CORMIX1 AN EXPERT SYSTEM FOR MIXING ZONE ANALYSIS OF CONVENTIONAL AND TOXIC SINGLE PORT AQUATIC DISCHARGES

by

Robert L. Doneker and Gerhard H. Jirka
DeFrees Hydraulics Laboratory
Department of Environmental Engineering
Cornell University, Ithaca, New York 14853

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Project Officer

Thomas O. Barnwell, Jr.
Assessment Branch
Environmental Research Laboratory
Athens, Georgia 30613

ENVIRONMENTAL RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
ATHENS, GEORGIA 30613

FOREWORD

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Chapter I
Legal Background and Introduction

1.A History of the Clean Water Act

Prior to 1948, States, local, and regional agencies were primarily responsible for controlling water pollution. After the realization in the mid-1800's of the role of contaminated water in the transmission of disease, State Boards of Health were formed to administer water pollution control programs. Most early pollution control programs focused on water-borne infectious diseases like typhoid and cholera (Ortolano,1984).

Table 1.1 outlines key federal water pollution control legislation since 1948. The 1948 Water Pollution Control Act was designed to provide technical services to the States to strengthen their water pollution control programs. The 1948 Act focused on the primacy of the State role in water quality management. Federal action against polluters could only be taken with the consent of the State from which the pollution was alleged to originate.

The Federal Water Pollution Control Act (FWPCA) of 1956 expanded the federal role in controlling water pollution. The Act provided a program of subsidies for municipal treatment plant construction, strengthened powers of enforcement against polluters, increased funding for State water pollution control efforts, and provided new support for research and teaching.

Each of these programs were included in the many amendments to the Act in the 1960's and 1970's.

The Water Quality Act of 1965 set new requirements for States to establish ambient water quality standards and increased the level of federal funding. Water quality standards were designed to protect designated water uses within a stretch of river. The Act required that State agencies set water quality criteria to meet these standards. Criteria established the suitability of water for different activities. If the uses of water within a stretch of river and the criteria designed to protect those uses were known, ambient water quality standards could be set.

1.A.1 The Federal Water Pollution Control Act of 1972

Prior to the 1972 Federal Water Pollution Control Act (FWPCA) only States had power to develop ambient water quality

Table 1.1 Key Federal Water Pollution Control Laws
Source: Ortolano, 1984

Year	Title	Selected New Elements of Federal Strategy*
1948	Water Pollution Control Act	Funds for State water pollution control agencies Technical assistance to States Limited provisions for legal action against polluters
1956	Federal Water Pollution Control Act (FWPCA)	Funds for water pollution research and training Construction grants to municipalities Three stage enforcement process
1965	Water Quality Act	States set water quality standards States prepare implementation plans
1972	FWPCA Amendments	Zero discharge of pollutants as a goal BPT and BAT effluent limitations NPDES permits Enforcement based on permit violations
1977	Clean Water Act	BAT requirements for toxic substances BCT requirements for conventional pollutants
1981	Municipal Waste Treatment Construction Grants Amendments	Reduced federal share in construction grants program

*The table entries include only significant new changes established by the law.

standards applicable to interstate or navigable waters. Water quality standards depended upon intended use -agricultural, industrial, or recreational.

Enforcement of water quality standards was only possible if water quality fell below standards. This hampered enforcement efforts because proof of causation was difficult in waters receiving wastes from various polluters. State water quality standards could be lowered to attract industry away from States with more stringent water quality standards.

Congress decided to take rigorous action in 1972 with the FWPCA amendments. The Act established a uniform system of water quality standards, permits, and enforcement. The "goals" of the legislation were to produce fishable, swimmable water by 1983 and a total elimination of water pollution by 1985 (Findley and Farber, 1983).

Major changes in the FWPCA of 1972 included i) national water quality goals, ii) technology-based effluent limitations, iii) a national discharge permit system, and iv) federal court action against sources in violation of permit conditions (Ortolano, 1984).

Congressional intent in passing the FWPCA was to rule out arguments of assimilative capacity of receiving waters. Congress wanted uniformity of standards and enforcement. Ambient water quality standards were intended to be "more stringent" than effluent standards. The aim of the 1972 amendments was to restore and maintain "the chemical, physical, and biological integrity of the nation's waters" (Weyerhauser Co. v. Costle 590 F.2d 1001).

The 1972 amendments gave broad powers to the federal Environmental Protection Agency (USEPA) administrator to define pollutants and to determine and promulgate effluent limitations. Effluent limitations were set according to industry through the National Pollution Discharge Elimination System (NPDES) permit system. These discharge limits were set independent of the particular context in which the pollution discharge occurs. Dischargers in violation of NPDES pollution limits were subject to enforcement action.

The Act contained ambient water quality standards that supplemented federal discharge standards for point sources. Point sources were defined as "any discernable, confined, and discrete conveyance .... from which pollutants are, or may be discharged."

The 1972 FWPCA required that industry dischargers meet "best practicable control technology currently available"

(BPT) standards by 1977 and "best available technology economically achievable" (BAT) standards by 1983.

The Act required public sources of pollution to use secondary treatment by 1977 and use "best practicable waste treatment over life of the works" by 1983.

Specific sections of the Act include:

Section 301 of the Act set standards for point sources that were not publicly owned treatment works (POTW). It requires dischargers to reduce emissions using "best practicable control technology currently available" (BPT) by 1977 and "best available technology economically achievable" (BAT) by 1983.

Section 302 of the Act set ambient water quality standards. Ambient water quality standards were to comply with State or federal law, whichever was more stringent to achieve ambient water quality goals.

Section 306 of the Act pertains to new sources. This section required such facilities to meet standards equivalent to 1983 BAT standards.

Section 307 covers toxic water pollutants. It requires that standards be developed for toxic water pollutants based on public health and welfare and not technical feasibility.

Section 402 of the Act empowers the federal government to create a National Pollution Discharge Elimination System (NPDES). This pollution permit system empowers the USEPA to set national effluent standards and grants States, with USEPA approval, the responsibility of administering the program. NPDES applies to any discharge to receiving waters. NPDES permits had to incorporate applicable limitations under sections 301, 302, 306, and 307 of the Act, including enforcement to meet 1977 and 1983 deadlines.

Section 505 of provides the right of citizen suits to enforce provisions of the Act. States have the primary responsibility to enforce the provisions of the Act, but the Federal government has the right to step in and enforce any provision of the Act.

1.A.2 The Clean Water Act of 1977

In 1977 the FWPCA was amended by congress. These amendments are known as the Clean Water Act (CWA). Five general categories of pollutants covered in the Act are; i) conventional, ii) nonconventional, iii) toxics, iv) heat, and v) dredge and fill spoil. The Act distinguishes between new and existing source for setting effluent standards. Table 1.2 lists examples of the first three pollutant catagories.

Pollutants designated as "conventional" would be "as defined by the administrator in compliance with the Act as amended, generally those pollutants that are naturally occurring, biodegradable, oxygen demanding materials and solids. In addition, compounds which are not toxic and which are similar in characteristic to naturally occurring, biodegradable substances are to be designated as conventional pollutants for the purposes of the provision" (Congressional Research Service, 1977).

Pollutants designated as "nonconventional" would be "those which are not toxic or conventional." (Congressional Research Service, 1977). Table 1.3 illustrates the kinds of effluent standards set by USEPA under the 1977 amendments.

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.

Congress modified BAT standards in the Clean Water Act of 1977. This action was in response to criticism the original BAT effluent limitations required too high a percentage removal of pollutants and the cost of reduction in these residuals would be much greater than the benefits. BAT standards apply to unconventional and toxic pollutants.

A variance provision for BAT standards for nonconventional pollutants is contained in section 301(g) of the Act. It allows the USEPA along with State approval to modify effluent standards for nonconventional pollutants if this did not interfere with water quality standards or public health.

All river segments within States are classified as water quality limited or effluent limited under section 303(e) of the Act. Effluent limited segments are defined as those stream reaches for which ambient water quality standards can be met in 1977 by application of best practicable control technology currently available (BPT) to industry and secondary treatment to publicly owned treatment works (POTW). When ambient water quality standards can not be met by BPT for industry and secondary treatment for POTW, these reaches are classified as water quality limited.

Table 1.2 Examples of Conventional, Nonconventional, and Toxic Pollutants

Source: Technical Guidance Manual For The Regulations Promulgated Pursuant to Section 301(g) of the CWA 1977.

Conventional	Nonconventional	Toxic
biochemical oxygen demand (BOD)	chemical oxygen demand (COD)	zinc cyanides
pH	chlorine	toluene
total suspended solids(TSS)	aluminum	benzene
fecal coliform bacteria	barium	asbestos
oil and grease	ammonia	copper

Table 1.3 Examples of Technology-Based Effluent Limitations Under The Clean Water Act of 1977
Source: Ortolano, 1984.

Publicly Owned Treatment Works:

Requirements for 85% BOD removal, with possible case-by-case variances that allow lower removal percentages for marine discharges.

Industrial Discharges (bases for effluent limitations)

Toxic pollutants - BAT

Conventional pollutants - BCT; in determining required control technology, USEPA is directed to consider "the reasonableness of the relationship between the costs of attaining a reduction in effluent and the effluent reduction benefits derived."

Nonconventional pollutants - BAT, but with possible case-by-case variances that allow for lower degrees of treatment.

1.B Development of Mixing Zone Concept

The concept of a mixing zone is defined as an "allocated impact zone" where numeric water quality criteria can be exceeded as long as acutely toxic conditions are prevented. A mixing zone can be thought of as a limited area or volume where the initial dilution of a discharge occurs (Water Quality Standards Handbook,1982). Water quality criteria apply to the boundary of the mixing zone, not within the mixing zone itself. EPA and its predecessor agencies have published numerous documents giving guidance for determining mixing zones such as the National Academy of Science Water Quality Criteria 1968 (Green Book), EPA publications Quality Criteria for Water 1976 (Red Book), and Guidelines for State and Area Wide Water Quality Management Program. Guidance published by EPA in Water Quality Standards Handbook (Oct. 1982) supersedes these sources.

In setting requirements for mixing zones, USEPA requires that the size be "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 and avoids impingement on biologically important areas....shore hugging plumes should be avoided." Within the mixing zone USEPA requires "any mixing zone should be free of point or nonpoint source related:

(a) Material in concentrations that will cause acute toxicity to aquatic life;

(b) Materials in concentrations that settle to form objectionable deposits;

(c) Floating debris, oil scum and other matter in concentrations that form nuisances;

(d) Substances in concentrations that produce objectionable color, odor, taste or turbidity; and

(e) Substances in concentrations which produce undesirable aquatic life or result in a dominance of nuisance species."

(USEPA, Water Quality Standards Handbook, 1982).

The proposed rules for mixing zones recognizes 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. State standards require that water quality criteria be met at the edge of the regulatory mixing zone 1) to provide a continuous zone of free passage that meets water quality criteria for free-swimming and drifting organisms and 2) to prevent impairment of critical resource areas (USEPA, Technical Support Document for Water Quality-based Toxics Control, 1985). A review of individual State mixing zone policies shows that 48 out of 50 States make use of a mixing zone in some form and can be seen in Table 1.4

For discharges into streams, 17 of the 31 States that propose a mixing zone specify that the mixing zone shall not exceed 1/4 of the cross-sectional area and/or volume of the stream flow, and the remaining 3/4 of the stream shall be maintained as a zone of passage for swimming and drifting organisms.

The remaining States have varying requirements allowing dimensions of the mixing zone to be as low as 1/5 of the cross-sectional area (Ohio) to as much as 3/4 of the cross-sectional area (South Dakota). West Virginia is the only State that specifies a length dimension for mixing zones. The length of the mixing zone must be less than 10 times the average width of the stream or less than 5 times the average width of the stream for warm water and cold water streams, respectively.

In States which specify a mixing zone for lakes, dimensions for the mixing zone vary from 10% of the surface area of the lake to 300-1000' radial limits around the discharge point.

Pennsylvania and Arizona are the two States that do not make reference to a mixing zone. Therefore the USEPA does not recognize any mixing zone for these States and water quality criteria must be met at the point of discharge unless the applicant and the State develop a mixing zone on a case by case basis.

With the exception of West Virginia, the length of the mixing zone is not specified. Usually, the size of the mixing zone is determined on a case-by-case basis taking into account the critical resource areas that need to be protected. Mixing zones should be used and evaluated in cases where mixing is not complete within a short distance of the outfall. EPA recommends careful evaluation of mixing to prevent zones of chronic toxicity that extend for miles downstream because of poor mixing. (USEPA, Technical Support Document for Water Quality-based Toxics Control, 1985).

Table 1.4 State Legal Mixing Zones

Source: Draft Technical Guidance Manual for the Regulations Promulgated Pursuant To Section 301(g)

State	Water Body	Dimensions
Alabama	0	0
Alaska	river,streams	<= 1/3 CS
	lakes	<= 10% SA
Arizona	NR	NR
Arkansas	large streams	<=1/4 CS
California	0	0
Colorado	0	0
Connecticut	streams	<=1/4 CS
Delaware	streams	<=1/3 CS
	lakes	<=10% SA
D.C	estuary	<=10% SA
Georgia	0	0
Florida	streams,rivers	<=800 meters <=10% total length
	lakes, estuaries	<=125,600 m**2 (600' radius) <=10% SA
Hawaii	0	0
Idaho	0	0
Illinois	all	<=600' radius
	streams	<=1/4 CS
Indiana	streams	<=1/4 CS
Iowa	streams	<=1/4 CS
Kansas	streams	<=1/4 CS
Kentucky	streams	<=1/3 CS
Louisiana	streams	<=1/4 CS
Maine	streams	<=1/4 CS
Maryland	0	0
Massachusetts	0	0
Michigan	streams	<=1/4 CS
	Lake Michigan	<=1000' radius
Minnesota	streams	<=1/4 CS
Mississippi	0	0
Missouri	streams	<= 1/4 CS
Montana	0	0
Nebraska	0	0
New Jersey	streams	<=1/4 CS (thermal)
New Hampshire	streams	<=1/4 CS
New Mexico	streams	<=1/4 CS
New York	streams	<=1/2 CS (thermal)

Table 1.4 (Continued)

Nevada	streams	<=1/3 CS
North Carolina	0	0
North Dakota	streams	<=1/4 CS
Ohio	receiving watercourse	<=1/3 CS
	mouth of receiving	<=1/5 CS
Oklahoma	streams	<=1/4 CS
Oregon	0	0
Pennsylvania	NR	NR
Rhode Island	streams	<=1/4 CS (thermal)
South Carolina	0	0
S. Dakota	streams	<=3/4 CS or 100 yds of streams width
Tennessee	0	0
Texas	streams	<=1/4 CS
Utah	0	0
Vermont	streams	<=1/4 CS
Virginia	0	0
Washington	0	0
W. Virginia	warm water fish streams	<=33% CS, length <=10*width
	cold water fish streams	<=20% CS, length <=5*width
	lakes	<=300' any direction
Wisconsin	streams	<=1/4 CS
Wyoming	0	0
Guam	0	0
Puerto Rico	streams	<=1/4 CS
	IMZ	<= 400 '
	FMZ	<= 4000 '
Virgin Islands	streams	<= 1/4 CS

Where:

CS = cross-sectional area
NR = no reference
IMZ = initial mixing zone
SA = surface area
0 = not listed
FMZ = Final mixing zone

1.C Special Mixing Zone Requirements for Toxics

In order to prevent lethal concentrations of toxics in the regulatory mixing zone, regulations can prohibit lethal concentrations in the pipe itself, or require that a concentration known as the criterion maximum concentration (CMC) be met within a short distance from the outfall. The CMC is a concentration that prevents lethality or acute affects in tested species. If dilution of the toxic discharge in the ambient environment is allowed, this requirement, which will be defined here as a toxic dilution zone (TDZ), is more restrictive than the legal mixing zone for conventional and nonconventional pollutants. In order to provide turbulent mixing that will minimize organism exposure time to toxic material, the outfall structure must meet the following requirements for a TDZ (USEPA, Toxics, 1985):

-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 spatial direction.

-The CMC must be met within a distance of 50 times the discharge length scale in any spatial direction. The discharge length scale is defined as the square-root of the cross-sectional area of any discharge outlet. This restriction will ensure a dilution factor of at least 10 within this distance under all possible circumstances, including situations of severe bottom and surface interaction.

-The CMC must be met within a distance of 5 times the local water depth in any horizontal direction. The local water depth is defined as the natural water depth (existing prior to the installation of the discharge outlet) prevailing under mixing zone design condition (e.g. low flow for rivers). This restriction will prevent locating the discharge in very shallow environments or very close to shore, which would result in significant surface and bottom concentrations.

1.D The NPDES Permit System

Any discharge into a navigable watercourse must have a National Pollution Discharge Elimination System (NPDES) permit. The permit is designed to insure that the discharge meets all applicable standards. The permit is granted either by USEPA, or, if the State has a USEPA approved program, the State. The applicant must supply the reviewing agency with all data needed to grant the permit. Data required in the application include:

Name and exact location of facility

- Nature of business engaged at a facility, including what is or what will be manufactured

- The manufacturing process and maximum production levels

- Schematic of water flow through the facility

- Exact location, flow rates, flow frequencies, and chemical composition of each facility discharge

- The waste-water treatment currently or to be employed for each waste stream

- Pollutant test data

1.E Need for Regulatory Assessment Tools

Implementation of the mixing zone policy in the NPDES permitting process requires that the applicants and regulators predict the initial dilution of the discharge and the characteristics of the mixing zone. If the discharge is toxic, the CMC value must be determined for the discharge and special requirements for a TDZ must be met within the mixing zone. Given the large number of possible ambient environments, discharge configurations, and mixing zone definitions, the analyst needs considerable training and experience to conduct accurate and reliable effluent mixing analysis.

Dilution of the effluent in the receiving water is caused by different mechanisms along its path. In the "near field" of the source, dilution is caused mainly by jet induced entrainment. Further away, in the so-called "far field" the jet velocity decreases and ambient diffusion becomes the primary mechanism of effluent dilution.

