layer boundary (surface or pycnocline) which it is being advected by the ambient current. The mixing rate is relatively small. This zone extends from beginning to end of the diffuser line.

*** The zones listed above constitute the HYDRODYNAMIC MIXING ZONE in which strong initial mixing takes place. ***

4) Buoyant spreading at layer boundary: The plume spreads laterally along the layer boundary (surface or pycnocline) while it is being advected by the ambient current. The plume thickness may decrease during this phase. The mixing rate is relatively small. The plume may interact with a nearby bank

or shoreline.

5) Passive ambient mixing: After some distance the background turbulence in the ambient shear flow becomes the dominating mixing mechanism. The passive plume is growing in depth and in width. The plume may interact with the channel bottom and/or banks.

*** Predictions will be terminated in zone 4 or 5 depending on the definitions of the LEGAL MIXING ZONE or the REGION OF INTEREST. ***

****
FLOW CLASS MU1V

The discharge configuration is hydrodynamically "stable", that is the discharge strength (measured by its momentum flux) is weak in relation to the layer depth and in relation to the stabilizing effect of the discharge buoyancy (measured by its buoyancy flux). The buoyancy effect is very strong in the present case.

The following flow zones exist:

1) Weakly deflected plane jet in crossflow: The flow issuing from the equivalent slot diffuser is initially dominated by the effluent momentum (jet-like) and is weakly deflected by the ambient current.

2) Weakly deflected plane plume: After some distance the discharge buoyancy becomes the dominating factor (plume-like). The plume deflection by the ambient current is still weak.

3) Layer boundary impingement / upstream spreading: The weakly bent jet/plume impinges on the layer boundary (water surface or pycnocline) at a near-vertical angle. After impingement the flow spreads in all directions (more or less radially) along the layer boundary. In particular, the flow spreads some distance upstream against the ambient flow, and laterally across the ambient flow. This spreading is dominated by the strong buoyancy of the discharge.

*** The zones listed above constitute the HYDRODYNAMIC MIXING ZONE in which strong initial mixing takes place. ***

4) Buoyant spreading at layer boundary: The plume spreads laterally along the layer boundary (surface or pycnocline) while it is being advected by the ambient current. The plume thickness may decrease during this phase. The mixing rate is relatively small. The plume may interact with a nearby bank

or shoreline.

5) Passive ambient mixing: After some distance the background turbulence in the ambient shear flow becomes the dominating mixing mechanism. The passive plume is growing in depth and in width. The plume may interact with the channel bottom and/or banks.

*** Predictions will be terminated in zone 4 or 5 depending on the definitions of the LEGAL MIXING ZONE or the REGION OF INTEREST. ***

SPECIAL CASE: If the ambient is stagnant, then advection and diffusion by the ambient flow (zones 4 and 5) cannot be considered. The mixing is limited to the hydrodynamic mixing zone (zones 1 to 3) and the predictions will be terminated at this stage.

Such stagnant water predictions may be a useful initial mixing indicator for a given site and discharge design.

For practical final predictions, however, the advection and diffusion of the ambient flow - no matter how small in magnitude - should be considered.

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FLOW CLASS MU2

A unidirectional multiport diffuser with perpendicular alignment is discharging into an ambient flow. Frequently, this is called a "co-flowing diffuser". The discharge configuration is hydrodynamically "unstable", that is the discharge strength (measured by its momentum flux) is very strong in relation to the layer depth and in relation to the stabilizing effect of the discharge buoyancy (measured by its buoyancy flux). Rapid vertical mixing takes place over the full layer depth.

The following flow zones exist:

1) Acceleration zone for unidirectional coflowing diffuser: The net horizontal momentum flux provided by the diffuser jets leads to a wholescale acceleration of the ambient water, that flows across the diffuser line leading to rapid entrainment and mixing in this zone. The diffuser plume is mixed over the full layer depth, and contracts laterally in the direction of the flow (acceleration process). The length of this zone is about one half the diffuser length.

2) Diffuser-induced plume in co-flow: The diffuser induced momentum flux is still controlling the flow. However, lateral

entrainment and diffusion lead to a spreading of the diffuser plume and additional mixing. The plume moves predominantly in the direction of the ambient flow. At the beginning, the plume is vertically mixed over the full layer depth. At some distance, stratification may take place depending on the strength and direction of the plume buoyancy.

*** The zones listed above constitute the HYDRODYNAMIC MIXING ZONE in which strong initial mixing takes place. ***

3) Buoyant spreading at layer boundary: The plume spreads laterally along the layer boundary (surface or pycnocline) while it is being advected by the ambient current. The plume thickness may decrease during this phase. The mixing rate is relatively small. The plume may interact with a nearby bank or shoreline.

4) Passive ambient mixing: After some distance the background turbulence in the ambient shear flow becomes the dominating mixing mechanism. The passive plume is growing in depth and in width. The plume may interact with the channel bottom and/or banks.

*** Predictions will be terminated in zone 3 or 4 depending on the definitions of the LEGAL MIXING ZONE or the REGION OF INTEREST. ***

SPECIAL CASE: If the ambient is stagnant, then advection and diffusion by the ambient flow (zones 3 and 4) cannot be considered. The mixing is limited to the hydrodynamic mixing zone (zones 1 and 2) and the predictions will be terminated at this stage.

Such stagnant water predictions may be a useful initial mixing indicator for a given site and discharge design.

For practical final predictions, however, the advection and diffusion of the ambient flow - no matter how small in magnitude - should be considered.

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FLOW CLASS MU3

A unidirectional multiport diffuser with parallel alignment (commonly called a "tee diffuser" is discharging into a weak ambient flow. The discharge configuration is hydrodynamically "unstable", that is the discharge strength (measured by its momentum flux) is very strong in relation to the layer depth and in relation to the stabilizing effect of the discharge buoyancy (measured by its buoyancy flux).

The following flow zones exist:

1) Acceleration zone for unidirectional co-flowing diffuser (tee): The net horizontal momentum flux provided by the diffuser jets leads to a wholescale acceleration of the ambient water, that is diverted across the diffuser line leading to rapid entrainment and mixing in this zone. The diffuser plume is mixed over the full layer depth, and contracts laterally in the direction of the flow (acceleration process). The length of this zone is about one half the diffuser length. Plume deflection by the ambient current is insignificant.

2) Diffuser-induced plume in cross-flow: The diffuser induced momentum flux is still controlling the flow. However, lateral entrainment and diffusion lead to a spreading of the diffuser plume and additional mixing. Initially, the plume is cross-flowing, but it becomes progressively deflected into the direction of the ambient flow. At the beginning, the plume is vertically mixed over the full layer depth. At some distance, stratification may take place depending on the strength and direction of the plume buoyancy.

*** The zones listed above constitute the HYDRODYNAMIC MIXING ZONE in which strong initial mixing takes place. ***

3) Buoyant spreading at layer boundary: The plume spreads laterally along the layer boundary (surface or pycnocline) while it is being advected by the ambient current. The plume thickness may decrease during this phase. The mixing rate is relatively small. The plume may interact with a nearby bank or shoreline.