The most direct way of determining pollutant concentration downstream is by physical measurement. Non-polluting tracers can also be injected to give indications of effluent dilution. Such field studies require considerable time and effort, and field personnel need specialized training to perform studies reliably. Field studies are in many cases impractical and expensive. For example, if in situ observations are used they must represent conditions that are present during critical dilutions, not merely a typical dilution (Draft 301 (g)). Field studies for analysis of dilution for toxic discharges is patently unacceptable, so simulation must be used to determine dilutions.

Because of the complexity of the physical mixing process, permit writers are increasingly relying on mathematical models to analyze the fate and transport of pollutants (Tait, 1984). The difficulty with many present models is that they tend to become specialized and give accurate results only for a particular type of outfall. The user must be careful to use a model that was intended to make prediction under the conditions with which he is concerned (Draft 301 (g)).

USEPA has developed a number of models to predict the initial dilution of discharges. A few these are PLUME, OUTPLM, DHKPLM, MERGE, and LINE. Applicants are not required to use these models in analysis, but must be able to prove that the methodology chosen gives reasonable estimates of initial dilution.

1.F Justification for Expert Systems Approach

In determining the characteristics of the mixing zone, the analyst, either the NPDES applicant or regulatory authority, may choose from a wide variety of predictive models. The models range in complexity from simple analytical formulae to highly intricate numerical solutions to differential equations. Although the USEPA has prepared assessment manuals and actually endorsed certain models in specific situations, the average user has little reliable guidance on which model is appropriate for a particular situation, or which is actually best (Mullenhoff, et. al., 1985). Examples of "model abuse" are ubiquitous. Often unnecessarily complicated models are employed, creating a needless burden for both regulators and dischargers.

Even when a particular model is appropriate for a given discharge, the model may not give reliable results over a wide range of conditions. Model developers often fail to explicitly specify limits of applicability, or model users may simply overlook important restrictions to model applicability. An example of a frequent error in the application of the USEPA plume models is the violation of the assumption of the infinite receiving environment. In reality, the plume may attach to the bottom or may become vertically fully mixed, possibilities which may occur due to changes in the ambient environment such as low flow conditions. Consequently, analysts have reported model "predictions" in which the plume diameter exceeds actual water depth!

Once the correct choice of model is assured, the analyst often faces the considerable task of assembling the required design data base. This can be a frustrating and cumbersome task for the unexperienced analyst who has little guidance on what design base to choose, where to obtain data, which data is crucial to the analysis, and which data may simply be estimated. Because of these difficulties, a large investment in time is required for the analyst to become fully familiar and proficient with the use of at least one model, or more likely, a group of models. The analyst in reality must become highly skilled or an "expert" in the use and interpretation of number of simulation models. Such expertise in model use requires expensive training and is rare. This is the reason for the development of expert system tools for the analyst.

In essence expert systems mimic the way an expert or highly experienced person would solve a problem. 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 is encoded into a "knowledge base" which enables inexperienced personnel to solve complex problems by using the same basic reasoning process that an expert would apply. The knowledge base includes a set of "objective" or widely accepted facts about a general problem area. This includes the set of parameters or data an expert would seek in order to characterize a specific problem. The inference procedures are "subjective" rules of judgement which the expert might use when analyzing the problem. The inference procedures provide the rules for selecting an appropriate solution to the problem from the knowledge base. The inference procedures allow the expert system user to search rapidly and systematically through the knowledge base to obtain a solution to the given problem. This element uses structured search techniques based upon mathematical logic.

The development of an expert system for mixing zone analysis promises significant advantages compared with existing conventional simulation techniques for water pollution control and management:

-it assures the proper choice of model for a given physical situation.

-it assures that the chosen model is applied methodically without skipping essential elements.

-it guides the acquisition or estimation of data for proper model prediction.

-it allows a flexible application of design strategies for a given point source, screening of alternatives, and if necessary, switching to different predictive models thus avoiding rigid adherence to a single model.

-it flags borderline cases for which no predictive model exists, suggesting either avoidance of such designs or caution by assigning a degree of uncertainty.

-it allows a continuous update of the knowledge base as improved predictive models, experimental data, and field experience with particular designs become available.

-it provides a documented analysis listing the knowledge and decision logic that have lead to the problem solution. Thus, unlike conventional programs or computer algorithms an expert system is not a "black box".

-it provides a common framework whereby both regulators (Federal or State), applicants, and the scientific community can arrive at a consensus on the state-of-the-art hydrodynamic mixing and pollution control.

-finally, and perhaps most importantly, it provides a teaching environment whereby the initially inexperienced analyst through repeated interactive use gains physical insight and understanding about initial mixing processes.

Expert systems are a technology that has enormous potential utility to solving problems in environmental science. At the present time, several preconditions must be satisfied before this technology can be applied successfully, such as (Barnwell et al., 1986):

-The problem domain must be narrow, e.g. restricted to a particular well defined problem area.

-Expertise to solve the problem must exist; Expert Systems cannot create expertise, they can only document, disseminate, and enhance it.

-Formalization of concepts involved must be available in a format compatible with the tool used.

If these preconditions can be satisfied, Expert systems appear to be a powerful addition to the analyst's repertoire of solution faculties. The analysis and simulation of the discharge of pollutants into water courses meet these preconditions. Experts in hydrodynamic mixing exist. It is a well defined problem area, the problem being too complex for glib analysis, but not too large to codify the knowledge needed to solve the problem nor intractable to the novice if expertise is available. Mixing zone analysis appears ideally suited for exploiting Expert Systems technology.

1.G CORMIX1 Summary

The problem addressed is to develop a tool for the analysis and design of submerged single-port continuous buoyant discharges into a non-stratified aqueous environment. The expert system will be labeled CORMIX1, for Cornell Mixing Zone Expert System, Subsystem 1. CORMIX1 is a subsystem of CORMIX, to be developed, which will include stratified environments, negatively-buoyant discharges, and bottom attachments. CORMIX1 is primarily intended for applications to flowing ambients(such as rivers or estuaries), although the limiting cases of non-buoyant discharges and stagnant environments are included. The emphasis of CORMIX1 will be on discharge geometry and characteristics of legal mixing zone (LMZ) requirements, including the toxic dilution zone (TDZ). CORMIX1 will summarize dilution characteristics of the proposed design, flag undesirable designs, give dilution characteristics at legally important regions if specified, and will have the capability to recommend design alterations to improve dilution characteristics.

The subsequent chapters in Volume I are Chapter II Hydrodynamic Background on Mixing Processes, Chapter III CORMIX1 Program Structure, Chapter IV Data Comparison and Validation, Chapter V Design Case Studies, and Chapter VI Conclusions and Recommendations. Chapter II contains discussions of the hydrodynamic analysis used to simulate the jet mixing process. Chapter III details CORMIX1 program structure, logic programming, and FORTRAN simulation programming. Chapter IV presents a validation for the hydrodynamic simulations by comparison with field and laboratory data. Chapter V contains two typical design examples demonstrating the use of CORMIX1 for mixing zone analysis. Chapter VI outlines conclusions of CORMIX1 performance and recommendations for future improvements.

Volume II contains the CORMIX1 source code listings and the output from an interactive session using the design examples presented in Chapter V of this volume.

Chapter II
Hydrodynamic Background on Mixing Processes

The hydrodynamics of a buoyant effluent continuously discharging into a receiving body of water can be conceptualized as a mixing process occurring in two separate regions. In the first region, the initial jet characteristics of momentum flux, buoyancy flux, and outfall geometry influence the jet trajectory and mixing. This region will be referred to as the "near field", and encompasses the jet subsurface flow and surface impingement. In this region, designers of the outfall can affect the initial mixing characteristics through appropriate manipulation of design variables.

As the turbulent plume travels further away from the source the characteristics of the issuing source become less important. Conditions existing in the ambient environment will control trajectory and dilution of the turbulent plume through buoyant surface spreading and passive diffusion. This region will be referred to here as the "far field".

The hydrodynamic analysis treats the near field and far field regions separately. An illustration of the near field and the far field of a subsurface plume rising to the surface and traveling downstream appears in Figure 2.1.

The strategy for analysis will be to first present the mechanics of subsurface near field properties for pure jets and pure plumes in stagnant ambient environments, extend these results to ambient crossflows, and finally to generalize the analysis to flows containing momentum and buoyancy. The general results will be extended to include non-vertical trajectories and transitions between flow regions. The effects of flow surface interaction will then be discussed, followed by a discussion of the far field mixing process.

2.A Analysis of Subsurface Flow Regions

A release with no buoyancy is referred to as a "nonbuoyant jet" or "pure jet". A release of buoyancy only (no initial momentum) is called a "pure plume". A release containing both momentum and buoyancy is designated a "buoyant jet" or "forced plume". For simplicity, a region within the actual pure jet, pure plume, or buoyant jet or forced plume will often be referred to as a "flow".

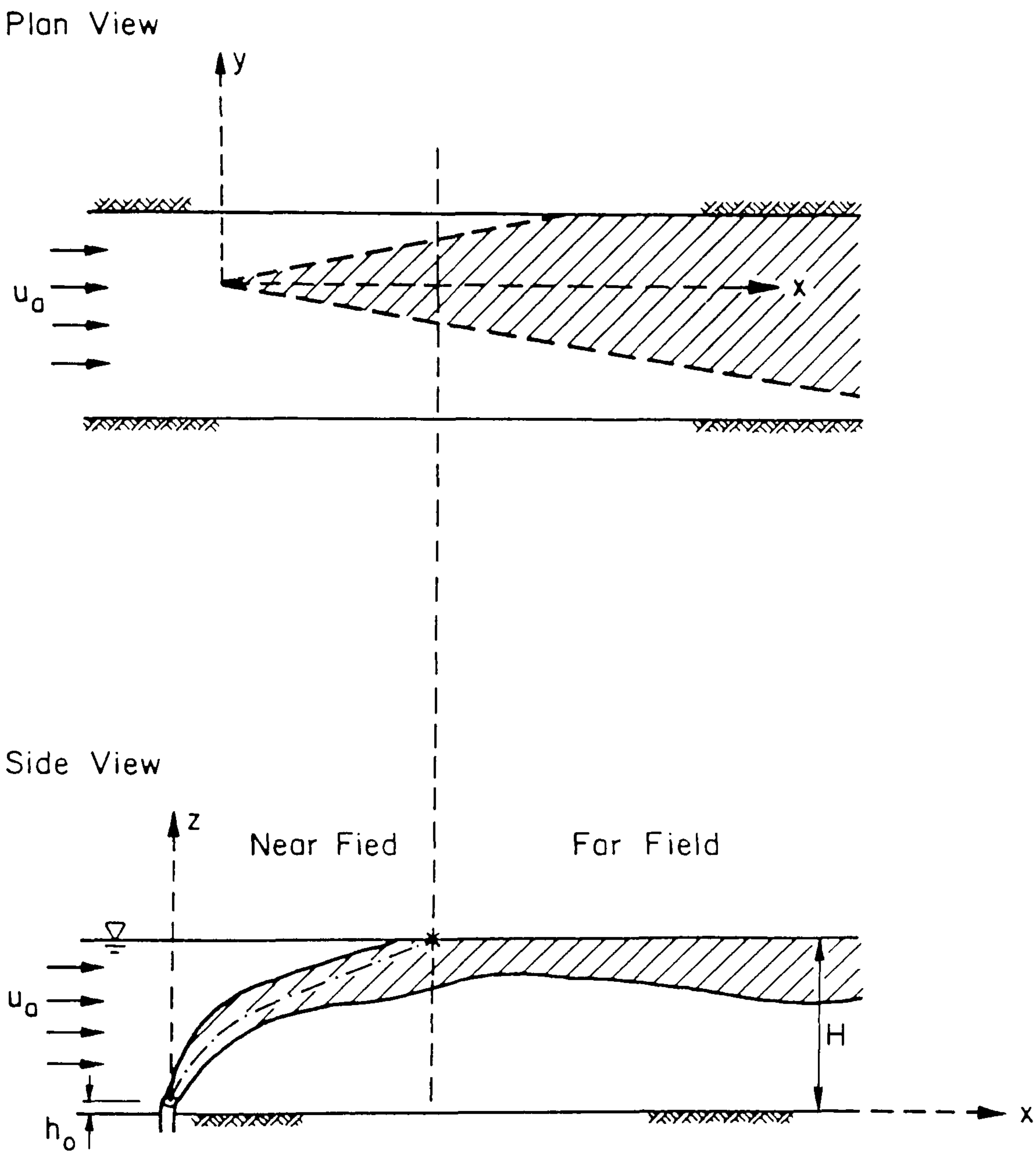


Figure 2.1 Illustrative Near Field and Far Field of Submerged Single Port Discharge

For a buoyant jet in a stagnant unstratified environment, List and Imberger (1973) propose three flow regions where buoyant jet behavior is determined by different effects. In the first region, near the issuing source, the geometry of the discharge is important. In the second region, initial kinematic momentum flux of the discharge predominates. In the third and ultimate region, yet further away from the source, buoyancy flux of the initial discharge becomes important. Characterizing the flow by the predominating mechanism controlling the flow within a region is the essence of "asymptotic analysis" which will be pursued herein.

The effects of momentum and buoyancy thus can be considered separately to reduce the number of independent variables under consideration. For example, the solution for a pure jet in a crossflow can be applied as an approximate solution to that portion of buoyant jet flow where jet momentum dominates the flow. Likewise the results for a pure plume can be applied to the buoyancy-dominated regions for the buoyant plume.

Additional factors, such as crossflow velocities, can also be treated within the framework of asymptotic analysis as shown by Wright (1977).

2.A.1 Description of Turbulent Jets and Plumes

Most people are familiar with the sight of smoke rising from a smokestack into the atmosphere. The smoke plume rises and spreads narrowly; rising near vertically at first and eventually bending over as it is carried away by the ambient wind. The smoke plume is an example of a turbulent plume, the discharge contains both momentum and buoyancy. The buoyancy is produced by the lower density of the heated air with respect to the cooler ambient air.

The discharge of a fluid such as sewage into the ocean behaves in a similar fashion. The sewage has momentum from being injected through the discharge orifice. The sewage has the density of freshwater and thus is buoyant with respect to the greater density of the ambient saltwater.

Turbulent jets are characterized by a long narrow turbulent zone. Following release from a nozzle, the jet flow becomes unstable at its boundary and breaks down into the turbulent motion. Typically, the size of the turbulent eddies increases with increasing distance along the trajectory (Holley and Jirka, 1986).

2.A.2 Elements of Dimensional Analysis of Buoyant Jets

Several assumptions are made in order to reduce the independent variables under consideration. Only fully turbulent jets are considered so the effects of viscosity can be neglected. The Boussinesq approximation is assumed; density differences between the jet and the ambient environment are small and are important only in terms of the buoyancy force.

The three variables used to describe buoyant jet characteristics in crossflow are the kinematic fluxes of mass, $Q_0 = (\pi/4)D^2 u_0$, momentum $M_0 = u_0 Q_0$, and buoyancy $J_0 = g_0' Q_0$, where D is the diameter of the orifice, u_0 is the exit velocity, u_a is the crossflow velocity, and g_0' is the reduced gravitational acceleration caused by the density difference between the jet and ambient environment. This term is defined as $g_0' = g(\rho_a - \rho_0)/\rho_a$ where g is the gravitational acceleration and ρ_a and ρ_0 are the ambient and jet discharge densities, respectively.

For the case of a buoyant jet discharged into a flowing environment, dimensional analysis proceeds as follows. A general dependent variable, ϕ, such as local centerline jet velocity, can then be expressed as a function of the various independent variables:

$$\phi = f(Q_0, M_0, J_0, u_a, s) \qquad (1)$$

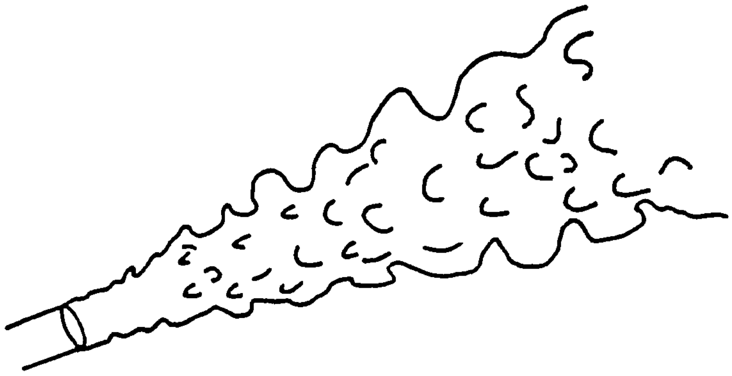
where s is the distance along the jet trajectory. A function is then empirically created by grouping the independent variables on the right hand side of Eq. (1) together. The created function has to be dimensionally consistent with the desired dependent variable.

First, the following paragraphs present the details of dimensional analysis for the simple case of a pure jet and a pure plume in a stagnant environment. Then, the general case of a buoyant jet in crossflow is presented. The jet and ambient flow variables can be combined into various length scales that measure the relative forces affecting a flow within a particular trajectory distance.

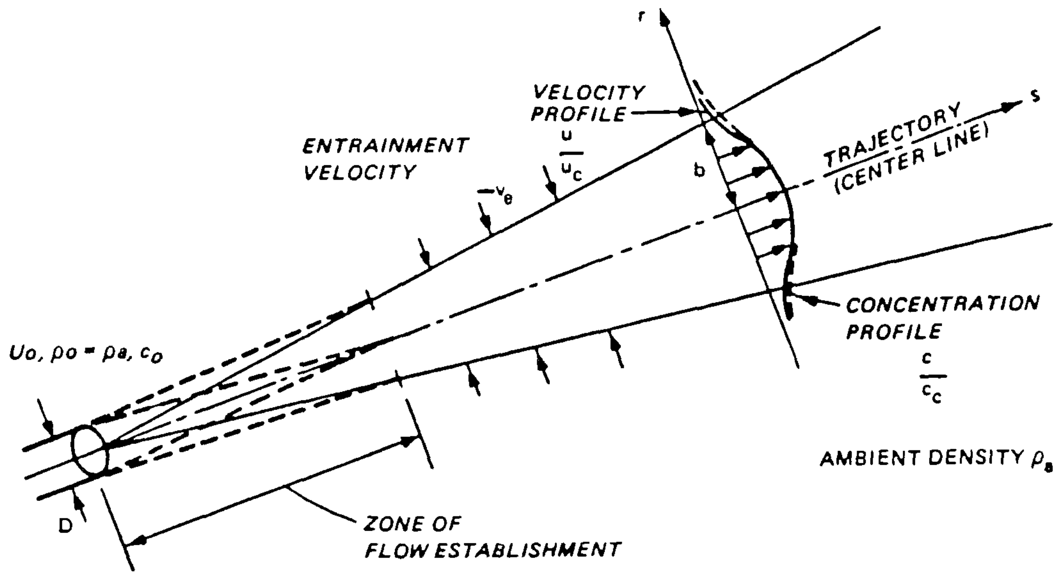
The asymptotic approach will provide solutions that are valid only within certain specified regions and furthermore require experimentally determined coefficients. The individual solutions, however, can be linked by appropriate transition conditions to provide an overall prediction which can be considered a first order approximation to the complete problem.

<u>2.A.2.1. Simple Jet in Stagnant Environment</u>

Consider a pure jet in a stagnant ambient fluid (Figure 2.2). Initially as the flow exits the orifice the velocity profile is near uniform. After a short distance s along the



a. Instantaneous appearance



b. Time-averaged conditions

Figure 2.2 Pure Jet in Stagnant Environment (Ref. Holley and Jirka, 1986) jet trajectory, the velocity distribution is assumed to be gaussian. The region where this velocity distribution transformation occurs is called the zone of flow establishment (zofe). The details of the zofe will not be considered in any of the following analysis; i.e. the jet is assumed to come from a point source.

The maximum velocity u_c occurs along the trajectory centerline and a similarity profile is assumed for the velocity distribution. Similar conditions pertain to the centerline concentration c_c of pollutant mass. The jet centerline velocity u_c decreases with distance s from the orifice as the jet entrains the stagnant ambient fluid. However, the momentum flux M at any section along the trajectory is conserved. The magnitude and variation of the jet centerline velocity depend primarily upon the initial kinematic momentum flux and the distance along the trajectory, $u_c = \phi(M_0, s)$. Using techniques of dimensional analysis, the result implies that $u_c s/M_0^{1/2}$ = constant

$$u_c = cM_0^{1/2}s^{-1} \tag{2}$$

where c is a constant.

The width b of the jet at trajectory distance s can also be expressed as $b = \phi(M_0, s)$. The only possible dimensionally consistent equation is b/s = constant

$$b = b_1 s \tag{3}$$

where b_1 is a constant.

The dilution S at any cross-section along the jet is defined by $S = c_0/c_c$, where c_0 is the concentration at the exit nozzle. From the mass conservation equation $c_0 Q_0 \equiv c_c u_c b^2$, and dilution S as a function of s

$$S = s_1 M_0^{1/2} s/Q_0 \tag{4}$$

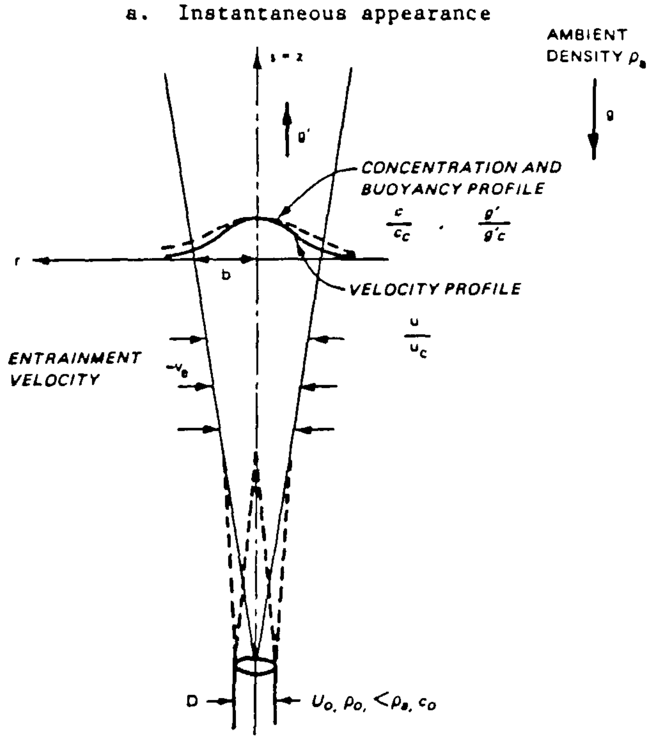
where s_1 is a constant.

2.A.2.2. Simple Plume in Stagnant Environment

A pure plume rises vertically and has an increase in vertical momentum flux with distance z above the source (Figure 2.3). The buoyancy flux is constant for any cross-section of the plume as it rises. For the pure plume, the centerline velocity is a function of the buoyancy flux and distance z, $u_c = \phi(J_0, z)$. The centerline velocity of the jet can be obtained from dimensional reasoning

$$u_c \quad c(J_0 z)^{1/3} \tag{5}$$

a. Instantaneous appearance



b. Time-averaged conditions

Figure 2.3 Simple Plume in Stagnant Environment (Ref. Holley and Jirka, 1986)

The width b of the plume at trajectory distance z is expressed as $b = \phi(J_0, z)$, leading to

$$b = b_3 z \tag{6}$$

where b_3 is a constant.

Dilution S for the pure plume is given by mass continuity equation as was shown in Eq. (4) for the pure jet. Noting that buoyancy flux is conserved in the pure plume, the dilution for the pure plume can expressed by the buoyant acceleration g' which decreases with distance z as the plume rises and becomes diluted by the ambient fluid. The decrease in g' is directly proportional to the amount of ambient fluid entrained in the plume, so $S = g_0'/g'$. Using the continuity equation for buoyancy flux, dilution can expressed $S = \phi(J_0, Q_0, z)$ as $g' z^{5/3}/J_0^{2/3}$ = constant

$$S = s_3 \; J_0^{1/3} z^{5/3}/Q_0 \tag{7}$$

<u>2.A.2.3 Generalizations: Jet/Plume Interactions and Effects of Crossflow</u>

If additional parameters influence the flow field, then a general asymptotic solutions for the whole flow field can not be found. However, there may be individual regions where specific asymptotic solutions of the type developed in the preceding sections may still apply. The next section presents the analysis for the discharge of the simple jet or plume into a uniform ambient crossflow u_a. As the jet or plume rises it will be deflected by the ambient current as illustrated in the several examples of Figure 2.4.

As can be seen in Figure 2.4 there are still specific regions where the flow exhibits certain simple behavior. These regions are separated by the transition zones which are described by length scales (labeled l_M, l_m, l_b in Figure 2.4). The development of these important length scales which specify the spatial distribution of the asymptotic regimes of general buoyant jets in crossflow is presented in the next section.

<u>2.A.3 Length Scales for Buoyant Jets With or Without Crossflow</u>

In general, functional relationships in the form of length scales are sought which describe the relative importance of discharge flux to momentum flux, momentum flux to buoyancy flux, and discharge to crossflow in controlling flow behavior. The length scales will describe the distance over which the dynamic quantities in Eq. (1) control the flow.

<u>2.A.3.1 Discharge Length Scale</u>

Initially as the jet exits the port in the zone of flow

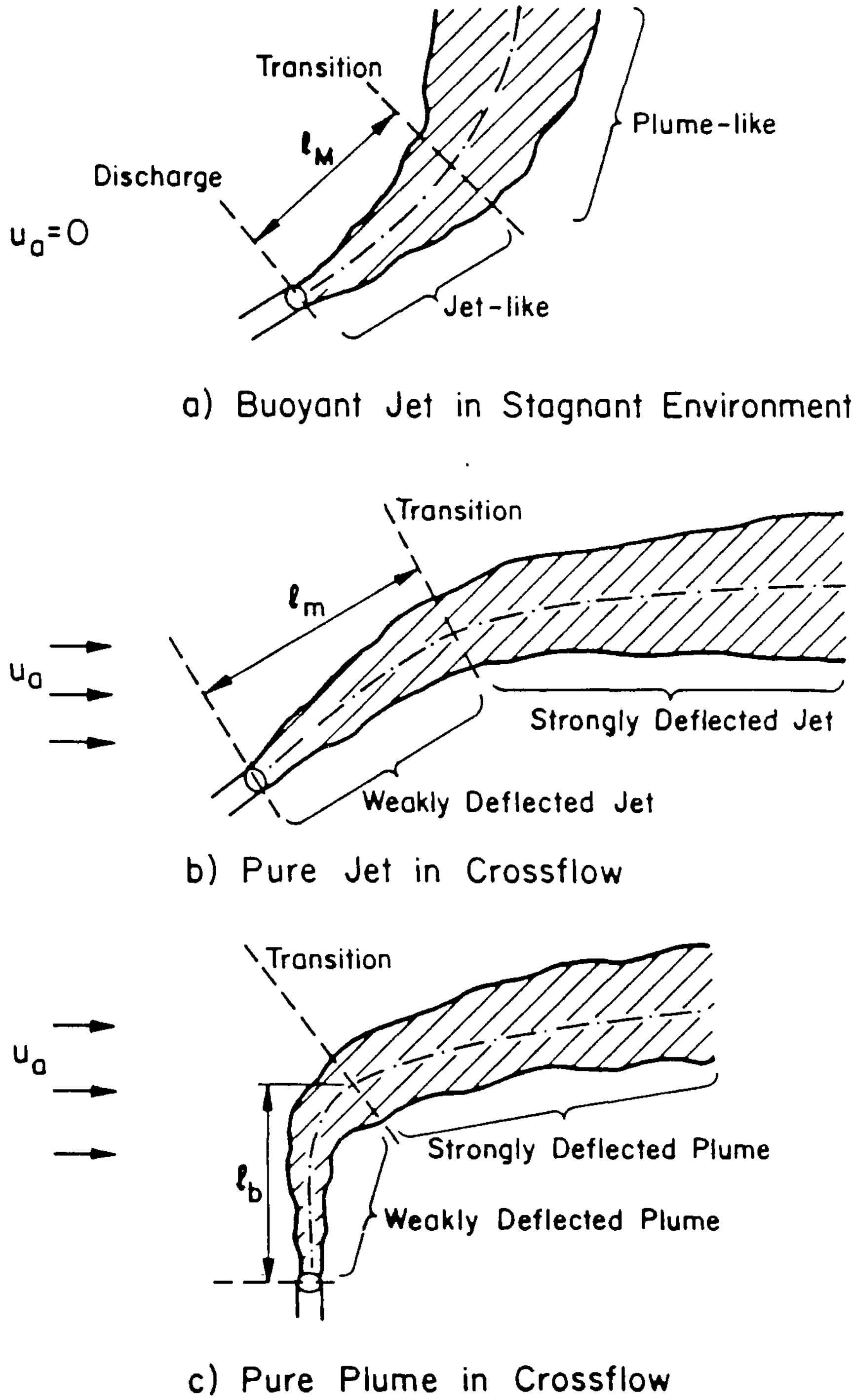


Figure 2.4 Examples of Combined Effects of Momentum Flux Buoyancy Flux and Crossflow on Flow Behavior

establishment, port geometry controls the flow. The distance over which the port has effect on the flow can be characterized as a discharge length scale. Momentum controls the flow initially for the buoyant jet. The discharge length scale l_Q relates the mass flux to momentum flux, and from dimensional reasoning

$$l_Q = Q_0/M_0^{1/2} \qquad (8)$$

which is proportional to the diameter D of the orifice for a round jet. For distances less than l_Q the flow will be in the zone of flow establishment. Thus for $s/l_Q << O(1)$ the source geometry will have a significant effect on the flow behavior, but for $s/l_Q >> O(1)$ the effect of the initial geometry is lost to jet momentum or buoyancy which will control the flow behavior.

2.A.3.2 Jet/Crossflow Length Scale

The presence of a crossflow u_a will deflect the jet as shown in Figure 2.4b. The behavior of the pure jet in crossflow depends on the relative magnitude of the crossflow to jet momentum. The distance to the position where the jet becomes strongly affected (i.e. deflected in the case of an oblique discharge) by the ambient crossflow is given by a jet/crossflow length scale l_m

$$l_m = M_0^{1/2}/u_a . \qquad (9)$$

Thus for $s/l_m << O(1)$ the initial jet momentum will dominate and crossflow is of secondary importance, and for $s/l_m >> O(1)$ ambient velocity will have the most important influence on jet behavior.

2.A.3.3 Plume/Crossflow Length Scale

Arguments presented for the effect of crossflow on the pure plume flow are in analogy for the jet in crossflow. The plume/crossflow length scale l_b for the pure plume rising to be deflected by the crossflow as shown in Figure 2.4c is determined through dimensional reasoning

$$l_b = J_0/u_a^3 . \qquad (10)$$

Thus for $z/l_b << O(1)$ the initial jet buoyancy will dominate and crossflow is of secondary importance, and for $z/l_m >> O(1)$ ambient velocity will have the most important influence on plume behavior.

2.A.3.4 Jet/Plume Length Scale

Most flows contain both momentum and buoyancy. Because of the buoyant acceleration, any jet containing buoyancy will have a momentum flux continually added to it. When a flow contains both momentum and buoyancy, momentum controls the flow initially until the buoyant acceleration overcomes the effect of initial momentum and ultimately controls the flow. The distance from momentum dominated to buoyancy dominated flow for a buoyant jet in a stagnant environment is characterized by a jet/plume length scale l_M (See Figure 2.4a). Dimensional analysis suggests the functional relationship

$$l_M = M_0^{3/4}/J_0^{1/2} \tag{11}$$

So for $z/l_M \ll O(1)$ flow behavior will be controlled by momentum and for $z/l_M \gg O(1)$ flow behavior will be controlled by buoyancy, i.e. approach that of a vertically rising plume.

In the rare case that $l_M < l_Q$, there will be no momentum dominated flow and the flow will be entirely plume-like expect for the region very near the issuing source.

The ratio of l_Q/l_M is proportional to the reciprocal of the usual discharge densimetric Froude number $F_0 = u_0/(g_0' D)^{1/2}$ which relates the momentum forces to buoyancy within the plume. The theoretical pure plume has a Froude number of O(1) and a pure jet $F_0 \rightarrow \infty$.

<u>2.A.4 Typical Regimes of Buoyant Jets</u>

This section presents analytical results for jets and plumes issued vertically upward from a point source, perpendicular to the crossflow.

<u>2.A.4.1 Weakly Deflected Jet in Crossflow (mdnf)</u>

For a relatively weak crossflow, the jet would behave the same as if it were in a stagnant environment, except that it is slightly advected by the ambient current (Figure 2.4b). This region is defined for $z/l_m \ll O(1)$.

Considering a jet issued perpendicular to the crossflow, after the region of flow establishment the vertical relation would be similar to Eq. (2) and the kinematic relationship for a jet moving horizontally with the crossflow velocity

$$dx/u_a = dz/u_c \tag{12}$$

Substitution for the vertical velocity given in Eq. (2) and integrating gives the trajectory relationship for the weakly deflected jet flow (Wright's (1977) "momentum-dominated near field", or mdnf[1]) expressed in terms of the jet/crossflow length scale

$$z/l_m = t_1 (x/l_m)^{1/2} \qquad (13)$$

where t_1 is a trajectory constant.

This relation holds in the region $z/l_m << O(1)$. Eq. (13) is valid for small values of l_Q/l_m. In the rare case that l_Q/l_m is large, the effect of geometry is important and Eq. (13) can not assumed to be valid.

Jet width b is similar to the jet issued in a stagnant environment and is given by Eq. (3).

The dilution S is similar to Eq. (4), and is expressed in terms of l_Q

$$S = s_1 (z/l_Q) \qquad (14)$$

where s_1 is the dilution constant for the mdnf flow.

2.A.4.2 Strongly Deflected Jet in Crossflow (mdff)

For $z/l_m >> O(1)$ the ambient flow will have a more direct effect on the flow pattern. For a strongly deflected jet the vertical velocity has decayed to less than the value for the ambient crossflow; thus ambient crossflow will have significantly deflected the jet as shown in Figure 2.4b.

The behavior of the bent-over jet is assumed to be roughly equivalent to that of a cylindrical line impulse located at the same vertical rise. Scorer (1954) describes a line impulse as an instantaneous release of nonbuoyant fluid along a horizontal line source. The characteristic variables are the momentum impulse, M'(defined as the kinematic momentum flux per unit length for an infinitesimal period of time), vertical rise, and time. Applying dimensional analysis

$$M't/z^3 = \text{constant} \qquad (15)$$

---

[1] In the following the abbreviated descriptions for subsurface flows (mdnf, mdff,bdnf and bdff) as suggested by Wright (1977) will be used for convenience since they are frequently used in the literature. Care must be exercised in their interpretation so as to avoid confusing them with the designation "near-field" and "far-field" as used in this study (See introductory comments at the beginning of this Chapter).

To apply this analogy to the pure jet, M_0/ua is substituted for M' and x/u_a replaces t in Eq. (15). The trajectory relation for the strongly deflected jet flow (i.e. Wright's (1977) "momentum-dominated far field", mdff) is then expressed in terms of the jet/crossflow length scale

$$z/l_m = t_2 (z/l_m)^{1/3} \qquad (16)$$

where t_2 is a trajectory constant.

Similar to Eq. (3) jet width b is proportional to position z

$$b = b_2 z \qquad (17)$$

where b_2 is a constant for the mdff flow.

The continuity equation is used to determine the dilution at any position z, $c_0 Q_0 = cb^2 u_a$. In terms of the jet/crossflow length scale the dilution

$$S = s_2 (z^2 / l_m l_Q) \qquad (18)$$

where s_2 is a dilution constant for the mdff flow.

2.A.4.3 Weakly Deflected Plume in Crossflow (bdnf)

For a relatively weak crossflow, the pure plume would behave the same as if it were in a stagnant environment, except that it is advected with the ambient current (Figure 2.4c).

For values of $z/l_b \ll O(1)$, the flow will behave as plume in a stagnant environment but will be advected with the crossflow. Proceeding in analogy to the mdnf flow (Section 2.A.4.1) the trajectory equation for the weakly deflected plume flow (i.e. Wright's (1977) "buoyancy-dominated near field", bdnf). The relationship in terms of the buoyant length scale

$$z/l_b = t_3 (x/l_b)^{3/4} \qquad (19)$$

Plume width b is similar to the plume issued in a stagnant environment and is given by Eq. (6).