4) Passive ambient mixing: After some distance the background turbulence in the ambient shear flow becomes the dominating mixing mechanism. The passive plume is growing in depth and in width. The plume may interact with the channel bottom and/or banks.

*** Predictions will be terminated in zone 3 or 4 depending on the definitions of the LEGAL MIXING ZONE or the REGION OF INTEREST. ***

SPECIAL CASE: If the ambient is stagnant, then advection and diffusion by the ambient flow (zones 3 and 4) cannot be considered. The mixing is limited to the hydrodynamic mixing zone (zones 1 and 2) and the predictions will be terminated at this stage.

Such stagnant water predictions may be a useful initial mixing indicator for a given site and discharge design.

For practical final predictions, however, the advection and diffusion of the ambient flow - no matter how small in magnitude - should be considered.

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FLOW CLASS MU4

A unidirectional multiport diffuser with parallel alignment (commonly called a "tee diffuser" is discharging into a strong ambient flow. The discharge configuration is hydrodynamically "unstable", that is the discharge strength (measured by its momentum flux) is very strong in relation to the layer depth and in relation to the stabilizing effect of the discharge buoyancy (measured by its buoyancy flux). The ambient current is very strong in the present case.

The following flow zones exist:

1) Unidirectional cross-flowing (tee) diffuser plume in strong current: The strong ambient crossflow rapidly deflects the diffuser induced plume flow. The diffuser plume is advected in the direction of the ambient flow. This plume deflection is associated with a recirculation zone at the downstream end (lee) of the plume. The plume is vertically mixed over the full layer depth in this zone.

*** The zones listed above constitute the HYDRODYNAMIC MIXING ZONE in which strong initial mixing takes place. ***

2) Buoyant spreading at layer boundary: The plume spreads laterally along the layer boundary (surface or pycnocline) while it is being advected by the ambient current. The plume thickness may decrease during this phase. The mixing rate is relatively small. The plume may interact with a nearby bank or shoreline.

3) Passive ambient mixing: After some distance the background turbulence in the ambient shear flow becomes the dominating mixing mechanism. The passive plume is growing in depth and in width. The plume may interact with the channel bottom and/or banks.

*** Predictions will be terminated in zone 2 or 3 depending on the definitions of the LEGAL MIXING ZONE or the REGION OF INTEREST. ***

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FLOW CLASS MU5

A staged multiport diffuser with predominantly perpendicular alignment is discharging into weak ambient flow. The discharge configuration is hydrodynamically "unstable", that is the discharge strength (measured by its momentum flux) is very strong in relation to the layer depth and in relation to the stabilizing effect of the discharge buoyancy (measured by its buoyancy flux).

The following flow zones exist:

1) Acceleration zone for staged diffuser: The net horizontal momentum flux provided by the staged diffuser jets produces strong lateral entrainment of the ambient water and gradual acceleration along the diffuser line. A strong concentrated current with vertical mixing over the full layer depth is set up. This zone extends from the beginning to the end of the diffuser line.

2) Diffuser-induced plume in cross-flow: The diffuser induced momentum flux is still controlling the flow. However, lateral entrainment and diffusion lead to a spreading of the diffuser plume and additional mixing. Initially, the plume is cross-flowing, but it becomes progressively deflected into the direction of the ambient flow. At the beginning, the plume is vertically mixed over the full layer depth. At some distance, stratification may take place depending on the strength and direction of the plume buoyancy.

*** The zones listed above constitute the HYDRODYNAMIC MIXING ZONE in which strong initial mixing takes place. ***

3) Buoyant spreading at layer boundary: The plume spreads laterally along the layer boundary (surface or pycnocline) while it is being advected by the ambient current. The plume thickness may decrease during this phase. The mixing rate is relatively small. The plume may interact with a nearby bank or shoreline.

4) Passive ambient mixing: After some distance the background turbulence in the ambient shear flow becomes the dominating mixing mechanism. The passive plume is growing in depth and in width. The plume may interact with the channel bottom and/or banks.

*** Predictions will be terminated in zone 3 or 4 depending on the definitions of the LEGAL MIXING ZONE or the REGION OF INTEREST. ***

SPECIAL CASE: If the ambient is stagnant, then advection and diffusion by the ambient flow (zones 3 and 4) cannot be considered. The mixing is limited to the hydrodynamic mixing zone (zones 1 and 2) and the predictions will be terminated at this stage.

Such stagnant water predictions may be a useful initial mixing indicator for a given site and discharge design.

For practical final predictions, however, the advection and diffusion of the ambient flow - no matter how small in magnitude - should be considered.

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FLOW CLASS MU6

A staged multiport diffuser with perpendicular alignment is discharging into a strong ambient flow. The discharge configuration is hydrodynamically "unstable", that is the discharge strength (measured by its momentum flux) is very strong in relation to the layer depth and in relation to the stabilizing effect of the discharge buoyancy (measured by its buoyancy flux). The ambient current is very strong in the present case.

The following flow zones exist:

1) Staged perpendicular plume in strong current: The strong ambient flow rapidly deflects the diffuser induced plume. Ambient water flows across the diffuser line, and the diffuser plume is advected in the direction of the ambient flow. The length of this zone is about one half of the diffuser length.

*** The zones listed above constitute the HYDRODYNAMIC MIXING ZONE in which strong initial mixing takes place. ***

2) Buoyant spreading at layer boundary: The plume spreads laterally along the layer boundary (surface or pycnocline) while it is being advected by the ambient current. The plume thickness may decrease during this phase. The mixing rate is relatively small. The plume may interact with a nearby bank or shoreline.

3) Passive ambient mixing: After some distance the background turbulence in the ambient shear flow becomes the dominating mixing mechanism. The passive plume is growing in depth and in width. The plume may interact with the channel bottom and/or banks.

*** Predictions will be terminated in zone 2 or 3 depending on the definitions of the LEGAL MIXING ZONE or the REGION OF INTEREST. ***

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FLOW CLASS MU7

A staged multiport diffuser with predominantly parallel alignment is discharging into an ambient flow. The discharge configuration is hydrodynamically "unstable", that is the discharge strength (measured by its momentum flux) is very strong in relation to the layer depth and in relation to the stabilizing effect of the discharge buoyancy (measured by its buoyancy flux).

The following flow zones exist:

1) Acceleration zone for staged diffuser: The net horizontal momentum flux provided by the staged diffuser jets produces strong lateral entrainment of the ambient water and gradual acceleration along the diffuser line. A strong concentrated current with vertical mixing over the full layer depth is set up. This zone extends from the beginning to the end of the diffuser line.

2) Diffuser-induced plume in co-flow: The diffuser induced momentum flux is still controlling the flow. However, lateral entrainment and diffusion lead to a spreading of the diffuser plume and additional mixing. The plume moves predominantly in the direction of the ambient flow. At the beginning, the plume is vertically mixed over the full layer depth. At some distance, stratification may take place depending on the strength and direction of the plume buoyancy.

*** The zones listed above constitute the HYDRODYNAMIC MIXING ZONE in which strong initial mixing takes place. ***

3) Buoyant spreading at layer boundary: The plume spreads laterally along the layer boundary (surface or pycnocline) while it is being advected by the ambient current. The plume thickness may decrease during this phase. The mixing rate is relatively small. The plume may interact with a nearby bank or shoreline.