The dilution S is similar to Eq. (7), and is expressed in terms of l_b, l_Q, and l_m

$$S = s_3 (l_b^{1/3} z^{5/3}) / (l_Q l_m) \qquad (20)$$

where s_3 is the dilution constant for the bdnf flow.

2.A.4.4 Strongly Deflected Plume in Crossflow (bdff)

For z/l_b >> O(1) the ambient flow will have a pronounced effect on the flow pattern. When strongly defected, theplume vertical velocity has decayed to less than the value for the ambient crossflow; so ambient crossflow will have significantly deflected the plume as shown in Figure 2.4c.

For z/l_b >> O(1), the plume should behave as a thermal, an instantaneous release of buoyancy-driven fluid along a line source. Again, note the analogy to the mdff flow (Section 2.A.4.2) caused by the line impulse M'. The important variables are J', the buoyant weight per unit length, vertical rise, and time. Dimensional reasoning implies

$$J' t^2 / z^3 = \text{constant} \tag{21}$$

Substituting x/u_a for t and replacing J' by J_o/u_a in Eq. (21) yields the trajectory relationship for the strongly defected plume flow (Wright's (1977) "buoyancy-dominated far field", bdff) expressed in terms of length scales

$$z/l_b = t_4 (x/l_b)^{2/3} \tag{22}$$

where t_4 is a constant.

Plume width b is analogous to Eq. (6)

$$b = b_4 z \tag{23}$$

where b_4 is a constant for the bdff flow.

The continuity equation is used to determine the dilution at any position s, $c_o Q_o = c b^2 u_a$. In terms of the jet/crossflow length scale the dilution

$$S = s_4 z^2 / (l_Q l_m) \tag{24}$$

where s_4 is a dilution constant for the bdff flow.

The various trajectory and dilution relationships presented in the previous sections are summarized in Table 2.1; Table 2.2 lists tentative constants proposed for simulation studies for CORMIX1. These values are to be further determined in future work.

2.A.4.5 General Behavior in Unbounded Crossflow

The general case of the trajectory and dilution for a flow containing both momentum and buoyancy is considered next. The correct choice of flow regions depends on relative importance of the various length scales associated with a particular discharge (Figures 2.4b and 2.4c).

Table 2.1 Trajectory and Dilution Relations for Submerged Flows
Source: Wright, (1977)

Flow Region	Trajectory	Dilution
mdnf	$z/l_m = t_1 (x/l_m)^{1/2}$	$S = s_1 (z/l_Q)$
mdff	$z/l_m = t_2 (x/l_m)^{1/3}$	$S = s_2 (z^2/l_m l_Q)$
bdnf	$z/l_b = t_3 (x/l_b)^{3/4}$	$S = s_3 (l_b^{1/3} z^{5/3})/(l_Q l_m)$
bdff	$z/l_b = t_4 (x/l_b)^{2/3}$	$S = s_4 z^2/(l_Q l_m)$

Where:*

mdnf = weakly deflected jet
"momentum dominated near field"

mdff = strongly deflected jet
"momentum dominated far field"

bdnf = weakly deflected plume
"buoyancy dominated near field"

bdff = strongly deflected plume
"buoyancy dominated far field"

*Designations in quotes according to Wright, (1977)

Table 2.2 Trajectory and Dilution Constants

mdnf:	$t_1=2.65$	$s_1=0.42$	$b_1=0.34$
mdff:	$t_2=1.44$	$s_2=0.38$	$b_2=0.34$
bdnf:	$t_3=2.36$	$s_3=0.42$	$b_2=0.34$
bdff:	$t_4=1.15$	$s_4=0.41$	$b_2=0.34$

The possibility of flow attachment to the bottom is not included in the analysis. Future work on CORMIX1 will include the effect of bottom attachments.

<u>a) Possible Transitions</u>

If the buoyant jet is discharged into an unbounded crossflow, the ratio of l_m/l_b will indicate which of the regions (i.e. mdnf, mdff, bdnf, and bdff) occur for a particular flow. Provided that l_m and l_b are both substantially larger than l_Q (generally true in practice) two possible transitions can occur (See Figure 2.5).

<u>Case 1)</u> For $l_m/l_b >> O(1)$ the buoyancy in the plume is relatively weak compared to momentum, and a large distance is required for the buoyancy to generate additional momentum to control flow characteristics. Therefore the flow will develop as: mdnf -> mdff -> bdff.

<u>Case 2)</u> If $l_m/l_b << O(1)$, the buoyancy force is much stronger and the flow will be a weakly deflected jet when buoyancy forces begin to dominate. Therefore the flow will develop as: mdnf -> bdnf -> bdff.

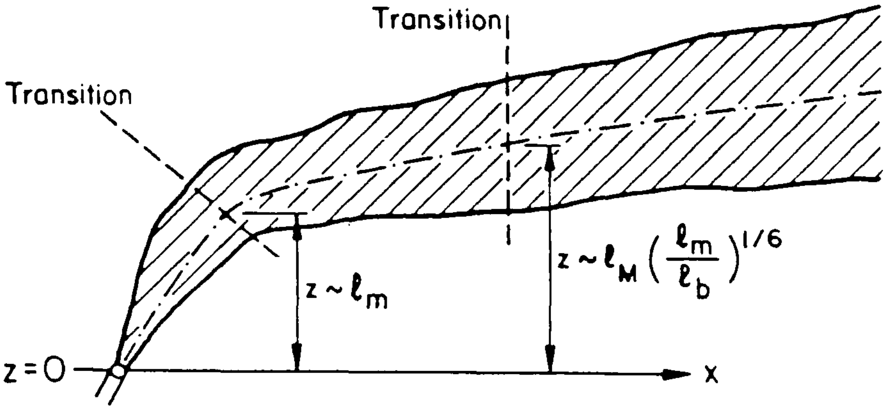
<u>b) Coordinate Systems for Oblique Discharges:</u>

In CORMIX1 a global cartesian coordinate system (x,y,z) is placed at the bottom of the water body with the origin (0,0,0) directly below the center of the discharge orifice. The height of the discharge orifice above the bottom is h_0. 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 (i.e. the discharge angle above horizontal) is θ_0. The discharge-crossflow angle σ_0 is the angle between the projection of y^* on the x-y plane and the x-axis ($\sigma_0 = 0.0^\circ$ for co-flowing discharges, $\sigma_0 = 180^\circ$ for counter-flowing discharges).

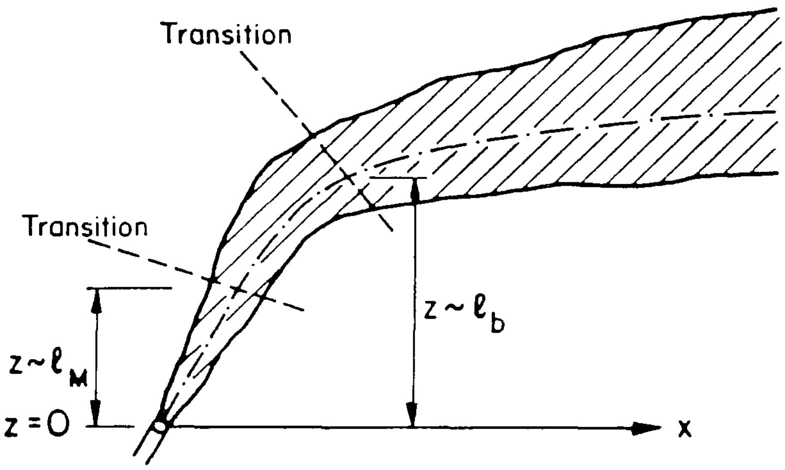
A primed coordinate position, (x',y',z'), within a given flow region is specified with respect to the virtual source for that flow region. A virtual source is needed for each flow region because the previous asymptotic analyses assume a point discharge source, which is physically unrealistic. The primed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

$$(x,y,z) = (x',y',z') + (x_v,y_v,z_v) \qquad (25)$$

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



a) $\ell_m \gg \ell_b$; Momentum Dominates



b) $\ell_m \ll \ell_b$; Buoyancy Dominates

Figure 2.5 General Behavior for Buoyant Jets in Unconfined Crossflow (Assuming Near-Vertical Discharge)

(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 equations for the given flow region.

In general, the analysis is extended to non-vertical 3-D trajectories within the ambient crossflow. A supplementary transverse coordinate ζ is defined here in a plane given by the x-axis and the discharge axis y^*. Any vertical projection of the jetflow is controlled by the vertical component of the discharge momentum flux as well as the buoyancy flux (which always acts vertically). The transverse (horizontal) projection of the jet flow is solely controlled by the horizontal component of the discharge momentum flux. A detailed 3-D computational framework is included in CORMIX1, but the algebraic expressions are not presented here.

c) Transitions Between Flow Regions

Transition rules are needed to give the spatial 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 region.

For example, transition rule 1 gives the final value of a weakly deflected jet coordinate when it is followed by a weakly deflected plume. The transition from one region to the other is characterized by the jet/plume length scale l_M. If the horizontal discharge angle is γ_0, the final supplementary coordinate ζ_f, and the final x-coordinate x_f, transition rule 1 yields

$$\zeta_f = C(1) l_M \qquad \gamma_0 > 45.0^\circ \qquad (26)$$

$$x_f = C(1) l_M \qquad \gamma_0 \leq 45.0^\circ \qquad (27)$$

where C(1) is a constant of the order of 1, and γ_0 is the angle defined by the discharge axis y^* and the crossflow (x-axis).

The dilution and size of the plume will be constant at the transitions while a slight discontinuity in the centerline velocity profile will occur.

A complete list of all transition rules used in CORMIX1, included those for bounded flows, appears in Table 2.3. All constants of the order 1, C(1), are assumed to be 1 in CORMIX1. Future work plans include further refinement of these constants with experimental data.

Table 2.3 Flow Transition Rules

Trans. Rule	Current Flow Module	Next Flow Module	Relation
0	01	11 21 34	$z_f = h_0$
1	11	21	$\gamma_0 \geq 45^\circ \quad \zeta_f = C(1) l_M$ $\gamma_0 < 45^\circ \quad x_f = C(1) l_M$
2	11	22	$\gamma_0 \geq 45^\circ \quad \zeta_f = C(1) l_m$ $\gamma_0 < 45^\circ \quad x_f = C(1) l_m$
3	21	22	$z_f = C(1) l_b$
4	16	22	$\zeta_f = C(1) l_M (l_b / l_m)^{1/6}$
5	22 16 11	31 31 33	$z_f = H$
6	21	32	$z_f = 0.8H + 0.2h_0$
7	41	62	$x_f = x_i + (2/3)(b_i^{3/2} / l_b^{1/2}) \{[(8.0 l_b h_i)/(S_i f l_m l_Q)]^{3/2} - 1\}$

Module
- 01 = zone of flow establishment (zofe)
- 11 = weakly deflected jet (mdnf)
- 16 = strongly deflected jet (mdff)
- 22 = strongly defected plume (bdff)
- 31 = near-horizontal surface approach
- 32 = near-vertical surface impingement with buoyant upstream spreading
- 33 = near-vertical surface impingement with vertical mixing
- 34 = near-vertical surface impingement, upstream spreading, vertical mixing, buoyant restratification
- 41 = buoyant surface spreading
- 61 = passive diffusion

2.B Flow Interaction With Free Surface

The preceding section assumed a turbulent plume rising with a crossflow in an infinitely deep water body. No boundary effects of the flow meeting the surface were considered. This section analyzes the boundary effects of a flow interacting with the water surface within the near field.

The interaction of the flow with the water surface will be characterized by the local ambient water depth H. The ratio of the water depth length scale H to the length scales discussed previously is used to characterize the flow interaction with the surface.

2.B.1 Flow Classification of Near-Field Regions

The flow classification system appears in Figure 2.6. The flow classification system uses the ratio of l_m/H to characterize the discharge as "deep water" or "shallow water" based on the momentum of the flow as it contacts the surface. A deep water discharge will have relatively weak momentum as the flow contacts the surface, while a shallow water discharge will have relatively strong momentum as the flow impinges on the surface.

Ratios of l_b/H and l_M/H are used to further classify the properties of the flow as it contacts the surface in both deep and shallow water.

Discharges can be classified as "stable" or "unstable". Flows with strong vertical momentum at surface contact tend to be unstable. In this case the jet is deflected downward by the surface and an unstable recirculation zone occurs around the jet as it entrains the fluid deflected down from the surface. In a stable discharge, buoyancy tends to have a stabilizing effect on the flow as contacts the surface, causing the flow to form a stratified layer on the surface.

2.B.2 Analysis of Surface Interaction Processes

Four major possible flow regions exist (Figure 2.7) for the flow interaction with the surface; i) near-horizontal surface approach, ii) near-vertical surface impingement with upstream spreading, iii) near-vertical surface impingement with full vertical mixing, and iv) near-vertical surface impingement with unstable recirculation, buoyant restratification, and upstream spreading. As shown in Figure 2.6, each of these four possible flows can be defined by combinations of the ratio of the length scales l_m, l_b, and l_M, with the local water depth H.

A control volume approach is used for the following

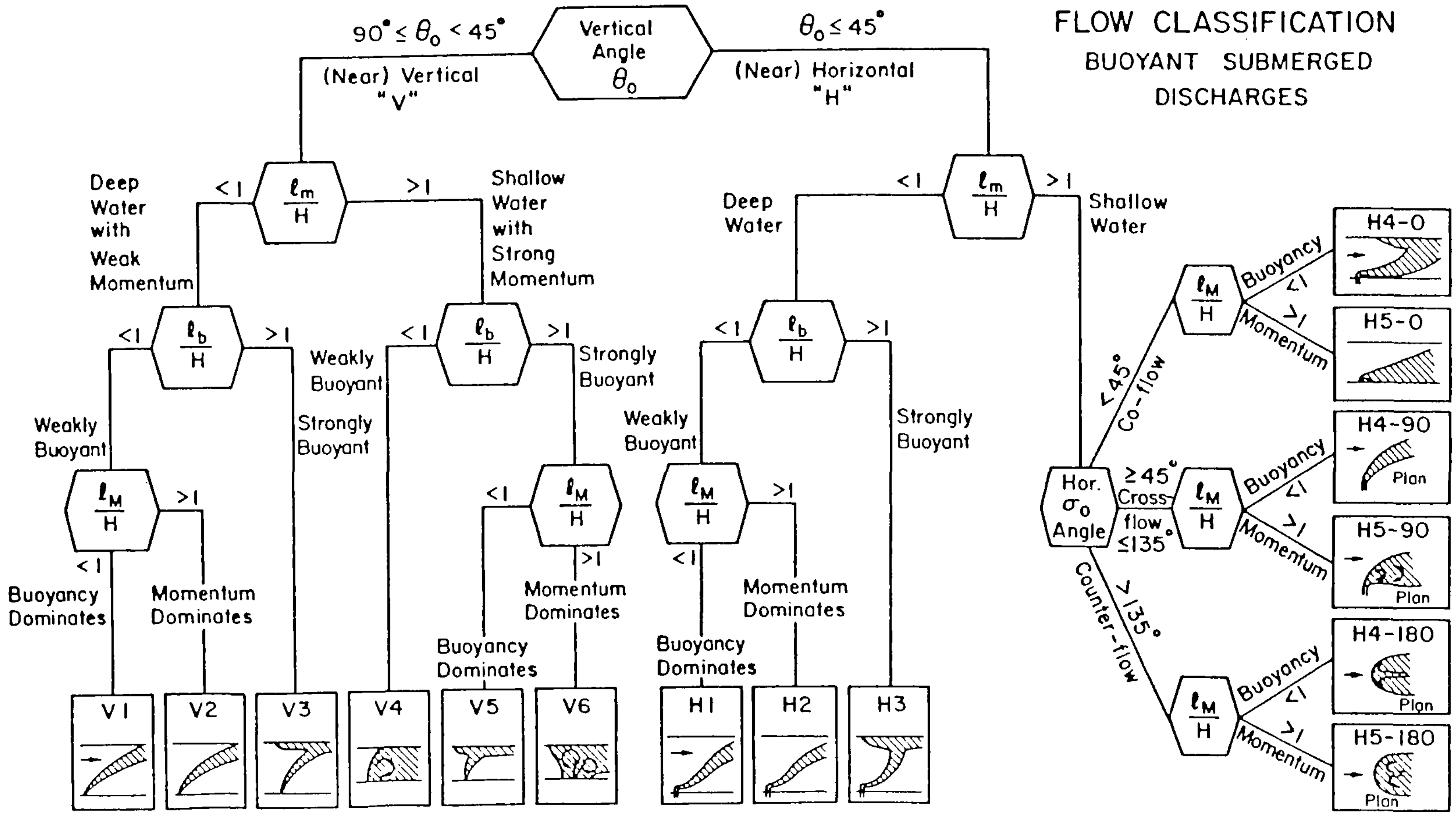
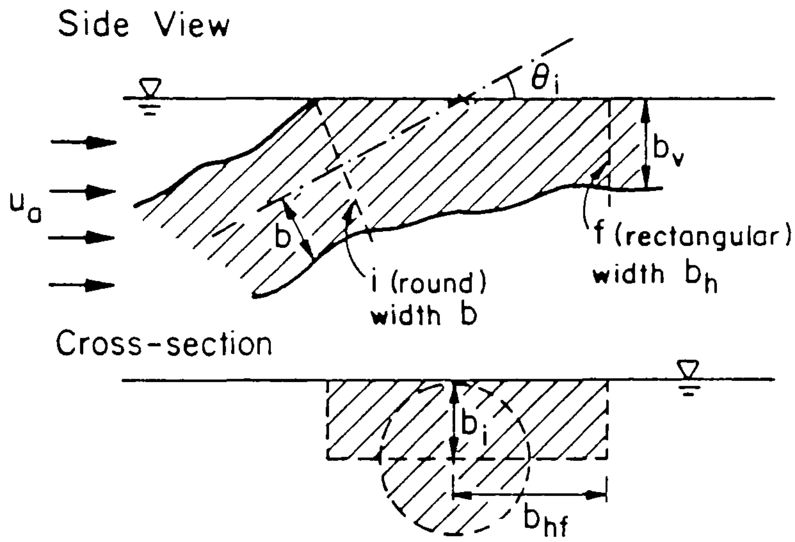
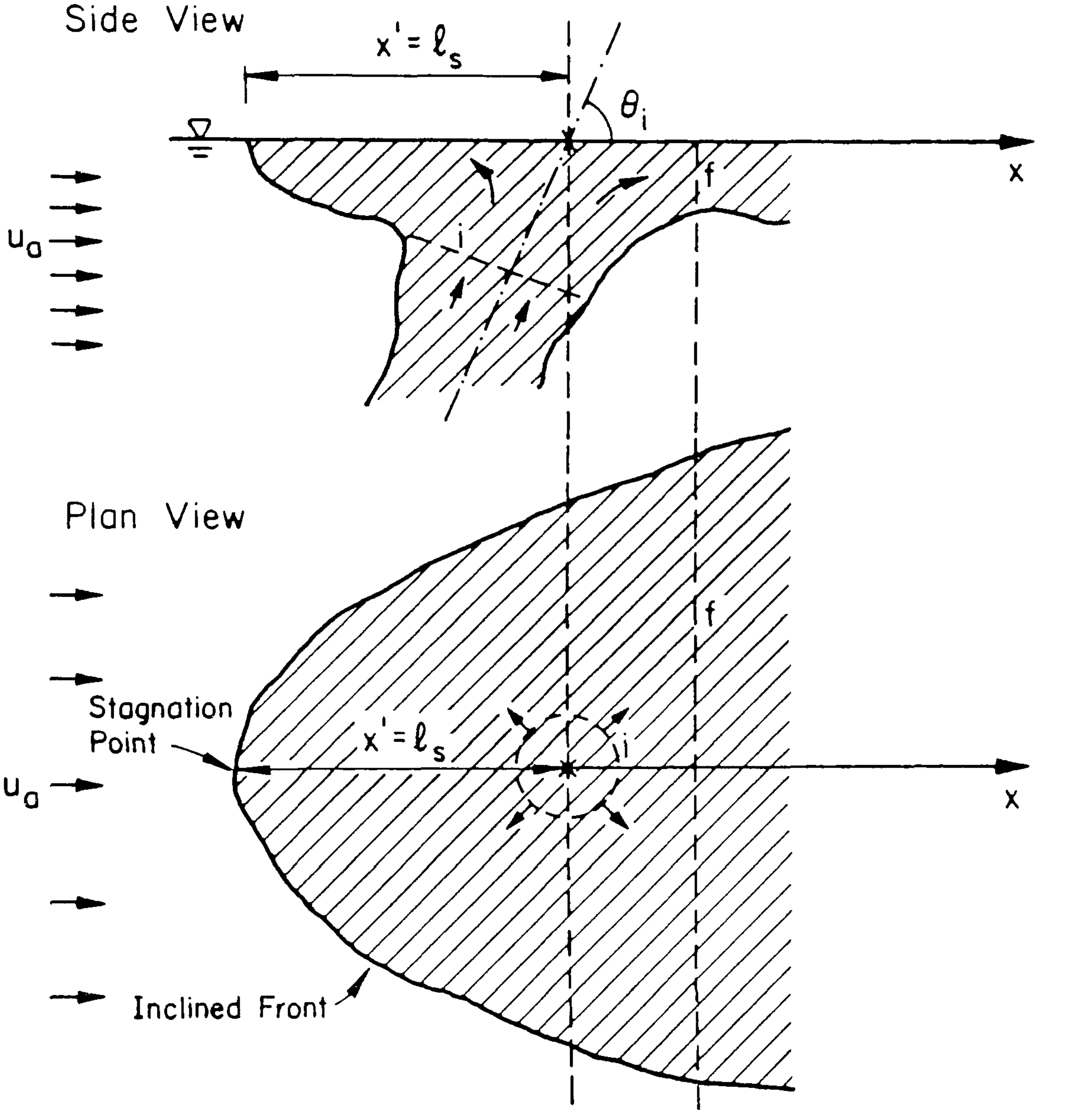


Figure 2.6 Flow Classification System
Note: Two additional flow classifications V1' and H1' (defined when $l_m > l_b$; the flow is mdnf→ mdff→ bdff), are included in CORMIX1 but for simplicity are omitted in Figure 2.6.



a) Surface Approach (Near-Horizontal)

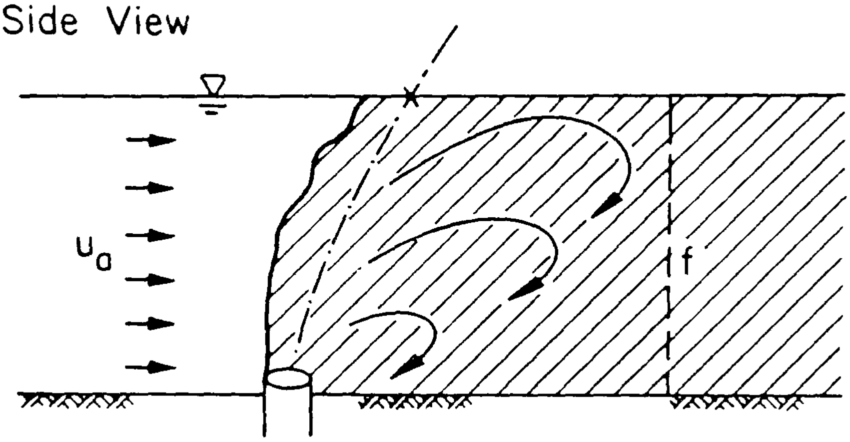
Figure 2.7 Four Major Conditions of Flow Interaction with Water Surface (i indicates inflow values in control volume and f outflow values)



b) Surface Impingement with Buoyant Upstream Spreading

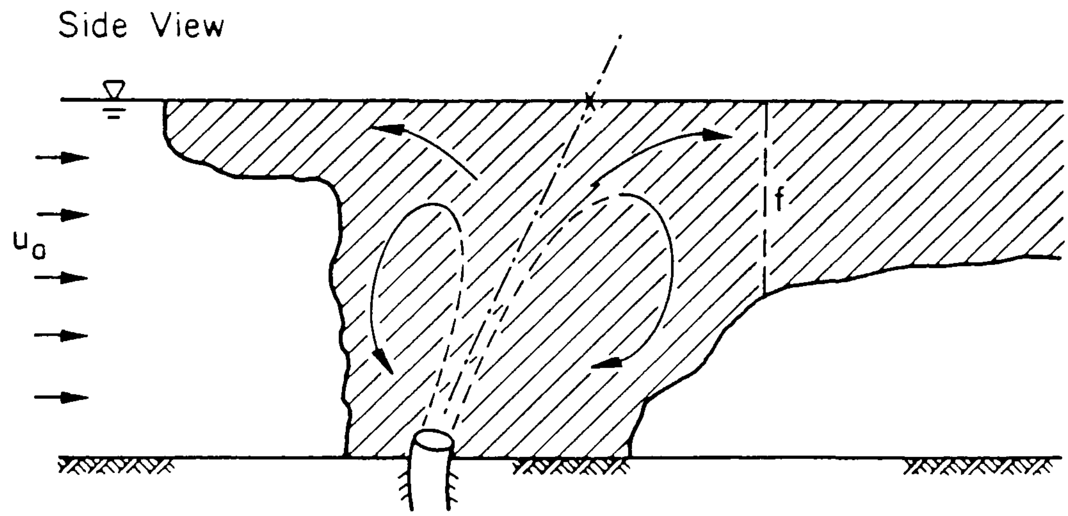
Figure 2.7 (continued)

Side View



c) Surface Impingement with Full Vertical Mixing

Figure 2.7 (continued)



d) Surface Impingement with Buoyant Upstream Spreading, Full Vertical Mixing, and Buoyant Restratification

Figure 2.7 (continued)

sections. When the plume contacts the surface, b_v and b_h are defined as the vertical depth and horizontal 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.

2.B.2.1 Near Horizontal Surface Approach

In this surface approach condition, the bent over flow approaches the water surface near horizontally at impingement angle $\theta_i < 45°$ (Figure 2.7a). The flow is advected with the ambient velocity field at a rate equal to u_a. This situation occurs for weakly buoyant and deep water cases, hence the flow will be strongly deflected when it contacts the surface. This type of surface interaction occurs for flow classifications V1 and V2 which are defined as deep water with weakly buoyant discharge (for $l_m/H < O(1)$ and $l_b/H < O(1)$, respectively).

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 (Figure 2.7a). Using a control volume approach the initial centerline dilution is related to the final bulk dilution, and a bulk mixing process is assumed with $S_f = 2^{1/2} S_i$ (Fan 1967). An equivalent cross-section aspect ratio for the outflow section of 2:1 is assumed. The continuity equation for the control volume in Figure 2.7a

$$u_a b_i^2 \pi = u_a 2 b_{hf} * b_{vf} \qquad (28)$$

where b_i is the initial dilution and half-width, b_{vf} is the final flow vertical width, and b_{hf} is the final flow horizontal half-width. This is evaluated as $b_{vf} = b_{hf} = b_i (\pi/2)^{1/2}$.

2.B.2.2 Near-Vertical Surface Impingement With Buoyant Upstream Spreading

In this surface approach condition, the weakly bent flow impinges on the surface at a near-vertical angle θ_i (Figure 2.7b), where $\theta_i > 45°$. After impingement the flow spreads more or less radially along the water surface as a density current. 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 stabilizing effects of buoyancy are greater than the destabilizing forces of jet momentum and the crossflow, thus this is classified as a stable discharge condition. This type of surface interaction occurs in flow classifications V3, V5, H3 and H5 and is defined for strongly buoyant discharges ($l_b/H > O(1)$) in both deep water ($l_m/H \leq O(1)$) and shallow water ($l_m/H > O(1)$). For deep water discharges, $l_m < l_b$ implies $l_M/H \leq 1$, so the flow will be weakly deflected plume at surface approach. For shallow water cases, to insure that the flow is a weakly deflected plume, the additional requirement will be that $l_M/H \leq 1$.

The lateral spreading of the flow in the surface impingement region is driven by both the flow momentum and buoyancy force. Of interest is the upstream intrusion length l_s, dilution S, horizontal width b_h, and vertical depth b_v of the density current at surface impingement.

The analysis of this flow region follows results presented by Lee and Jirka, (1981), and Jones, et al., (1983). Lee and Jirka analyze the properties of a buoyant subsurface discharge in stagnant water including the effects of recirculation and buoyant restratification. Jones, et al. presents a methodolgy to predict the upstream spreading of a buoyant radial discharge in crossflow. The strategy for solution will be to use the results of Lee and Jirka to provide initial conditions for the methodology of Jones, et al. for predicting buoyant upstream spreading and horizontal width.

A length scale l_N representing the turbulent mixing action of the horizontal momentum flux versus stability effect of buoyancy force is given by

$$l_N = (\text{defected horizontal momentum flux})^{3/4}/J_o^{1/2} \quad (29)$$

For the weakly deflected plume, Holley and Jirka, (1986) give an expression for the vertical momentum of a plume

$$M \cong 0.85 J_o^{2/3} s^{4/3} \quad (30)$$

Where, s ($\cong$ H) is the distance along the plume trajectory. Substituting appropriate values into Eq. (29), the length scale for a weakly deflected plume at impingement

$$l_N \cong 0.367H(1-\cos\theta_i) \quad (31)$$

where the factor $(1-\cos\theta_i)$ accounts for the deflected horizontal momentum flux, in analogy to the vane equation in classical fluid mechanics.

Jones, et al. defines an intrusion length scale l_I, by relating the interaction of the buoyancy force with the crossflow force

$$l_I = J_o / 2\pi c_D u_a^3 \qquad (32)$$

where c_D is a drag coefficient of O(1).

Thus, for a weakly deflected plume at surface approach, the ratio of length scales obtained from Eqs. (31) and (32)

$$l_I / l_N \cong 0.54(l_b/H)(1/(1-\cos\theta_i)) \qquad (33)$$

which describes the relative importance of buoyancy to momentum forces at surface impingement.

The upstream intrusion length L_s is found from observing the Figure 5-14 in Jones, et al.,

$$L_s / l_I = 4.2(l_I/l_N)^{-2/3} \qquad \text{for } l_I/l_N \leq 3.3 \qquad (34a)$$

$$L_s / l_I = 1.9 \qquad l_I/l_N > 3.3 \qquad (34b)$$

Noting that $l_I \cong l_b/5$ with $c_D \cong 1$ and since the flow is a weakly deflected plume at surface approach, the upstream intrusion length L_s in Eq. (34a) can be expressed

$$L_s = 1.26 l_b((1-\cos(\theta_i))/(l_b/H))^{2/3} \qquad (35a)$$

for $l_b/H \leq 6.11(1-\cos(\theta_i))$, and in Eq. (34b)

$$L_s = 1.91 l_b \qquad (35b)$$

for $l_b/H > 6.11(1-\cos(\theta_i)$.

To calculate the dilution in this region, first note that Jones, et al. in Figure 7-8 gives the dilution for a radial surface discharge

$$S/F_s = 1.6(l_I/l_N)^{1/3} \qquad (36)$$

where F_s is a radial surface spreading Froude number. This Froude number is defined

$$F_s = u_r/(g' l_o)^{1/2} \qquad (37)$$

where l_o is a characteristic length scale defined

$$l_o = (2\pi r_I h_I)^{1/2} \qquad (38)$$

where r_I and h_I are the radius and depth of the buoyant radial surface spreading flow, respectively.

Now the results of Lee and Jirka are used to evaluate the surface spreading Froude number F_s, so the dilution S from Eq.

(36) can be found. In this analysis, the initial radial surface spreading region uses a simplified control volume to relate the properties of the vertically buoyant jet at the entrance of the surface impingement region to the characteristic parameters of the horizontal axisymmetric buoyant surface jet at the exit of this region.

Lee and Jirka define the Froude number at surface impingement

$$F_I = u_r/(g' h_I) \quad (39)$$

where u_r is the radial surface spreading velocity and h_I is the depth after impingement. For large values of H/D, the value $F_I \cong 4.62$ and the value $h_I/H \cong 0.0775$.

The radius of the flow r_I is $r_I \cong \epsilon H$, where $\epsilon \cong 0.11$. By substituting these asymptotic values into Eq. (38), the characteristic length scale l_o from Jones, et al. becomes

$$l_o \cong 0.23H \quad (40)$$

which when combined with asymptotic values for Eq. (39) gives

$$F_s = F_I (h_I/l_o)^{1/2} \cong 2.65 \quad (41)$$

indicating that the flow in this region is jet-like. Finally, note that the radial surface spreading Froude number F_s can be expressed as in terms of the discharge flux variables as $Q/(M_o^{5/4}/J_o^{1/2})$.

This result can be then used to determine a bulk dilution at the end of the region S_f. From Eqs. (36) and (41) the expression for final dilution in the surface impingement region

$$S_f = 3.49 S_i (l_b/H)^{1/3} (1-\cos(\theta_i))^{1/3} \quad (42)$$

The geometry of the surface flow as revealed by Jones, et al. will be used to determine the width and depth within the region. From Jones, et al. Figure 7.1, the width, b_{hf}, at impingement is assumed to be 2.6 times larger that L_s:

$$b_{hf} = 2.6 L_s \quad (43)$$

The typical depth of the flow in the upstream intrusion region h_s, is found using the vertical length scale from Jones, et al. where

$$h_s = c_D u_a^2/g' \quad (44)$$

with $c_D = 0.8$. Noting that $g' = g'_0/S_f$, where S_f is the total bulk dilution, using the continuity equation $u_a^2 Q_0/J_0 = u_a^3 Q_0 M_0^{1/2}/(J_0 u_a M_0^{1/2}) = l_Q l_m/l_b$ the stagnation flow thickness h_s

$$h_s = 0.8 S_f l_m l_Q / l_b \qquad (45)$$

The final depth b_{vf} (at x=0) is found using the continuity equation, b_{vf} (x=0) = $Q_0 S_f/(b_{vf} u_a)$, and the previous equation

$$b_{vf} = l_b h_s / (0.8 b_{hf}) \qquad (46)$$

2.B.2.3 Near-Vertical Surface Impingement With Full Vertical Mixing

In this case, the weakly bent flow impinges on the water surface at a near-vertical angle (Figure 2.7c). This case is defined by shallow water ($l/H > O(1)$) and weak buoyancy ($l_b/H < O(1)$). Given the shallow ambient water depth and the weak buoyancy of the discharge, the flow becomes unstable after impingement. This occurs in flow classifications V4 and H4, and results in a recirculation region immediately downstream that extends over the full water depth. The recirculation region causes the flow to entrain ambient fluid from the flow itself causing dilution within the plume to decrease. Because of unstable recirculation, the centerplane dilution decreases to $S_f = S_i/R$, where R is a recirculation factor. Experimental data indicate R ranges from 1.0 to 2.0, and an average value of 1.5 will be assumed. The final flow width, b_{hf}, is found from the continuity equation

$$b_{hf} = S_f l_m l_Q / (2H) \qquad (47)$$

and final outflow location x_f is approximated as

$$x_f = x_i + 2H \qquad (48)$$

where x_i is the plume position at the beginning of the region. The distance 2H accounts for the typical length of a recirculating zone (Holley and Jirka, 1985).

2.B.2.4 Near-Vertical Surface Impingement With Unstable Recirculation, Buoyant Restratification, and Upstream Spreading

In this surface approach region, the flow rises near vertically and impinges on the water surface (Figure 2.7d). After impingement the mixed flow recirculates over the limited water depth and becomes partially re-entrained into the flow. This surface interaction occurs in flow classification V6 and is defined by shallow water ($l_m/H > O(1)$), strongly buoyant

($l_b/H >$ O(1)), as well as momentum dominated ($l_M/h >$ O(1)). Both momentum and buoyancy are strong, but momentum dominates in the near field. The degree of recirculation and hence the overall mixing in this region is controlled by restratification of the flow at edge of the recirculating region. The restratified flow spreads along the water surface. In particular the flow spreads some distance upstream against the ambient current, and laterally across the ambient flow.

The analysis of the flow is based on the work of Lee and Jirka, (1981) which was originally developed for stagnant conditions. The final dilution S_f is given by

$$S_f = 0.76H^{5/3}/(l_M^{2/3} l_Q) \qquad (49)$$

The dilution is controlled by buoyancy forces only, the effects of momentum become dissipated by the turbulent mixing action. This result can be understood if the values of l_M and l_Q are replaced in Eq. (49) by their respective efflux definitions, the results show that dilution is a function of the buoyancy flux only.