4) Passive ambient mixing: After some distance the background turbulence in the ambient shear flow becomes the dominating mixing mechanism. The passive plume is growing in depth and in width. The plume may interact with the channel bottom and/or banks.

*** Predictions will be terminated in zone 3 or 4 depending on the definitions of the LEGAL MIXING ZONE or the REGION OF INTEREST. ***

SPECIAL CASE: If the ambient is stagnant, then advection and diffusion by the ambient flow (zones 3 and 4) cannot be considered. The mixing is limited to the hydrodynamic mixing zone (zones 1 and 2) and the predictions will be terminated at this stage.

Such stagnant water predictions may be a useful initial mixing indicator for a given site and discharge design.

For practical final predictions, however, the advection and diffusion of the ambient flow - no matter how small in magnitude - should be considered.

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FLOW CLASS MU8

An alternating multiport diffuser with predominantly perpendicular alignment is discharging into an ambient flow. For this diffuser configuration the net horizontal momentum flux is zero so that no significant diffuser-induced currents are produced in the water body. However, the local effect of the discharge momentum flux is strong in relation to the layer depth and in relation to the stabilizing effect of the discharge buoyancy, so that the discharge configuration is hydrodynamically "unstable".

The following flow zones exist:

1) Alternating perpendicular diffuser with unstable near-field zone: The destabilizing effect of the discharge jets produces an unstable near- field zone. For stagnant or weak cross-flow conditions, a vertical recirculation zone is being produced leading to mixing over the full layer depth: however, the flow tends to re-stratify outside this zone that extends a few layer depths around the diffuser line. For strong cross-flow, additional destratification and mixing are produced.

or, alternatively, a second possibility exists for strongly buoyant discharges:

1) Near-vertical surface impingement, upstream spreading, vertical mixing, and buoyant restratification: The destabilizing effect of the discharge jets produces an unstable near-field zone. For stagnant or weak cross-flow conditions, a vertical recirculation zone is being produced leading to mixing over the full layer depth: however, the flow tends to re-stratify outside this zone that extends a few layer depths around the diffuser line. In particular, upstream spreading will occur due to the strong buoyancy of the discharge.

*** The zones listed above constitute the HYDRODYNAMIC MIXING ZONE in which strong initial mixing takes place. ***

2) Buoyant spreading at layer boundary: The plume spreads laterally along the layer boundary (surface or pycnocline)

while it is being advected by the ambient current. The plume thickness may decrease during this phase. The mixing rate is relatively small. The plume may interact with a nearby bank or shoreline.

3) Passive ambient mixing: After some distance the background turbulence in the ambient shear flow becomes the dominating mixing mechanism. The passive plume is growing in depth and in width. The plume may interact with the channel bottom and/or banks.

*** Predictions will be terminated in zone 2 or 3 depending on the definitions of the LEGAL MIXING ZONE or the REGION OF INTEREST. ***

SPECIAL CASE: If the ambient is stagnant, then advection and diffusion by the ambient flow (zones 2 and 3) cannot be considered. The mixing is limited to the hydrodynamic mixing zone (zone 1) and the predictions will be terminated at this stage.

Such stagnant water predictions may be a useful initial mixing indicator for a given site and discharge design.

For practical final predictions, however, the advection and diffusion of the ambient flow - no matter how small in magnitude - should be considered.

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FLOW CLASS MU9

An alternating multiport diffuser with predominantly parallel alignment is discharging into an ambient flow. For this diffuser configuration the net horizontal momentum flux is zero so that no significant diffuser-induced currents are produced in the water body. However, the local effect of the discharge momentum flux is strong in relation to the layer depth and in relation to the stabilizing effect of the discharge buoyancy, so that the discharge configuration is hydrodynamically "unstable".

The following flow zones exist:

1) Near-vertical surface impingement, upstream spreading, vertical mixing, and buoyant restratification: The destabilizing effect of the discharge jets produces an unstable near-field zone. For stagnant or weak cross-flow conditions, a vertical recirculation zone is being produced leading to mixing over the full layer depth: however, the flow tends to re-stratify outside this zone that extends a few layer depths around the diffuser line. In particular,

upstream spreading will occur due to the strong buoyancy of the discharge.

or, alternatively, for cases with stronger crossflow:

1) Density current developing along parallel diffuser line: The plume develops along the diffuser line due to continuous inflow of mixed buoyant water. The plume spreads laterally along the layer boundary (surface or pycnocline) which it is being advected by the ambient current. The mixing rate is relatively small. This zone extends from beginning to end of the diffuser line.

*** The zones listed above constitute the HYDRODYNAMIC MIXING ZONE in which strong initial mixing takes place. ***

2) Buoyant spreading at layer boundary: The plume spreads laterally along the layer boundary (surface or pycnocline) while it is being advected by the ambient current. The plume thickness may decrease during this phase. The mixing rate is relatively small. The plume may interact with a nearby bank or shoreline.

3) Passive ambient mixing: After some distance the background turbulence in the ambient shear flow becomes the dominating mixing mechanism. The passive plume is growing in depth and in width. The plume may interact with the channel bottom and/or banks.

*** Predictions will be terminated in zone 2 or 3 depending on the definitions of the LEGAL MIXING ZONE or the REGION OF INTEREST. ***

SPECIAL CASE: If the ambient is stagnant, then advection and diffusion by the ambient flow (zones 2 and 3) cannot be considered. The mixing is limited to the hydrodynamic mixing zone (zone 1) and the predictions will be terminated at this stage.

Such stagnant water predictions may be a useful initial mixing indicator for a given site and discharge design.

For practical final predictions, however, the advection and diffusion of the ambient flow - no matter how small in magnitude - should be considered.

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FLOW CLASS MNU1

A submerged negatively buoyant effluent issues the discharge port. The discharge configuration is hydrodynamically "stable", that is the discharge strength (measured by its momentum flux) is weak in relation to the layer depth and in relation to the stabilizing effect of the negative discharge buoyancy (measured by its buoyancy flux). The ambient current is scale in this case.

The following flow zones exist:

1) Negatively buoyant line plume: The flow issuing from the equivalent slot diffuser is dominated by the negative effluent buoyancy. Depending on vertical discharge angle, the flow may rise somewhat; but due to the strong buoyancy, it will quickly descend to the bottom. The length of this region is controlled by the jet to plume length scale.

2) Bottom boundary impingement / upstream spreading: The weakly bent jet/plume impinges on the bottom boundary at a near-vertical angle. After impingement the flow spreads more or less radially along the bottom. In particular, the flow spreads some distance upstream against the ambient flow, and laterally across the ambient flow. This spreading is dominated by the strong buoyancy of the discharge.

*** The zones listed above constitute the HYDRODYNAMIC MIXING ZONE in which strong initial mixing takes place. ***

3) Buoyant spreading at bottom boundary: The plume spreads laterally along the bottom while it is being advected by the ambient current. The plume thickness may decrease during this phase. The mixing rate is relatively small. The plume may interact with a nearby bank or shoreline.

4) Passive ambient mixing: After some distance the background turbulence in the ambient shear flow becomes the dominating mixing mechanism. The passive plume is growing in depth and in width. The plume may interact with the layer surface and/or banks.

*** Predictions will be terminated in zone 3 or 4 depending on the definitions of the LEGAL MIXING ZONE or the REGION OF INTEREST. ***

SPECIAL CASE: If the ambient is stagnant, then advection and diffusion by the ambient flow (zones 3 and 4) cannot be considered. The mixing is limited to the hydrodynamic mixing zone (zones 1 and 2) and the predictions will be terminated at this stage.

Such stagnant water predictions may be a useful initial mixing indicator for a given site and discharge design.

For practical final predictions, however, the advection and diffusion of the ambient flow - no matter how small in magnitude - should be considered.

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FLOW CLASS MNU2

A submerged negatively buoyant effluent issues either horizontally or vertically from the discharge port. The effect of ambient velocity is relatively strong.

Alternatively, this flow may arise - even though the discharge may be positively buoyant - when the discharge is oriented downward and is arrested near the bottom by some ambient stratification.

The discharge configuration is hydrodynamically "stable", that is the discharge strength (measured by its momentum flux) is weak in relation to the layer depth and in relation to the stabilizing effect of the negative discharge buoyancy (measured by its buoyancy flux).

The following flow zones exist:

1) Weakly deflected plane jet in crossflow: The flow issuing from the equivalent slot diffuser is initially dominated by the effluent momentum (jet-like) and is weakly deflected by the ambient current.

2) Strongly deflected plane jet in crossflow: The jet has become strongly deflected by the ambient current and is slowly rising toward the trapping level.

3) Strongly deflected plane plume: After some distance, the plume buoyancy starts to affect the flow. The plume is slightly deflected by the current and is slowly descending towards the bottom level.

4) Bottom layer approach: The bent-over submerged jet/plume approaches the terminal level. Within a short distance the concentration distribution becomes relatively uniform across the plume width and thickness.

or

4) Density current developing along parallel diffuser line: The plume develops along the diffuser line due to continuous inflow of mixed buoyant water. The plume spreads laterally along the layer boundary (bottom) while it is being advected by the ambient current. The mixing rate is relatively small. This zone extends from beginning to end of the diffuser line.

*** The zones listed above constitute the HYDRODYNAMIC MIXING ZONE in which strong initial mixing takes place. ***

5) Buoyant spreading at bottom boundary: The plume spreads laterally along the bottom while it is being advected by the ambient current. The plume thickness may decrease during this phase. The mixing rate is relatively small. The plume may interact with a nearby bank or shoreline.

6) Passive ambient mixing: After some distance the background turbulence in the ambient shear flow becomes the dominating mixing mechanism. The passive plume is growing in depth and in width. The plume may interact with the layer surface and/or banks.

*** Predictions will be terminated in zone 5 or 6 depending on the definitions of the LEGAL MIXING ZONE or the REGION OF INTEREST. ***

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FLOW CLASS MNU3

A submerged negatively buoyant effluent issues from a unidirectional diffuser that may have an arbitrary alignment relative to the weak ambient current.

The discharge configuration is hydrodynamically "stable", that is the discharge strength (measured by its momentum flux) is weak in relation to the layer depth and in relation to the stabilizing effect of the negative discharge buoyancy (measured by its buoyancy flux). The ambient current is scaled in this case. As a consequence, the mixed effluent will form a layer near the bottom of the ambient layer. However, the total momentum flux in this case is large enough to induce a significant current flow in this bottom layer.

The following flow zones exist:

1) Weakly deflected (2-D) wall jet: The flow issuing horizontally from the equivalent slot diffuser adheres to the bottom and spreads vertically through turbulent diffusion. A gradual deflection by the ambient current takes place.

2) Diffuser-induced bottom density current: Driven by the horizontal net momentum flux a bottom density current will propagate forward while spreading laterally with small mixing. This current is further deflected by the ambient flow into the downstream direction.

*** The zones listed above constitute the HYDRODYNAMIC MIXING ZONE in which strong initial mixing takes place. ***

3) Buoyant spreading at bottom boundary: The plume spreads laterally along the bottom while it is being advected by the ambient current. The plume thickness may decrease during this phase. The mixing rate is relatively small. The plume may interact with a nearby bank or shoreline.

4) Passive ambient mixing: After some distance the background turbulence in the ambient shear flow becomes the dominating mixing mechanism. The passive plume is growing in depth and in width. The plume may interact with the layer surface and/or banks.

*** Predictions will be terminated in zone 3 or 4 depending on the definitions of the LEGAL MIXING ZONE or the REGION OF INTEREST. ***

SPECIAL CASE: If the ambient is stagnant, then advection and diffusion by the ambient flow (zones 3 and 4) cannot be considered. The mixing is limited to the hydrodynamic mixing zone (zones 1 and 2) and the predictions will be terminated at this stage.

Such stagnant water predictions may be a useful initial mixing indicator for a given site and discharge design.

For practical final predictions, however, the advection and diffusion of the ambient flow - no matter how small in magnitude - should be considered.

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FLOW CLASS MNU4

A submerged negatively buoyant effluent issues from a unidirectional diffuser that may have an arbitrary alignment relative to the strong ambient current.

The discharge configuration is hydrodynamically "stable", that is the discharge strength (measured by its momentum flux) is weak in relation to the layer depth and in relation to the stabilizing effect of the negative discharge buoyancy (measured by its buoyancy flux). The ambient current is scaled in this case. As a consequence, the mixed effluent will form a layer near the bottom of the ambient layer. However, the total momentum flux in this case is large enough to induce a significant current flow in this bottom layer.

The following flow zones exist:

1) Weakly deflected (2-D) wall jet: The flow issuing horizontally from the equivalent slot diffuser adheres to the bottom and spreads vertically through turbulent diffusion. A

gradual deflection by the ambient current takes place.

*** The zones listed above constitute the HYDRODYNAMIC MIXING ZONE in which strong initial mixing takes place. ***

2) Buoyant spreading at bottom boundary: The plume spreads laterally along the bottom while it is being advected by the ambient current. The plume thickness may decrease during this phase. The mixing rate is relatively small. The plume may interact with a nearby bank or shoreline.

3) Passive ambient mixing: After some distance the background turbulence in the ambient shear flow becomes the dominating mixing mechanism. The passive plume is growing in depth and in width. The plume may interact with the layer surface and/or banks.

*** Predictions will be terminated in zone 2 or 3 depending on the definitions of the LEGAL MIXING ZONE or the REGION OF INTEREST. ***

SPECIAL CASE: If the ambient is stagnant, then advection and diffusion by the ambient flow (zones 2 and 3) cannot be considered. The mixing is limited to the hydrodynamic mixing zone (zone 1) and the predictions will be terminated at this stage.

Such stagnant water predictions may be a useful initial mixing indicator for a given site and discharge design.

For practical final predictions, however, the advection and diffusion of the ambient flow - no matter how small in magnitude - should be considered.

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FLOW CLASS MNU5

A submerged negatively buoyant effluent issues from a staged diffuser that may have an arbitrary alignment relative to the weak ambient current.