The surface buoyant spreading properties after the unstable recirculation are analyzed similar to the development for the near-vertical surface impingement with buoyant upstream spreading presented in section 2.B.2.2. In particular, for the unstable case, the limit of $l_i/l_N \to \infty$ is of interest, so that Eq. (34b) applies.

Since the near-field momentum is dissipated, the length of the upstream intrusion L_s is found from Jones, et al. (1984), Figure 5-14. This figure plots L_s/l_i vs. l_i/l_N and is a constant line of L_s/l_i = 1.9 for $l_i/l_N \to \infty$. Recalling $l_i \cong l_b/5$ from Eq. (32) for shallow ambient conditions and noting that, the relationship for upstream intrusion length L_s

$$L_s \cong 0.15 l_b \qquad (50)$$

The upstream intrusion thickness h_s is found in analogy from Section 2.B.2.2

$$h_s = 2S_f l_m l_Q / l_b \qquad (51)$$

The final half-width b_{hf}, is found from the continuity equation

$$b_{vf} = l_b h_s / (2b_{hf}) \qquad (52)$$

The region is assumed to extend downstream a distance equal to 2H as in Eq. (48).

2.C Analysis of Far-Field Mixing Process

After the flow interacts with the water surface as described by the previous sections, the far field mixing begins (Figure 2.1). This region consists of one or two regions, depending on discharge characteristics. In the general case, the flow contains sufficient buoyancy and there will be a buoyant surface spreading region followed by a passive diffusion region. The surface spreading region is characterized by dynamic horizontal spreading and gradual vertical thinning of the flow after interacting with the surface (Roberts, 1979, Koh and Brooks, 1975). Boundary interaction may occur, and in bounded sections the flow may become laterally fully mixed. 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 in this region. If the flow is non-buoyant or weakly buoyant there is no buoyant surface spreading region, only a passive diffusion region.

2.C.1 Buoyant Surface Spreading

In this region the buoyant surface plume spreads laterally along the water surface while it is being advected by the ambient current (Figure 2.8). The plume behaves as a density current and entrains some ambient fluid in the "head region" of the current. The mixing rate is usually relatively small. Furthermore, the surface plume may interact with a nearby bank or shoreline. The plume depth may decrease during this phase. The analysis of this region is based on arguments presented by Jones, et. al. (1985).

The continuity equation for the density current

$$u_a \partial h/\partial x + \partial(vh)/\partial y = w_e \qquad (53)$$

where w_e is the net velocity across the interface. Benjamin (1967) has derived an equation for the spreading velocity v_B

$$v_B^2/(g'h) = C \qquad (54)$$

where h is the density current thickness and C is a coefficient that depends on the relative depth h/H and is of order O(1 to 2). Combining the Eqs. (53) and (54) and integrating gives

$$u_a d(hb)/dx = q_e(x) \qquad (55)$$

where $q_e(x)$ is the localized head entrainment.

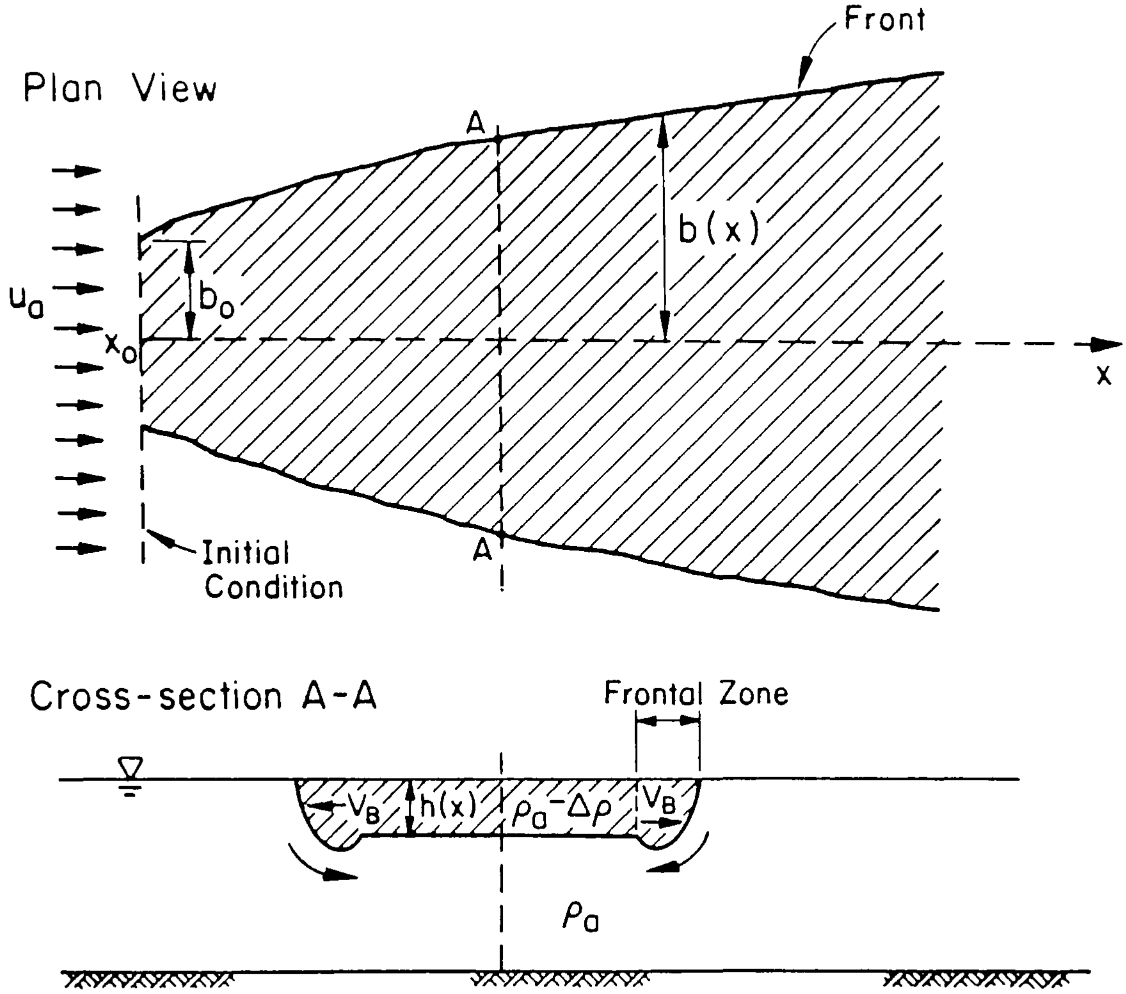


Figure 2.8 Buoyant Surface Spreading

The localized head entrainment is $q_e(x) = \beta v_B h$ where β is a constant O(0.15 to 0.25) (Simpson and Bitter, 1979; Jirka and Arita, 1987). The constant β will be set equal to 0.25 in CORMIX1.

The flow half-with b is obtained for any downstream distance x by using the boundary condition for the streamline ($v_B = u_a\, db/dx$) and integrating Eq. (53) (for the unattached case)

$$b_h = (b_i^{3/3} + 3/2 l_b^{1/2}(x - x_i))^{2/3} \qquad (56)$$

where x_i is the downstream distance at the beginning of the buoyant spreading region. The 2/3 power law of plume spreading is in agreement with the previous work of Larsen and Sorensen, (1968).

The vertical plume width b_v for any b_h in the region is given by integrating Eq. (54) to obtain

$$b_v = b_{vi}(b_h / b_{hi})^{\beta-1} \qquad (56)$$

where β represents the additional dilution caused by entrainment at the head of the density current.

The bulk dilution S given by c_0/c, is equivalent to g_0'/g' as is Eq. (7). Buoyancy conservation in the density current (analogous to momentum conservation) can be expressed

$$u_a \partial(g'h)/\partial x + \partial(g' v_B h)/\partial y = 0 \qquad (57)$$

Integrating Eq. (57) and noting that $\beta v_B h = \beta u_a h (db/dx)$ gives the expression for dilution S

$$S = S_i (b_v / b_{vi})^{\beta} \qquad (58)$$

<u>2.C.2 Passive Diffusion</u>

In this region the background turbulence in the ambient shear flow becomes the dominating mixing mechanism (Figure 2.9). The mixed surface flow is growing in depth and in width. The flow may interact with the channel bottom and/or banks.

The analysis of this region follows classical diffusion theory (e.g. Fischer, et al. 1979). The standard deviation σ of a diffusing plume in crossflow can be written in terms of the transverse turbulent diffusivity E

$$\sigma^2 = 2Ex/u_a \qquad (59)$$

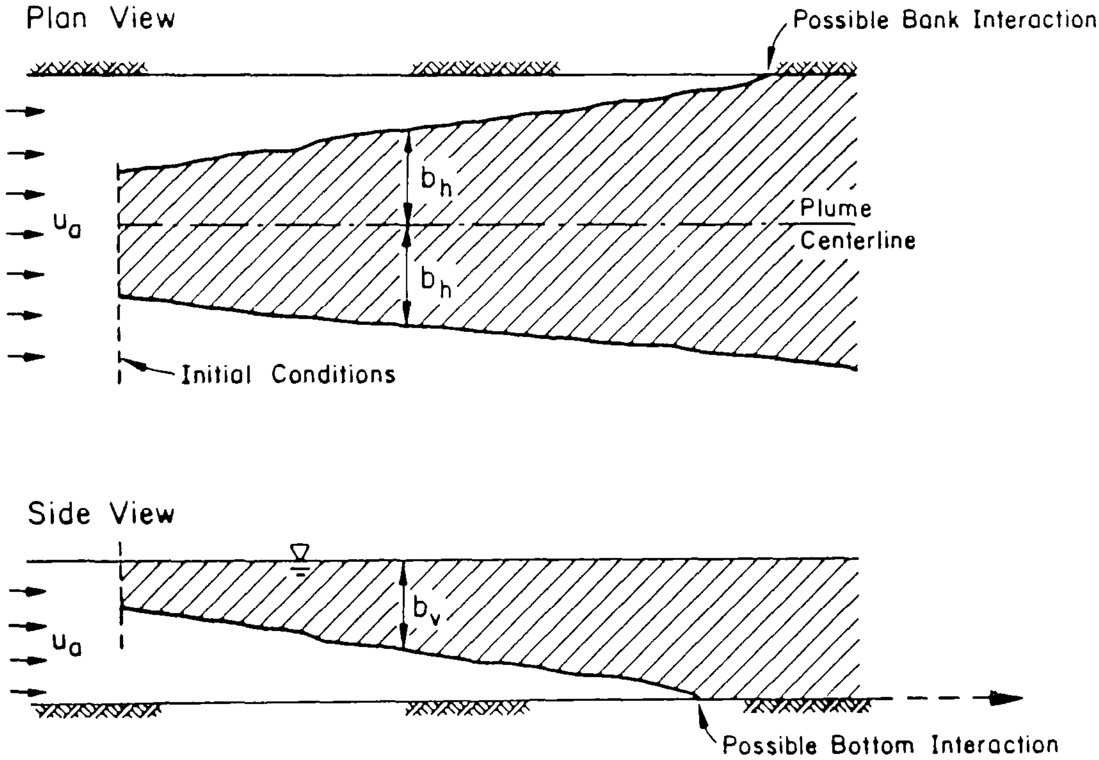


Figure 2.9 Passive Diffusion Process

In open channel flow the eddy diffusivity can be related to the friction velocity u_* and the channel depth H

$$E_z = 0.2u_* H \quad (60a)$$

for vertical diffusivity, and

$$E_y = 0.6u_* H \quad (60b)$$

for horizontal diffusivity. Due to some anisoptropy in a typical channel flow, the diffusivity in the horizontal transverse direction is larger than the diffusivity in the vertical direction. The friction velocity is given by $u_* = (f/8)u_a$ where f is the Darcy-Weisbach friction factor.

Solution of Eq. (59) gives the global coordinate system expressions for flow width b_v and depth b_h at any downstream distance x

$$b_v = ((2E_y/u_a)(x-x_i) + b_{vi}^2)^{1/2} \quad (61)$$

$$b_h = ((2E_z/u_a)(x-x_i) + b_{hi}^2)^{1/2} \quad (62)$$

where x_i, b_{vi}, and b_{hi} are the distance, width, and depth of the flow, respectively, at the beginning of the surface spreading region. This assumes that the above lengths are expressed in terms equal to one standard deviation, or $b_v = \sigma_y$ and $b_h = \sigma_z$.

The continuity equation applied to a plume in crossflow u_a, $\sigma_y \sigma_z = SQ_o$ yields the dilution S

$$S = \sigma_y \sigma_z / (l_m l_Q) \quad (63a)$$

In the case that when the plume is vertically fully mixed

$$S = \sigma_y H/(l_m l_Q) \quad (64b)$$

2.C.3 General Behavior in the Far-Field

a) Boundary Interaction

If buoyant surface spreading occurs, the process will continue until either the transition to passive turbulent diffusion occurs (as described in the next section 2.C.3 part b)) or the flow attaches to both banks in bounded sections, whichever occurs first.

The end of the passive turbulent diffusion region occurs when the plume becomes both vertically and laterally fully mixed and no change in dilution occurs with increasing downstream direction. In unbounded sections, the plume will never become laterally fully mixed, so the simulation terminates at some large downstream distance preset by CORMIX1.

b) Transition Between Surface Spreading and Passive Diffusion

A flux Richardson number, R_f, defined locally as the ratio of buoyant energy flux to shear energy production will be used as a stability criterion for the transition from the buoyant surface spreading to the passive diffusion flow. Written in terms of the eddy diffusivity convention (Tennekes an Lumley, 1972)

$$R_f = -gK_H(d\rho/dz)/(\rho K_M(du/dy)^2) \qquad (63)$$

in which K_M, K_H = eddy diffusivity for momentum and for a scalar(heat), ($K_H \equiv K_M$) respectively; $\rho(y)$ = local density; and $u(y)$ is the local velocity.

A critical value of $R_{fc} \equiv 0.10$ to 0.20 has been suggested by Monin and Yaglom, (1971) and Turner, (1973). Above this value, turbulence is damped and a stable profile can be maintained and the density current flow continues; below this value, turbulence erodes the stable density profile and turbulent diffusion then controls the flow.

For the buoyant surface spreading region Jirka (1979) suggests the appropriate Richardson number is of the form

$$R_f = \kappa^2 (g_o' H/u_*^2)(1/S)(h/H) \qquad (64)$$

where κ is von Karman constant ($\equiv 0.4$). The ratio of h/H in Eq. (64) is a length scale representing depth of the density current to overall channel depth.

Noting that S_i, b_{vi}, and x_i are the dilution, initial depth, and downstream distance at the start of the buoyant surface spreading flow, the distance to transition, x_t, to the passive spreading flow

$$x_t = x_o + (2/3)(b_i^{3/2}/l_b^{1/2})\{[(8 l_b h_o)/(f S_i l_m l_Q)]^{3/2} - 1\} \qquad (65)$$

If the plume is attached to one boundary l_b is replaced with $2l_b$.

Chapter III
CORMIX1 Program Structure

The Cornell Mixing Zone Expert System Subsystem 1 (CORMIX1) is a series of software subsystems or elements for the analysis and design of conventional or toxic single port submerged buoyant or nonbuoyant pollutant discharges into unstratified watercourses, with emphasis on the geometry and dilution characteristics of the initial mixing zone. It is designed as an analysis tool for regulators, dischargers, (and students of hydraulics).

The user supplies CORMIX1 with information about the discharge and ambient environment. CORMIX1 returns information detailing the hydrodynamic mechanisms controlling the flow, dilution, geometric information concerning the shape of the pollutant plume or flow in the ambient water body, and design recommendations allowing the user to improve the dilution characteristics of the flow. If specified by the user, CORMIX1 also presents information about the legal mixing zone dimensions and dilution, toxic mixing zone requirements, and zone of interest characteristics for the flow. The minimum hardware configuration for CORMIX1 is an IBM-PC/XT with a printer for hardcopy output.

The purpose of CORMIX1 is to obviate for the novice analyst the need for detailed hydrodynamic understanding and experience. A general environmental science or engineering background at the BS level appears to be minimum educational requirement needed to compile and supply relevant data, interpret the system information, and ultimately learn and become knowledgeable about hydrodynamic mixing through repeated interactive use. Two working days appears to be the minimum time needed for a first time user to gain initial facility with system requirements, limitations, and interpretation of results.

Figure 3.1 shows the system elements of CORMIX1. During system use the elements are loaded sequentially by the user. CORMIX1 is implemented in the programming language Fortran, and M.1 (Teknowledge, Inc.), an expert systems "shell".