The discharge configuration is hydrodynamically "stable", that is the discharge strength (measured by its momentum flux) is weak in relation to the layer depth and in relation to the stabilizing effect of the negative discharge buoyancy (measured by its buoyancy flux). The ambient current is scaled in this case. As a consequence, the mixed effluent will form a layer near the bottom of the ambient layer. However, the total momentum flux in this case is large enough to induce a significant current flow in this bottom layer.

The following flow zones exist:

1) Negatively buoyant staged acceleration zone: The negatively buoyant flow issuing from the equivalent slot diffuser and in the direction of the diffuser line adheres to the bottom and spreads laterally through turbulent diffusion. The vertical thickness of this flow zone is given by the jet to plume length scale, and it extends over the full diffuser length.

2) Weakly deflected (3-D) wall jet: The flow issuing horizontally from the equivalent slot diffuser adheres to the bottom and spreads vertically through turbulent diffusion. A gradual deflection by the ambient current takes place.

3) Diffuser-induced bottom density current: Driven by the horizontal net momentum flux a bottom density current will propagate forward while spreading laterally with small mixing. This current is further deflected by the ambient flow into the downstream direction.

*** The zones listed above constitute the HYDRODYNAMIC MIXING ZONE in which strong initial mixing takes place. ***

4) Buoyant spreading at bottom boundary: The plume spreads laterally along the bottom while it is being advected by the ambient current. The plume thickness may decrease during this phase. The mixing rate is relatively small. The plume may interact with a nearby bank or shoreline.

5) Passive ambient mixing: After some distance the background turbulence in the ambient shear flow becomes the dominating mixing mechanism. The passive plume is growing in depth and in width. The plume may interact with the layer surface and/or banks.

*** Predictions will be terminated in zone 4 or 5 depending on the definitions of the LEGAL MIXING ZONE or the REGION OF INTEREST. ***

SPECIAL CASE: If the ambient is stagnant, then advection and diffusion by the ambient flow (zones 4 and 5) cannot be considered. The mixing is limited to the hydrodynamic mixing zone (zones 1 to 3) and the predictions will be terminated at this stage.

Such stagnant water predictions may be a useful initial mixing indicator for a given site and discharge design.

For practical final predictions, however, the advection and diffusion of the ambient flow - no matter how small in magnitude - should be considered.

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FLOW CLASS MNU6

A submerged negatively buoyant effluent issues from a staged diffuser that may have an arbitrary alignment relative to the strong ambient current.

The discharge configuration is hydrodynamically "stable", that is the discharge strength (measured by its momentum flux) is weak in relation to the layer depth and in relation to the stabilizing effect of the negative discharge buoyancy (measured by its buoyancy flux). The ambient current is scaled in this case. As a consequence, the mixed effluent will form a layer near the bottom of the ambient layer. However, the total momentum flux in this case is large enough to induce a significant current flow in this bottom layer.

The following flow zones exist:

1) Negatively buoyant staged acceleration zone: The negatively buoyant flow issuing from the equivalent slot diffuser and in the direction of the diffuser line adheres to the bottom and spreads laterally through turbulent diffusion. The vertical thickness of this flow zone is given by the jet to plume length scale, and it extends over the full diffuser length.

2) Weakly deflected (3-D) wall jet: The flow issuing horizontally from the equivalent slot diffuser adheres to the bottom and spreads vertically through turbulent diffusion. A gradual deflection by the ambient current takes place.

*** The zones listed above constitute the HYDRODYNAMIC MIXING ZONE in which strong initial mixing takes place. ***

3) Buoyant spreading at bottom boundary: The plume spreads laterally along the bottom while it is being advected by the ambient current. The plume thickness may decrease during this phase. The mixing rate is relatively small. The plume may interact with a nearby bank or shoreline.

4) Passive ambient mixing: After some distance the background turbulence in the ambient shear flow becomes the dominating mixing mechanism. The passive plume is growing in depth and in width. The plume may interact with the layer surface and/or banks.

*** Predictions will be terminated in zone 2 or 3 depending on the definitions of the LEGAL MIXING ZONE or the REGION OF INTEREST. ***

SPECIAL CASE: If the ambient is stagnant, then advection and diffusion by the ambient flow (zones 3 and 4) cannot be considered. The mixing is limited to the hydrodynamic mixing zone (zones 1 and 2) and the predictions will be terminated at this stage.

Such stagnant water predictions may be a useful initial mixing indicator for a given site and discharge design.

For practical final predictions, however, the advection and diffusion of the ambient flow - no matter how small in magnitude - should be considered.

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FLOW CLASS MNU7

A unidirectional multiport diffuser with perpendicular alignment is discharging into an ambient flow. Frequently, this is called a "co-flowing diffuser". The discharge configuration is hydrodynamically "unstable", that is the discharge strength (measured by its momentum flux) is very strong in relation to the layer depth and in relation to the stabilizing effect of the discharge buoyancy (measured by its buoyancy flux). Rapid vertical mixing takes place over the full layer depth.

The following flow zones exist:

1) Acceleration zone for unidirectional coflowing diffuser: The net horizontal momentum flux provided by the diffuser jets leads to a wholescale acceleration of the ambient water, that flows across the diffuser line leading to rapid entrainment and mixing in this zone. The diffuser plume is mixed over the full layer depth, and contracts laterally in the direction of the flow (acceleration process). The length of this zone is about one half the diffuser length.

2) Diffuser-induced plume in co-flow: The diffuser induced momentum flux is still controlling the flow. However, lateral entrainment and diffusion lead to a spreading of the diffuser plume and additional mixing. The plume moves predominantly in the direction of the ambient flow. At the beginning, the plume is vertically mixed over the full layer depth. At some distance, stratification may take place depending on the strength and direction of the plume buoyancy.

*** The zones listed above constitute the HYDRODYNAMIC MIXING ZONE in which strong initial mixing takes place. ***

3) Buoyant spreading at layer bottom: The plume spreads laterally along the layer boundary (bottom) while it is being advected by the ambient current. The plume thickness may

decrease during this phase. The mixing rate is relatively small. The plume may interact with a nearby bank or shoreline.

4) Passive ambient mixing: After some distance the background turbulence in the ambient shear flow becomes the dominating mixing mechanism. The passive plume is growing in depth and in width. The plume may interact with the channel bottom and/or banks.

*** Predictions will be terminated in zone 3 or 4 depending on the definitions of the LEGAL MIXING ZONE or the REGION OF INTEREST. ***

SPECIAL CASE: If the ambient is stagnant, then advection and diffusion by the ambient flow (zones 3 and 4) cannot be considered. The mixing is limited to the hydrodynamic mixing zone (zones 1 and 2) and the predictions will be terminated at this stage.

Such stagnant water predictions may be a useful initial mixing indicator for a given site and discharge design.

For practical final predictions, however, the advection and diffusion of the ambient flow - no matter how small in magnitude - should be considered.

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FLOW CLASS MNU8

A unidirectional multiport diffuser with parallel alignment (commonly called a "tee diffuser" is discharging into a weak ambient flow. The discharge configuration is hydrodynamically "unstable", that is the discharge strength (measured by its momentum flux) is very strong in relation to the layer depth and in relation to the stabilizing effect of the discharge buoyancy (measured by its buoyancy flux).

The following flow zones exist:

1) Acceleration zone for unidirectional co-flowing diffuser (tee): The net horizontal momentum flux provided by the diffuser jets leads to a wholescale acceleration of the ambient water, that is diverted across the diffuser line leading to rapid entrainment and mixing in this zone. The diffuser plume is mixed over the full layer depth, and contracts laterally in the direction of the flow (acceleration process). The length of this zone is about one half the diffuser length. Plume deflection by the ambient current is insignificant.

2) Diffuser-induced plume in cross-flow: The diffuser induced momentum flux is still controlling the flow. However, lateral entrainment and diffusion lead to a spreading of the diffuser plume and additional mixing. Initially, the plume is cross-flowing, but it becomes progressively deflected into the direction of the ambient flow. At the beginning, the plume is vertically mixed over the full layer depth. At some distance, stratification may take place depending on the strength and direction of the plume buoyancy.

*** The zones listed above constitute the HYDRODYNAMIC MIXING ZONE in which strong initial mixing takes place. ***

3) Buoyant spreading at layer bottom: The plume spreads laterally along the layer boundary (bottom) while it is being advected by the ambient current. The plume thickness may decrease during this phase. The mixing rate is relatively small. The plume may interact with a nearby bank or shoreline.

4) Passive ambient mixing: After some distance the background turbulence in the ambient shear flow becomes the dominating mixing mechanism. The passive plume is growing in depth and in width. The plume may interact with the channel bottom and/or banks.

*** Predictions will be terminated in zone 3 or 4 depending on the definitions of the LEGAL MIXING ZONE or the REGION OF INTEREST. ***

SPECIAL CASE: If the ambient is stagnant, then advection and diffusion by the ambient flow (zones 3 and 4) cannot be considered. The mixing is limited to the hydrodynamic mixing zone (zones 1 and 2) and the predictions will be terminated at this stage.

Such stagnant water predictions may be a useful initial mixing indicator for a given site and discharge design.

For practical final predictions, however, the advection and diffusion of the ambient flow - no matter how small in magnitude - should be considered.

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FLOW CLASS MNU9

A unidirectional multiport diffuser with parallel alignment (commonly called a "tee diffuser" is discharging into a strong ambient flow. The discharge configuration is hydrodynamically "unstable", that is the discharge strength (measured by its momentum flux) is very strong in relation to the layer depth and in relation to the stabilizing effect of the discharge buoyancy (measured by its buoyancy flux). The ambient current is very strong in the present case.

The following flow zones exist:

1) Unidirectional cross-flowing (tee) diffuser plume in strong current: The strong ambient crossflow rapidly deflects the diffuser induced plume flow. The diffuser plume is advected in the direction of the ambient flow. This plume deflection is associated with a recirculation zone at the downstream end (lee) of the plume. The plume is vertically mixed over the full layer depth in this zone.

*** The zones listed above constitute the HYDRODYNAMIC MIXING ZONE in which strong initial mixing takes place. ***

2) Buoyant spreading at layer bottom: The plume spreads laterally along the layer boundary (bottom) while it is being advected by the ambient current. The plume thickness may decrease during this phase. The mixing rate is relatively small. The plume may interact with a nearby bank or shoreline.

3) Passive ambient mixing: After some distance the background turbulence in the ambient shear flow becomes the dominating mixing mechanism. The passive plume is growing in depth and in width. The plume may interact with the channel bottom and/or banks.

*** Predictions will be terminated in zone 2 or 3 depending on the definitions of the LEGAL MIXING ZONE or the REGION OF INTEREST. ***

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FLOW CLASS MNU10

A staged multiport diffuser with predominantly perpendicular alignment is discharging into weak ambient flow. The discharge configuration is hydrodynamically "unstable", that is the discharge strength (measured by its momentum flux) is very strong in relation to the layer depth and in relation to the stabilizing effect of the discharge buoyancy (measured by its buoyancy flux).

The following flow zones exist:

1) Acceleration zone for staged diffuser: The net horizontal momentum flux provided by the staged diffuser jets produces strong lateral entrainment of the ambient water and gradual acceleration along the diffuser line. A strong concentrated

current with vertical mixing over the full layer depth is set up. This zone extends from the beginning to the end of the diffuser line.

2) Diffuser-induced plume in cross-flow: The diffuser induced momentum flux is still controlling the flow. However, lateral entrainment and diffusion lead to a spreading of the diffuser plume and additional mixing. Initially, the plume is cross-flowing, but it becomes progressively deflected into the direction of the ambient flow. At the beginning, the plume is vertically mixed over the full layer depth. At some distance, stratification may take place depending on the strength and direction of the plume buoyancy.

*** The zones listed above constitute the HYDRODYNAMIC MIXING ZONE in which strong initial mixing takes place. ***

3) Buoyant spreading at layer bottom: The plume spreads laterally along the layer boundary (bottom) while it is being advected by the ambient current. The plume thickness may decrease during this phase. The mixing rate is relatively small. The plume may interact with a nearby bank or shoreline.

4) Passive ambient mixing: After some distance the background turbulence in the ambient shear flow becomes the dominating mixing mechanism. The passive plume is growing in depth and in width. The plume may interact with the channel bottom and/or banks.

*** Predictions will be terminated in zone 3 or 4 depending on the definitions of the LEGAL MIXING ZONE or the REGION OF INTEREST. ***

SPECIAL CASE: If the ambient is stagnant, then advection and diffusion by the ambient flow (zones 3 and 4) cannot be considered. The mixing is limited to the hydrodynamic mixing zone (zones 1 and 2) and the predictions will be terminated at this stage.

Such stagnant water predictions may be a useful initial mixing indicator for a given site and discharge design.

For practical final predictions, however, the advection and diffusion of the ambient flow - no matter how small in magnitude - should be considered.

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FLOW CLASS MNU11

A staged multiport diffuser with perpendicular alignment is discharging into a strong ambient flow. The discharge configuration is hydrodynamically "unstable", that is the discharge strength (measured by its momentum flux) is very strong in relation to the layer depth and in relation to the stabilizing effect of the discharge buoyancy (measured by its buoyancy flux). The ambient current is very strong in the present case.

The following flow zones exist:

1) Staged perpendicular plume in strong current: The strong ambient flow rapidly deflects the diffuser induced plume. Ambient water flows across the diffuser line, and the diffuser plume is advected in the direction of the ambient flow. The length of this zone is about one half of the diffuser length.

*** The zones listed above constitute the HYDRODYNAMIC MIXING ZONE in which strong initial mixing takes place. ***

2) Buoyant spreading at layer bottom: The plume spreads laterally along the layer boundary (bottom) while it is being advected by the ambient current. The plume thickness may decrease during this phase. The mixing rate is relatively small. The plume may interact with a nearby bank or shoreline.

3) Passive ambient mixing: After some distance the background turbulence in the ambient shear flow becomes the dominating mixing mechanism. The passive plume is growing in depth and in width. The plume may interact with the channel bottom and/or banks.

*** Predictions will be terminated in zone 2 or 3 depending on the definitions of the LEGAL MIXING ZONE or the REGION OF INTEREST. ***

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FLOW CLASS MNU12

A staged multiport diffuser with predominantly parallel alignment is discharging into an ambient flow. The discharge configuration is hydrodynamically "unstable", that is the discharge strength (measured by its momentum flux) is very strong in relation to the layer depth and in relation to the stabilizing effect of the discharge buoyancy (measured by its buoyancy flux).