M.1 is an expert systems programming language, or more precisely, a shell. A shell is a self-contained inference engine that does not contain the knowledge base, but has

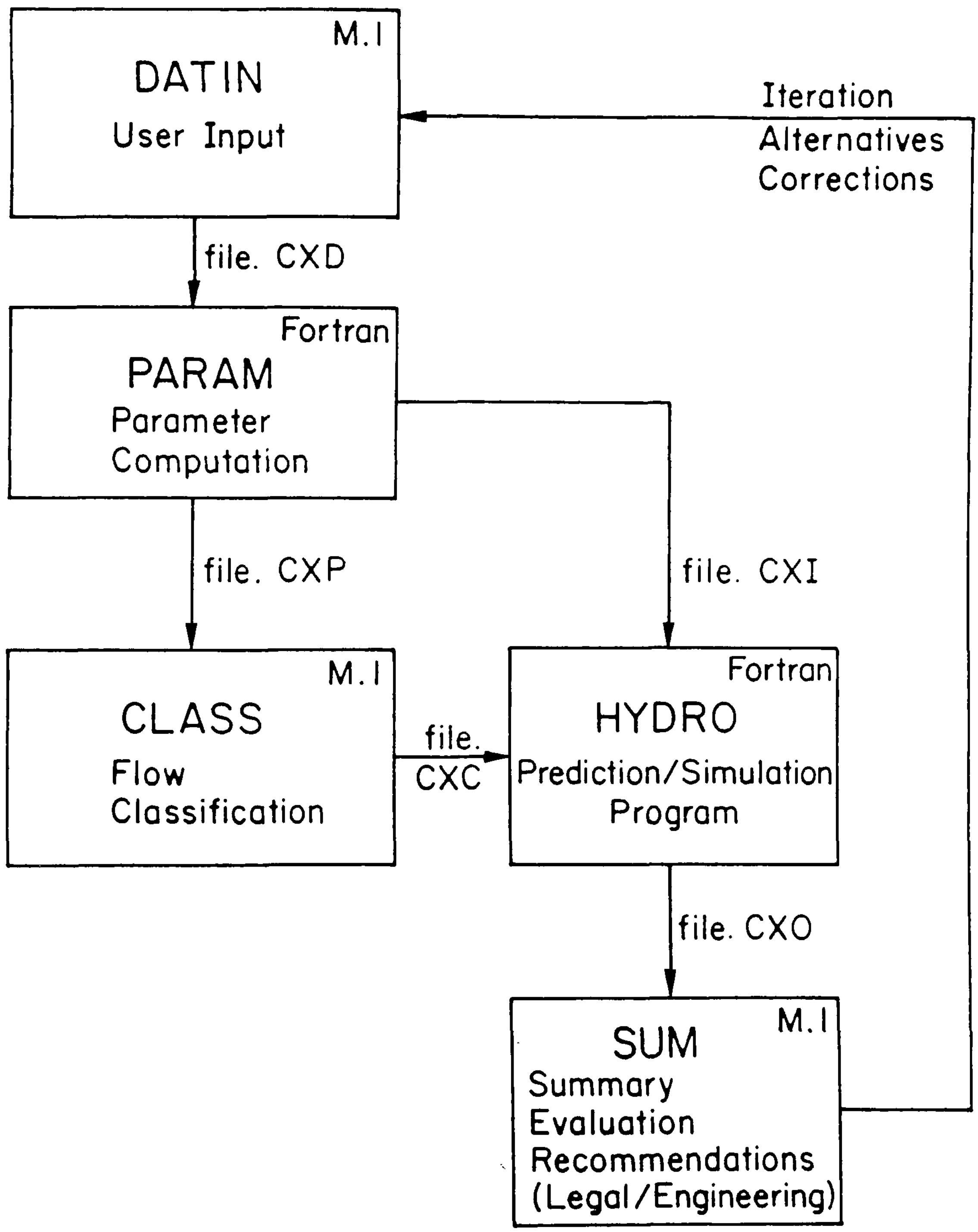


Figure 3.1 System Elements of CORMIX1

facilities for both forward and backward reasoning, debugging aids, consistency checking, input and output menus, and explanation facilities.

Two programming languages are used to exploit their respective strengths while avoiding their respective weaknesses. M.1, as a knowledge base language, is very efficient in knowledge representation and symbolic reasoning; however it is relatively weak in numerical computational ability. On the other hand, Fortran is ideal for computation of mathematical functions (Fortran stands for formula translator) but is poorly suited for the tasks associated with symbolic reasoning. Thus M.1 is employed to implement the knowledge acquisition, model selection, and analysis of the hydrodynamic simulation portions of the expert system. Fortran is used for the computation of various length scales and in the hydrodynamic flow simulation models.

It is interesting to note that the entire system could have been programmed in a language such as Fortran, or even assembly language; the real issue is one of programming efficiency. For instance, a routine written in 5 lines of Fortran code might take 100 lines of assembly level source code. Since M.1 was developed to encode and manipulate symbolic logic, it does so with great efficiency, allowing the programmer to write in 5 lines of code what might take 100 lines in Fortran or 1000 lines of assembly. In essence the selection of M.1 as the language for the symbolic reasoning tasks gives the programmer significant leverage.

3.A Discussion of Logic/M1 Elements

The M.1 elements of CORMIX1 are DATIN, CLASS, and SUM. M.1 is very similar in structure to PROLOG (PROgramming LOGic). PROLOG was developed in Europe and is designed to manipulate logical expressions(Clocksin and Mellish, 1984). An M.1 program is built from statements containing facts and if-then rules about facts. This is called the knowledge base. The knowledge base is supplied by the user corresponding to a problem domain, in this case buoyant submerged jets and hydrodynamic mixing processes.

M.1 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. The following section gives a more detailed explanation of how this is accomplished, using the CORMIX1 module DATIN as an illustrative example.

3.A.1 DATIN

DATIN is an M.1 program for the entry of relevant data and for the initialization of the other program elements. The user executes DATIN by typing "DATIN". DATIN then prompts the user for needed information.

CORMIX1 deals with submerged buoyant single port discharges into an unstratified water body. 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 DATIN gathers, appears in Figure 3.2.

Even in this simple schematized ambient geometry, there remains a tantalizing amount of geometric and dynamic detail: the discharge location in relation to the bottom and the shoreline; the discharge orientation may be with the flow, against the flow, or vertically upward across the flow, or at some arbitrary angle, the water depth may be deep or shallow; the ambient flow may be stagnant or fast and highly diffusive; and the discharge flow may be non-buoyant or highly-buoyant; with high or low efflux velocity.

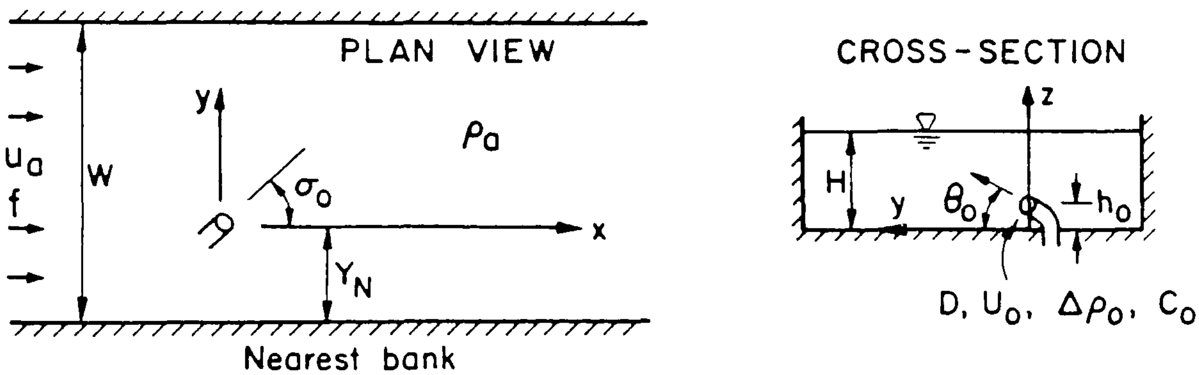
The purpose of DATIN is to specify completely the physical environment of the discharge, as well as legal or regulatory specifications. The following data groups need to be entered: general site and case identifer information, ambient conditions (geometry and hydrography), discharge conditions (geometry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

DATIN tries to satisfy the goal creating a valid parameter input file for the other CORMIX1 elements. The goal is the statement that drives the execution of DATIN. This is written in M.1 as

goal = param_input_file. [1]

Here the goal is to satisfy or find a valuation for the expression "param_input_file".

All rules in M.1 are stated as: **if** {expression(s) or clauses called the "premise" or "head" of the rule} - **then** {an expression or clause called the "conclusion" or "tail" of the rule} statements. The premise of a rule in M.1 can contain more than one expression connected by and/or



Flux quantities: Q_0 = discharge

$M_0 = U_0 Q_0$ = momentum flux

$J_0 = (\Delta\rho_0/\rho_a)\, g\, Q_0$ = buoyancy flux

Figure 3.2 Schematization of Discharge Configuration statements but the conclusion of the rule can contain only one expression. M.1 will try to satisfy the goal (here the expression "param_input_file") by searching for a rule in the knowledge base whose conclusion contains the expression "param_input_file = (valuation)".

A rule in DATIN that has "param_input_file = known" in its conclusion is (a separate line for each expression in the premise of the rule has been added to improve readability):

```
    if site_description = found and
    ambient_conditions = found and
    discharge_parameters = found and
    zone = found
then param_input_file = known.                              [2]
```

Here, in the conclusion of the rule the expression param_input_file is assigned the valuation "known".

First, a explanation is given on how M.1 uses information contained within **if** - **then** rules to assign valuations to expressions. M.1 always tries to satisfy a valuation in the conclusion of rule by proving its premise. Thus, M.1 tries to satisfy all expressions in the premise of the rule, beginning in statement [2] with the first expression "site_description = found". If the valuation of the variable in first clause is satisfied, i.e. the expression site_description does indeed have the valuation "found", then M.1 tries to satisfy the second expression, "ambient_conditions = found". If this valuation is satisfied, M.1 will try to satisfy the remaining expressions in the premise of the rule. Whenever in the premise the valuations for all expressions are satisfied, the rule succeeds or "fires". When the rule fires, the expression in the conclusion the rule can be given a valuation and added to the facts known in the knowledge base.

So how does M.1 know the expression "site_description" has the valuation "found"? Because there is another rule in the knowledge base which is

```
    if site_name = SN and
    discharger_name = DN and
    pollutant_name = PN and
    design_case = DC and
    grid_interval = NSTEP
then site_description = found.                              [3]
```

This statement is invoked by statement [2] in DATIN when it tries to find a valuation for the first expression "site_description". Since there is no present valuation for the expression "site_description", M.1 locates statement [3] with the expression "site_description" in its conclusion. If all expressions in the premise of statement [3] can be assigned valuations, then the expression site_description is assigned the valuation "found". All capitalized values in statement [3] (SN, DN, PN, DC, and NSTEP) are variables in M.1. Variables in M.1 are only assigned a valuation when considered within a rule. M.1 will try to find a valuation for site_name, the first expression in statement [3]. Within the DATIN there is another rule

question(site_name) ="Enter a descriptive name for the discharge location". [4]

This rule is a treated as a "fact", and M.1 prompts the user for a valuation of "site_name" with the message within the quotes of statement [4]. The user enters a value which is bound to the variable SN, giving the expression "site_name" the valuation of SN. M.1 continues to find valuations for the remainder of the expressions in statement [3] in a similar manner. When all expression in the premise of statement [3] are assigned a valuation, the conclusion "site_description = found" is added as a fact to the knowledge base, which will allow M.1 to return to statement [2] to seek a valuation for the expression "ambient_conditions".

Thus, as was shown with the previous example, the knowledge base DATIN is built from rules which contain expressions that force M.1 to seek valuations from other rules. The process of seeking valuations of expressions continues either until all the valuations are found or the rule base is exhausted without finding a valuation. M.1 will never assign a valuation which is in contradiction within a rule, so we are assured whatever valuations we conclude are taken from a rule within the knowledge base. Care must be taken in program structure however, since the search strategy of M.1 may not consider all rules needed to find a valuation for a given expression. In general, the rule base should be programmed in a "tree" structure, with the most general and independent rules at the beginning of the program, and rules which depend on valuations from other rules following in the program. The most dependent and nested rules should occur last in the knowledge base.

When a valuation for a clause in the premise of a rule is found not agree with the valuation given for that clause within the rule, e.g. the expression discharge_parameters in statement [2] is found to have the valuation "unknown", then the rule fails, no valuation can be assigned to the expression "param_input_file" from that rule. M.1 will stop trying to satisfy the remaining expressions in the premise of that rule. M.1 will continue to try to satisfy the expression "param_input_file" by looking for another rule in the knowledge base with "param_input_file" in the conclusion of a rule.

The actual rule corresponding to statement [2] in DATIN contains additional clauses that control the manner in which intermediate conclusions are stored in memory, messages are displayed on the monitor, and other statements which create and manipulate external files for use in other CORMIX1 modules.

When the rule in DATIN corresponding to statement [2] fires, the "cache" of DATIN is written to an external DOS file. The cache is a list of all expressions within DATIN that have been assigned a valuation. This cache file is read by the next sequential element in CORMIX1, the Fortran program PARAM. At its termination, DATIN directs the user to exit the M.1 environment and execute PARAM.

A complete program listing of the DATIN knowledge base appears in Appendix A.1. Appendix B contains the output of an interactive session using DATIN for the design examples in Chapter V.

3.C.2 CLASS

CLASS is an M.1 program that classifies the given discharge into one of the many possible flow configurations, e.g. a simple jet or plume, an unstable vertically mixed case, or mixing controlled by ambient flow. The user executes CLASS by typing "CLASS".

Only one flow classification can be selected for a particular discharge configuration from the many possible flow classifications explained in Section 2.B.1 and shown in Figure 2.6.

The goal of CLASS is to find a valuation for the expression "flow_class" from the flow classification scheme appearing in Figure 2.6. Each of the 17 possible flow classification has an alphanumeric label(eg. V1, V2, H3, etc.). CLASS inputs a cache created by PARAM 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. A rule corresponding to flow case V2 would appear in simplified form for illustration purposes as

```
if vertical_angle = THETA0 and
THETA0 > 45.0 and
THETA0 <= 90.0 and
```

$l_m/H < 1$ and
$l_b/H < 1$ and
$l_M/H > 1$
then flow_class = V2. [5]

When the appropriate flow classification rule fires, a detailed hydrodynamic description of the flow is provided to the user. This detailed output includes a description of the significant near field mixing processes, or the hydrodynamic mixing zone (HMZ). The HMZ is the region where the particular design of the outfall can have 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. CLASS also creates a cache output file that supplies the next CORMIX1 element, the Fortran hydrodynamic simulation program HYDRO, with instructions for running the appropriate simulation. At its termination CLASS directs the user to exit the M.1 environment and execute HYDRO.

The complete knowledge base for CLASS appears in Appendix A.2. The interactive output from CLASS appears in Appendix B as discussed in the design examples Chapter V.

3.C.3 SUM

SUM is an M.1 program that summarizes the hydrodynamic simulation results for the case under consideration. SUM is executed by the user by typing "SUM". SUM comments on the mixing characteristics, evaluates how applicable legal requirements are satisfied, and suggests possible design alternatives to improve dilution. Thus, SUM may be used as an interactive loop to guide the user back to DATIN to alter design variables.

The output of SUM is arranged in four groups; site summary, hydrodynamic simulation summary, data analysis, and design recommendations. The site summary gives the site identifier information, discharge and ambient environment data, and discharge length scales. The hydrodynamic simulation summary will list conditions at the end of the hydrodynamic mixing zone, legal mixing zone conditions, toxic dilution zone conditions, region of interest criteria, upstream intrusion information, bank attachment locations, and a passive diffusion mixing summary, depending if the preceding conditions are specified or occur. The data analysis section gives further details on toxic dilution zone criteria, legal mixing zone criteria, stagnant ambient environment information, and region of interest criteria. Finally the design recommendations section gives design suggestions for improving initial dilution. Factors effecting initial dilution are the discharge momentum flux, discharge angle, outfall location, discharge buoyancy, bank attachment, and ambient environment conditions.

The listing of the SUM knowledge base appears in Appendix A.3. The interactive listing of SUM appears in Appendix B and is discussed in the design examples Chapter V.

3.C Discussion of Hydrodynamic/Fortran Elements

The FORTRAN elements of CORMIX1 are PARAM and HYDRO. These element are programmed in FORTRAN because of the limitations of M.1 for computing mathematical expressions. PARAM and HYDRO are executed after the user has successfully completed DATIN and CLASS, respectively.

3.C.1 PARAM

PARAM is a Fortran program that computes relevant physical parameters for the given discharge situation. This includes the various length scales; l_Q, l_M, l_m, l_b, fluxes and other values needed by the other CORMIX1 elements. PARAM is executed by the user by typing "PARAM".

PARAM also computes the maximum value for each specified mixing or interest zone for each of the possible hydrodynamic simulation termination criteria, i.e. maximum downstream distance, plume area, or plume cross-section. At the termination of PARAM the user is directed to execute the next CORMIX1 element, CLASS.

A complete listing of the program PARAM appears in Appendix A.4. Appendix B provides the interactive output of PARAM using the design examples presented in Chapter V.

3.C.3 HYDRO

HYDRO is a Fortran program that runs the hydrodynamic simulation program for the flow classification program specified in CLASS. The simulation program elements are based on the similarity theory presented in Chapter II.

HYDRO consists of control programs or "protocols" for each hydrodynamic flow classification (V1,V2,H3, etc.) as specified by CLASS. Each protocol executes a series of subroutines or "modules" corresponding to the flow phenomena (e.g. Wirght's (1977) mdnf, mdff, bdnf, bdff; surface interaction modules, etc.) which may occur in that flow classification. Thus HYDRO assembles the appropriate simulation from the modules are which are arranged like "pigeon holes".

Table 3.1 lists all modules called by the protocols for a hydrodynamic simulation. The "type" column indicates whether the analysis was based on a continuous or control volume approach. Table 3.1 lists the flow classification as given in CLASS and the protocols for assembling the simulation modules corresponding to that flow classification. In Table 3.2, the protocols list the simulation modules to be called in order, from left to right, to complete the hydrodynamic simulation.

HYDRO creates a tabular output file of the simulation containing information on geometry (trajectory, width, etc.) and mixing (dilution, concentration). The user executes HYDRO by typing "HYDRO".

After HYDRO has executed, the user may view the tabula output file, giving detailed information on the trajectory and dilution of the hydrodynamic flow simulation. The program listing of HYDRO appears in Appendix A.5 and the interactive output appears in Appendix B as discussed in the design examples chapter V.

Table 3.1 Hydrodynamic Simulation Modules

MODULE (MOD)	NAME	TYPE
01	zofe	Control Volume
11	mdnf	Continuous
16	mdff	Continuous
21	bdnf	Continuous
22	bdff	Continuous
31	surface approach	Control Volume
32	surface impingement upstream spreading	Control Volume
33	surface impingement full vertical mixing	Control Volume
34	surface impingement unstable near-field	Control Volume
41	buoyant spreading	Continuous
61	passive diffusion	Continuous

Table 3.2 Hydrodynamic Simulation Protocols

Flow Classification: V1, H1

Modules:	01	11	21	22	31	41	61
Transition Rule:	0	1	3	5	0	7	
					↑ End of HMZ		

Flow Classification: V1P,H1P

Modules:	01	11	16	22	31	41	61
Transition Rule:	0	2	4	5	0	7	
					↑ End of HMZ		

Flow Classification: V2,H2

Modules:	01	11	16	31	41	61
Transition Rule:	0	2	5	0	7	
				↑ End of HMZ		

Flow Classification: V3, H3

Modules:	01	11	21	32	41	61
Transition Rule:	0	1	6	0	7	
				↑ End of HMZ		

Flow Classification: V4, H4

Modules:	01	11	33	61
Transition Rule:	0	5	0	
			↑ End of HMZ	

Flow Classification: V5, H5

Modules:	01	11	21	22	31	41	61
Transition Rule:	0	1	3	5	0	7	
					↑ End of HMZ		

Flow Classification: V6, H6

Modules:	01	34	41	61
Transition Rule:	0	0	7	
		↑ End of HMZ		

Chapter IV
Data Comparison and Validation

In this chapter the predictions of CORMIX1 will be compared with laboratory and field data. This chapter is not meant to be an extensive validation of CORMIX1 predictions for all possible flow classifications, but rather a limited test of key CORMIX1 elements. Future work plans for CORMIX1 include additional calibration and validation with both available laboratory and field data.