The following flow zones exist:

1) Acceleration zone for staged diffuser: The net horizontal

momentum flux provided by the staged diffuser jets produces strong lateral entrainment of the ambient water and gradual acceleration along the diffuser line. A strong concentrated current with vertical mixing over the full layer depth is set up. This zone extends from the beginning to the end of the diffuser line.

2) Diffuser-induced plume in co-flow: The diffuser induced momentum flux is still controlling the flow. However, lateral entrainment and diffusion lead to a spreading of the diffuser plume and additional mixing. The plume moves predominantly in the direction of the ambient flow. At the beginning, the plume is vertically mixed over the full layer depth. At some distance, stratification may take place depending on the strength and direction of the plume buoyancy.

*** The zones listed above constitute the HYDRODYNAMIC MIXING ZONE in which strong initial mixing takes place. ***

3) Buoyant spreading at layer bottom: The plume spreads laterally along the layer boundary (bottom) while it is being advected by the ambient current. The plume thickness may decrease during this phase. The mixing rate is relatively small. The plume may interact with a nearby bank or shoreline.

4) Passive ambient mixing: After some distance the background turbulence in the ambient shear flow becomes the dominating mixing mechanism. The passive plume is growing in depth and in width. The plume may interact with the channel bottom and/or banks.

*** Predictions will be terminated in zone 3 or 4 depending on the definitions of the LEGAL MIXING ZONE or the REGION OF INTEREST. ***

SPECIAL CASE: If the ambient is stagnant, then advection and diffusion by the ambient flow (zones 3 and 4) cannot be considered. The mixing is limited to the hydrodynamic mixing zone (zones 1 and 2) and the predictions will be terminated at this stage.

Such stagnant water predictions may be a useful initial mixing indicator for a given site and discharge design.

For practical final predictions, however, the advection and diffusion of the ambient flow - no matter how small in magnitude - should be considered.

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FLOW CLASS MNU13

An alternating multiport diffuser with predominantly perpendicular alignment is discharging into an ambient flow. For this diffuser configuration the net horizontal momentum flux is zero so that no significant diffuser-induced currents are produced in the water body. However, the local effect of the discharge momentum flux is strong in relation to the layer depth and in relation to the stabilizing effect of the discharge buoyancy, so that the discharge configuration is hydrodynamically "unstable".

The following flow zones exist:

1) Alternating perpendicular diffuser with unstable near-field zone: The destabilizing effect of the discharge jets produces an unstable near- field zone. For stagnant or weak cross-flow conditions, a vertical recirculation zone is being produced leading to mixing over the full layer depth: however, the flow tends to re-stratify outside this zone that extends a few layer depths around the diffuser line. For strong cross-flow, additional destratification and mixing are produced.

or, alternatively, a second possibility exists for strongly buoyant discharges:

1) Near-vertical surface impingement, upstream spreading, vertical mixing, and buoyant restratification: The destabilizing effect of the discharge jets produces an unstable near-field zone. For stagnant or weak cross-flow conditions, a vertical recirculation zone is being produced leading to mixing over the full layer depth: however, the flow tends to re-stratify outside this zone that extends a few layer depths around the diffuser line. In particular, upstream spreading will occur due to the strong buoyancy of the discharge.

*** The zones listed above constitute the HYDRODYNAMIC MIXING ZONE in which strong initial mixing takes place. ***

2) Buoyant spreading at layer bottom: The plume spreads laterally along the layer boundary (bottom) while it is being advected by the ambient current. The plume thickness may decrease during this phase. The mixing rate is relatively small. The plume may interact with a nearby bank or shoreline.

3) Passive ambient mixing: After some distance the background turbulence in the ambient shear flow becomes the dominating mixing mechanism. The passive plume is growing in depth and in width. The plume may interact with the channel bottom and/or banks.

*** Predictions will be terminated in zone 2 or 3 depending on the definitions of the LEGAL MIXING ZONE or the REGION OF INTEREST. ***

SPECIAL CASE: If the ambient is stagnant, then advection and diffusion by the ambient flow (zones 2 and 3) cannot be considered. The mixing is limited to the hydrodynamic mixing zone (zone 1) and the predictions will be terminated at this stage.

Such stagnant water predictions may be a useful initial mixing indicator for a given site and discharge design.

For practical final predictions, however, the advection and diffusion of the ambient flow - no matter how small in magnitude - should be considered.

****

FLOW CLASS MNU14

An alternating multiport diffuser with predominantly parallel alignment is discharging into an ambient flow. For this diffuser configuration the net horizontal momentum flux is zero so that no significant diffuser-induced currents are produced in the water body. However, the local effect of the discharge momentum flux is strong in relation to the layer depth and in relation to the stabilizing effect of the discharge buoyancy, so that the discharge configuration is hydrodynamically "unstable".

The following flow zones exist:

1) Near-vertical surface impingement, upstream spreading, vertical mixing, and buoyant restratification: The destabilizing effect of the discharge jets produces an unstable near-field zone. For stagnant or weak cross-flow conditions, a vertical recirculation zone is being produced leading to mixing over the full layer depth: however, the flow tends to re-stratify outside this zone that extends a few layer depths around the diffuser line. In particular, upstream spreading will occur due to the strong buoyancy of the discharge.

or, alternatively, for cases with stronger crossflow:

1) Density current developing along parallel diffuser line: The plume develops along the diffuser line due to continuous inflow of mixed buoyant water. The plume spreads laterally along the layer boundary (surface or pycnocline) which it is being advected by the ambient current. The mixing rate is relatively small. This zone extends from beginning to end of

the diffuser line.

*** The zones listed above constitute the HYDRODYNAMIC MIXING ZONE in which strong initial mixing takes place. ***

2) Buoyant spreading at layer bottom: The plume spreads laterally along the layer boundary (bottom) while it is being advected by the ambient current. The plume thickness may decrease during this phase. The mixing rate is relatively small. The plume may interact with a nearby bank or shoreline.

3) Passive ambient mixing: After some distance the background turbulence in the ambient shear flow becomes the dominating mixing mechanism. The passive plume is growing in depth and in width. The plume may interact with the channel bottom and/or banks.

*** Predictions will be terminated in zone 2 or 3 depending on the definitions of the LEGAL MIXING ZONE or the REGION OF INTEREST. ***

SPECIAL CASE: If the ambient is stagnant, then advection and diffusion by the ambient flow (zones 2 and 3) cannot be considered. The mixing is limited to the hydrodynamic mixing zone (zone 1) and the predictions will be terminated at this stage.

Such stagnant water predictions may be a useful initial mixing indicator for a given site and discharge design.

For practical final predictions, however, the advection and diffusion of the ambient flow - no matter how small in magnitude - should be considered.

Appendix C: Design Recommendations

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DESIGN RECOMMENDATIONS AND GENERAL ADVICE:

A reliable environmental analysis and mixing zone prediction is possible only if each design case is evaluated through several iterations of CORMIX. Small changes in ambient or discharge design conditions can sometimes cause drastic shifts in the applicable flow configuration (flow class) and the size or appearance of mixing zones. Iterative use of CORMIX will give information on the sensitivity of predicted results on design and ambient conditions.

Each predictive case should be carefully assessed as to:

- size and shape of LMZ,
- conditions in the TDZ (if present),
- bottom impact of the discharge flow,
- water surface exposure,
- bank attachment, and other factors.

In general, iterations should be conducted in the following order:

A) Diffuser design changes (geometry variations),
B) Sensitivity to ambient conditions, and
C) Discharge flow changes (process variations).

When investigating these variations the CORMIX user will quickly appreciate the fact that mixing conditions at short distances (near-field) are usually quite sensitive and controllable. In contrast, mixing conditions at large distances (far-field) often show little sensitivity unless the ambient conditions change substantially or drastic process variations are introduced.

A) DIFFUSER DESIGN CHANGES (GEOMETRY VARIATIONS):

Most of the following recommendations are motivated by the desire for improving conditions in the applicable mixing zones (i.e. minimizing concentrations and/or areal extents):

1) Diffuser location: Consider moving the outfall further offshore to a larger water depth in order to delay flow interaction with the bank/shore, and to improve near-field mixing.

2) Diffuser type: The diffuser type is dictated by its nozzle/port arrangement (angles THETA and BETA with or without fanning) and its alignment (angle GAMMA) relative to the

current. Many combinations are possible (see also the advice on discharge conditions in DATIN). No hard and fast rules can be given on the most desirable type and arrangement. The diffuser choice is often dictated by local bathymetry and other conditions, e.g. clearances for navigation or fishing.

Performance features for the three major types are:

A. UNIDIRECTIONAL DIFFUSER:
This type has a directed net momentum input. It tends to produce strong currents in the receiving water, especially under shallow conditions, often associated with benthic impacts. A fanned-out port/nozzle design variable BETA) usually gives somewhat improved dilutions.

Perpendicular alignment ("co-flowing diffuser"): This is the preferred type for non-reversing flows, as in rivers and in some coastal conditions. Note that in riverine situations the river flow provides an upper limit on the achievable dilution.

Parallel alignment ("tee diffuser"): This alignment may be acceptable for weak reversing coastal flows to provide offshore transport for the diffuser plume. It provides poor mixing under strong current conditions.

B. STAGED DIFFUSER:
This type also provides a directed momentum input. Hence, it can lead to strong induced currents, with plume contact at the bottom.

Perpendicular alignment: This is a good arrangement for shallow water conditions in the coastal environment under weak or strong reversing currents. Under weak currents it gives good offshore transport, and it efficiently captures the ambient flow under strong current conditions.

Parallel alignment: Generally not advantageous.

C. ALTERNATING DIFFUSER:
This type has no directed net momentum input. Its dilution efficiency is mostly dictated by its buoyancy flux and by the ambient current. It usually has the least benthic impact. A fanned-out (variable BETA) will give somewhat improved dilutions especially under shallow water conditions.

Perpendicular alignment: This is the preferred arrangement for deep water (e.g. sewage) diffusers in coastal environments with variable currents and stratification. It may also be advisable for more shallow conditions if minimal influences on the ambient regime current are desired.

Parallel alignment: May be desirable because of bathymetric or navigational reasons.

3) Diffuser length: By and large, a longer diffuser will give better dilutions. However, this may not be the case for diffusers in parallel alignment, especially with strong ambient currents. Also keep in mind the dilution limitations given by the total flow in riverine situations. Typically, an alternating type will require a longer diffuser than the unidirectional or staged type in order to achieve the same near-field mixing.

4) Number of ports/nozzles and port/nozzle diameter (discharge velocity): Remember that for a given discharge flow rate the port area and discharge velocity are inversely related: a small discharge port implies a high discharge velocity, and a consequently high discharge momentum flux. Typically, a high velocity discharge will maximize near-field mixing. Note, however, that high velocity discharges a) may lead to unstable near-field flow configurations perhaps involving undesirable mixing patterns, and b) usually have little, if any, effect on dilutions over the far-field where a LMZ may apply. Discharge velocities in typical engineering designs may range from 3 m/s to 8 m/s. Very high velocities may lead to excessive pumping energy requirements. Very low velocities (less than 0.5 m/s) may lead to undesirable sediment accumulation within the discharge pipe or tunnel.

5) Port/riser spacing: Given the other constraints on diffuser mixing (i.e. diffuser length and discharge velocity) the spacing is a dynamically unimportant variable that has a limited effect on overall mixing. However, the spacing plays a role in the merging process of the individual jets/plumes, and thus may affect the very initial mixing, e.g. as of interest in toxic dilution zone (TDZ) predictions. As a rough rule, merging takes place after a distance along the plume path of about three to five spacings. If the TDZ is encountered before then, additional single jet/plume predictions, using CORMIX1, may be needed.

6) Port height: In most cases, this is a dynamically unimportant parameter. However, there are important exceptions: For negatively buoyant discharges, the port height may control the amount of initial mixing prior to benthic contact. More generally, for deep water discharges the port height to water depth ratio has some effect on initial mixing. Finally, in the presence of crossflow, the port height influences the stability of the discharge, i.e.

the distinction between deep and shallow water discharges.

B) SENSITIVITY TO AMBIENT CONDITIONS:

Variations - of the order of 25 percent - of the following ambient design conditions should be considered:
- ambient velocity (or ambient flowrate),
- ambient depth (or river/tidal stage), and
- ambient density structure (notably density differences).

Such variability is important for two reasons:
1) the usual uncertainty in ambient environmental data, and
2) the schematization employed by CORMIX1.

Please refer to the detailed advice on the specification of environmental data, including the density structure, that is available in program element DATIN. In particular, note the advisory comments on stagnant ambient conditions.

C) DISCHARGE FLOW CHANGES (PROCESS VARIATIONS):

Actual process changes can result in variations of one or more of three parameters associated with the discharge: flowrate, density, or pollutant concentration. In some cases, such process changes may be difficult to achieve or too costly. Note, that "off-design" conditions in which a discharge operates below its full capacity also fall into this category.

1) Pollutant mass flux: The total pollutant mass flux is the product of discharge flow (m**3/s) times the discharge pollutant concentration (in arbitrary units). Thus, decreasing the pollutant mass flux will, in general, decrease the resulting pollutant concentration in the near-field and far-field. This occurs, of course, during off-design conditions.

2) Discharge flow: For a given pollutant mass flux, an increase in discharge flow implies an increase in discharge pollutant concentration, and vice versa. For the variety of flow classes contained in CORMIX2 there is no universal rule whether high or low volume discharges are preferable for optimizing near-field mixing. Mostly, the sensitivity is small, and even more so for far-field effects. Note that a change in discharge flow will influence, in turn, the discharge velocity and hence the momentum flux.

3) Discharge density: The actual density of the discharge flow controls the buoyancy effects relative to the ambient water. Occasionally, the discharge density is controllable through the amount of process heating or cooling occurring prior to

discharge. Usually, near-field mixing is enhanced by maximizing the total density difference (positive or negative) between discharge flow and ambient water. In most cases, however, this effect is minor.

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