The comparison of CORMIX1 predictions will focus on the near field flows, the unstable surface impingement process, and the near vertical impingement with buoyant upstream spreading module and buoyant surface spreading.

4.A Near Field Flows (sub-surface regions)

To validate the near field flows, CORMIX1 predictions were compared with laboratory data from Fan (1967), Wright (1977), and Platten and Keffer (1971).

Figures 4.1 and 4.2 show two cases of Fan's (1967) trajectory data plotted with CORMIX1 projections. Fan released a dyed salt solution into uniform ambient flow within a 40.0x1.10x0.61 m flume. Fan did not include the effects of surface impingement in his analysis. Photographs recorded trajectory and concentrations were measured with conductivity probes.

Figure 4.1 shows an experiment 20-12 with a jet injected perpendicularly ($\theta = 90.0°$) into crossflow (velocity ratio $R = u_0/u_a = 12$) and a Froude number $F_0 = 20$ representing a weakly deflected forced plume. In this experiment, CORMIX1 predicts a V1 classification with a mdnf -> mdff -> bdff flow. CORMIX1 appears to slightly under predict Fan's observed trajectory by about 20%. This discrepancy could be accounted for by Fan's method for defining the plume centerline as the intersection of lines of equal concentration within the plume cross-section, and not location of maximum concentration within the plume. CORMIX1 assumes a maximum concentration along the flow centerline.

Figure 4.2 illustrates experiment 40-4 where the effect of a larger crossflow with ($R = 4.0$) a less buoyant jet (F_0 =

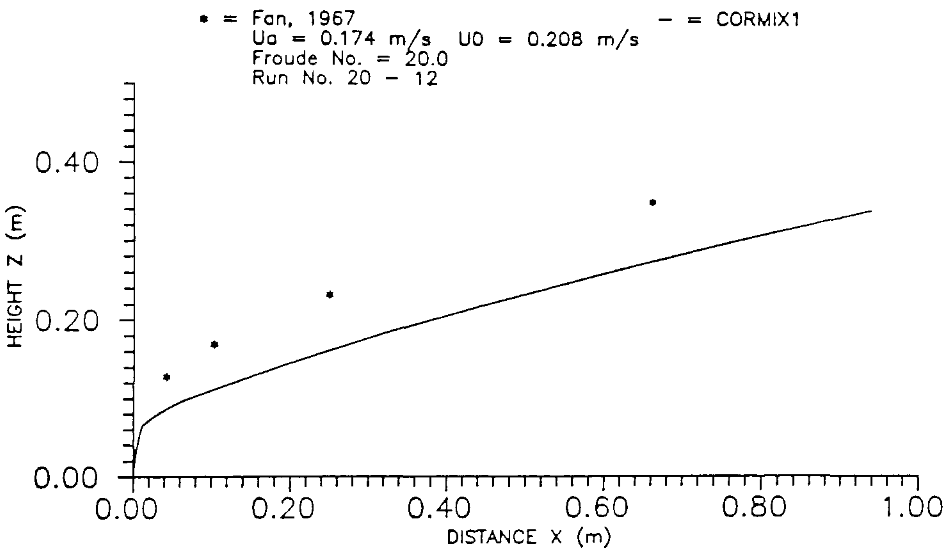


Figure 4.1 Fan's Buoyant Jet Trajectory, Expr. 20-12, R = 12

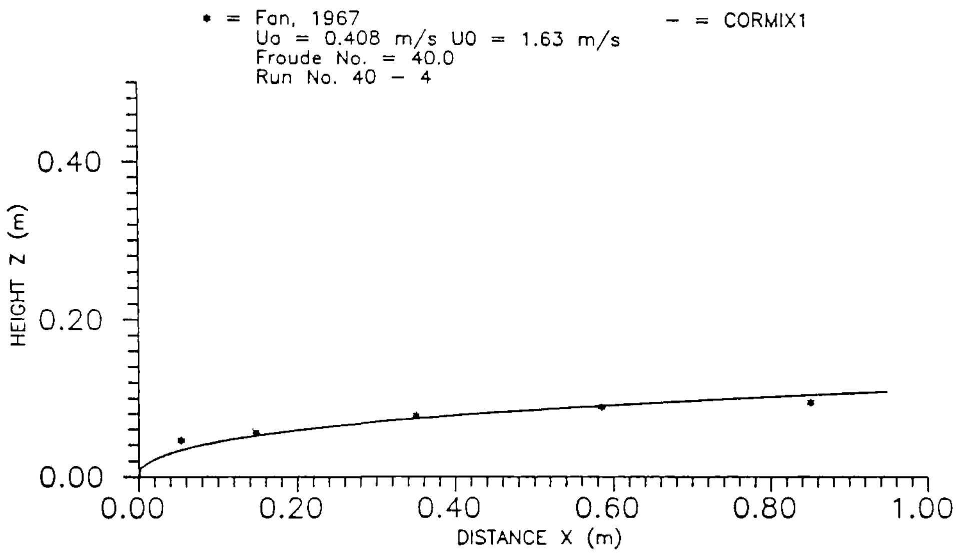


Figure 4.2 Fan's Buoyant Jet Trajectory, Expr. 40-1, R = 4

40.0) where the flow becomes significantly deflected soon after emerging from the discharge nozzle. In this experiment, CORMIX1 predicts a V1 classification with a mdnf -> mdff -> bdff flow. CORMIX1 trajectory predictions appear to agree well with Fan's data.

Dilution predictions from CORMIX1 that correspond with the experiments in Figures 4.1 and 4.2 are presented in Figures 4.3 and 4.4, respectively. In both cases, dilution predictions are in close agreement with Fan's results. It should be noted that all CORMIX1 near field predictions are continuous, the apparent "kink" in Figure 4.4 (and Figures 4.5 and 4.6) is due to the chosen step size and could be eliminated by a higher resolution.

Figure 4.5 shows CORMIX1 trajectory predictions for laboratory experiment 2-2 by Wright, (1977). Wright conducted his experiments in a 8.7x0.61x0.61 m towing tank. Figure 4.5 shows an experiment with R = 37 and F_0 = 67. As can be seen, CORMIX1 predictions appear to be in strong agrement with Wright's data. Unfortunately, no dilution data was available for this experiment.

Figure 4.6 shows the effect on a nonbuoyant jet of changing the angle between the axis of the discharge to the horizontal plane from $\theta_0 = 90°$, as in the previous examples, to $\theta_0 = 60°$. This experiment by Platten and Keffer was conducted with air in a 2.44 x 1.22 m wind tunnel. CORMIX1 predictions appear to be in good agreement near the source, but tend to deflect more strongly. No dilution data was available for this experiment.

<u>4.B Near Vertical Surface Impingement With Buoyant Upstream Spreading</u>

Field data for a deep wastewater outfall off the California coast was obtained by the Allan Hancock Foundation (1964); (see also Chen, 1980). In this case, a strongly buoyant discharge with $g_0' = 0.225$ ($\Delta\rho/\rho = 0.025$) was released 16.8 m below the surface through a 2.0 m diameter outfall into the ocean with an ambient current of 0.175 m/s. CORMIX1 predicts a flow classification of V5, indicating a stable discharge configuration with buoyant upstream spreading after surface impingement. The results of the CORMIX1 simulation and the actual data appear in Figures 4.7a and 4.7b. Figure 4.7a shows a side view of the discharge as predicted by CORMIX1. Unfortunately, no field data is available to compare with these subsurface predictions. Field data is limited to photographic observation of the surface plume. Figure 4.7b shows a plan view of the CORMIX1 prediction with field data available from this remote sensing evidence (Chen, 1980). CORMIX1 predicts an upstream intrusion of 91 m with a flow

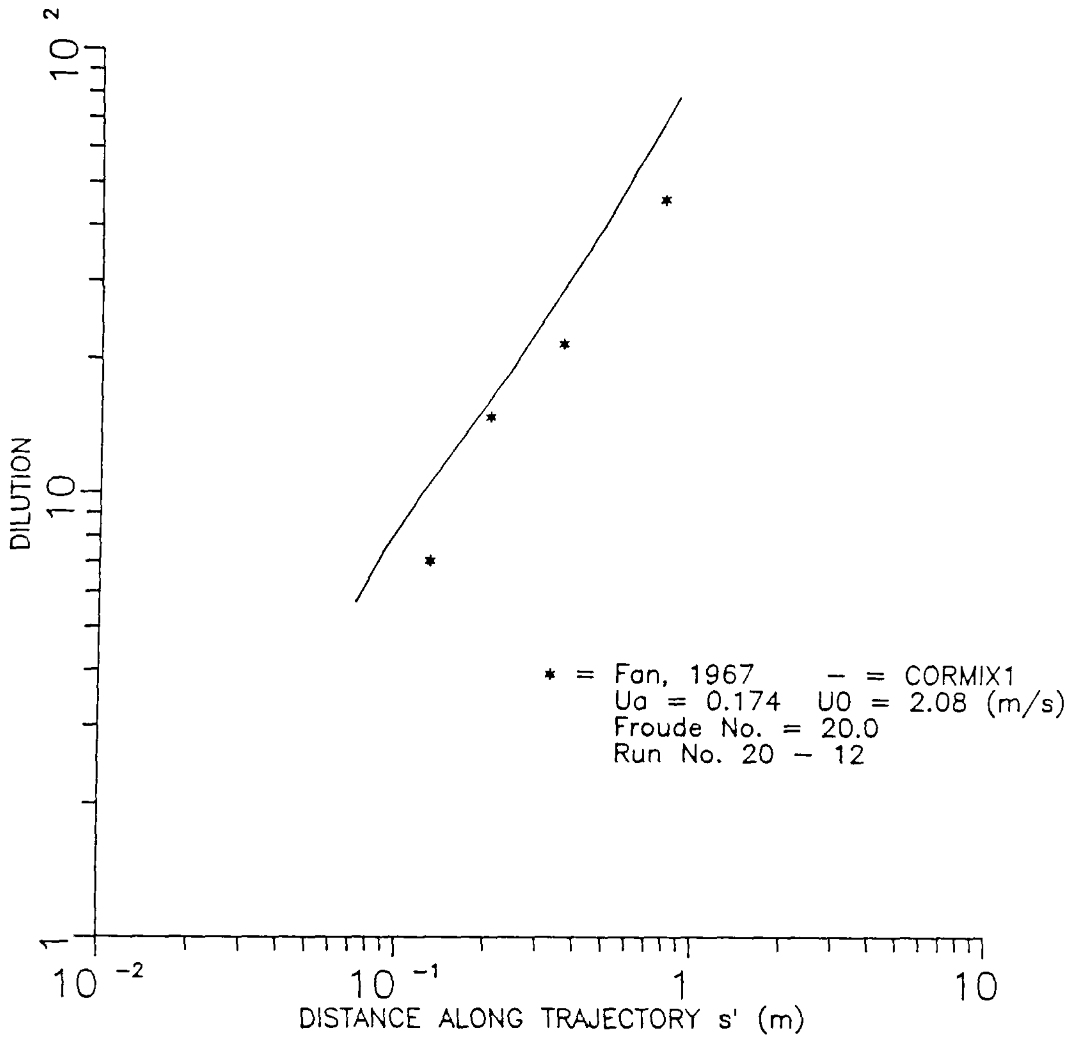


Figure 4.3 Fan's Buoyant Jet Dilution, Expr. 20-12, R = 12

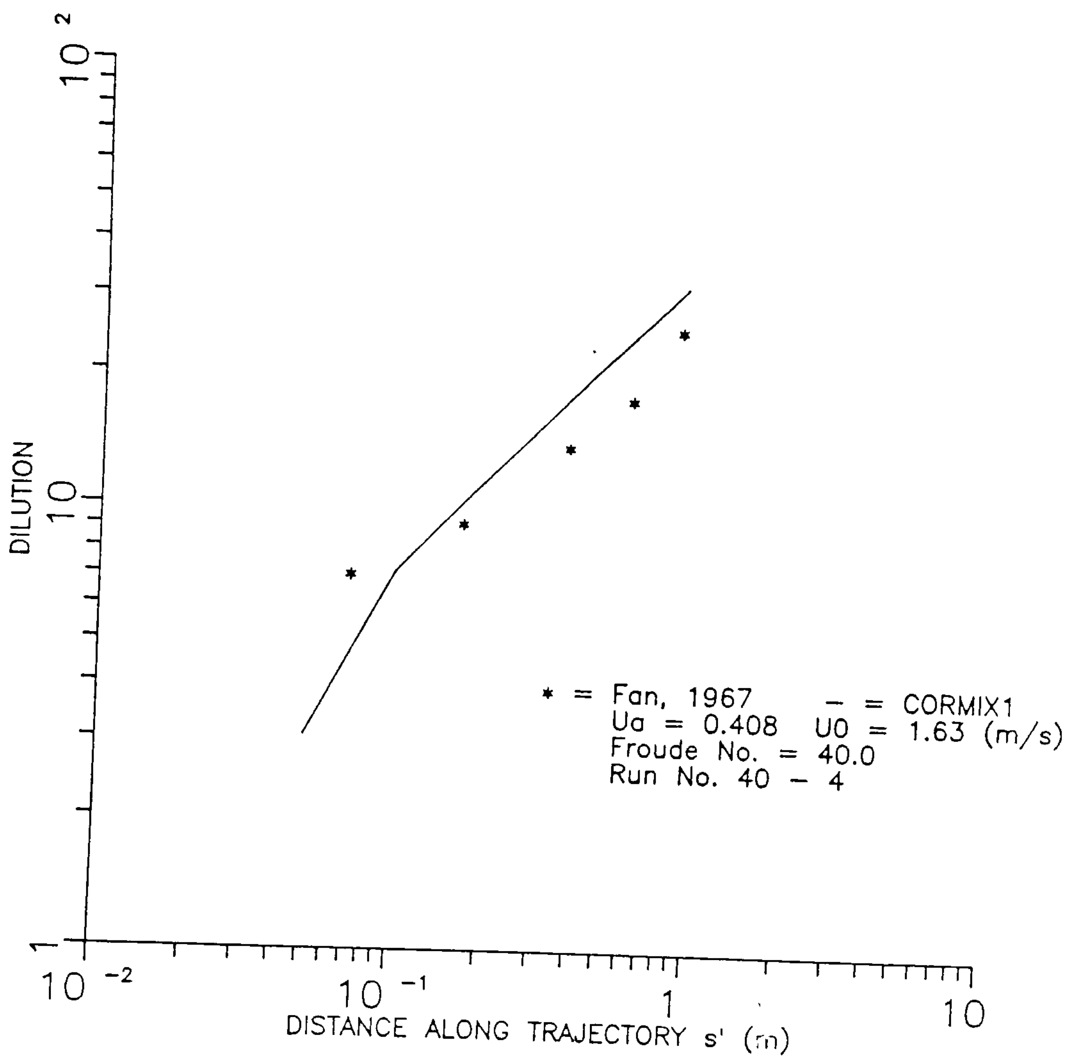


Figure 4.4 Fan's Buoyant Jet Dilution, Expr. 40-4, R = 4

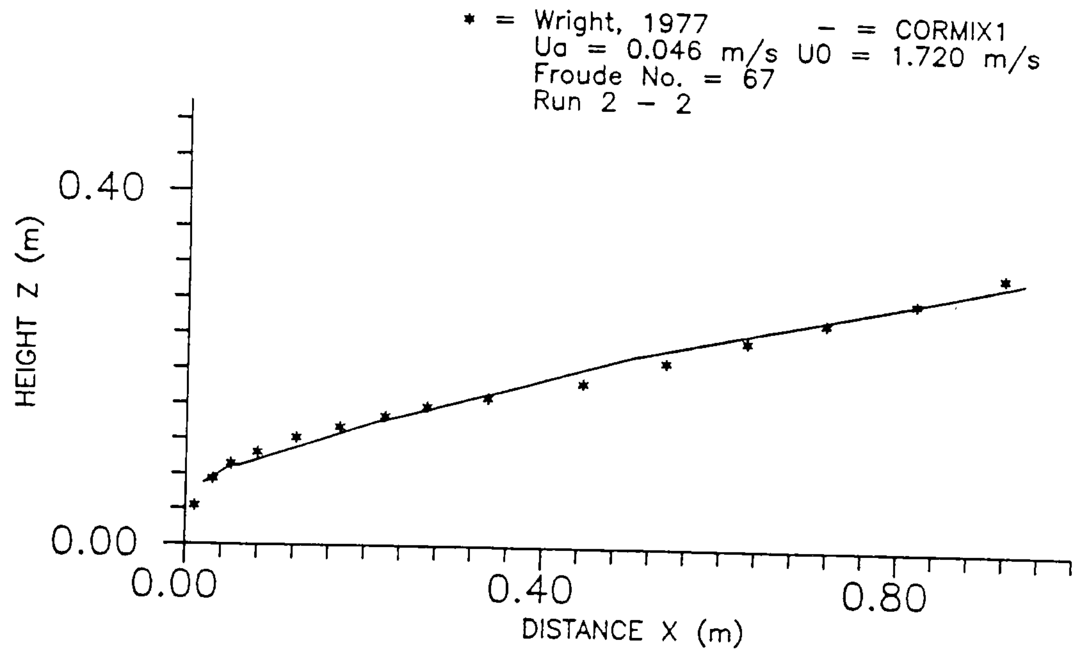


Figure 4.5 Wright's Buoyant Jet Trajectory, Expr. 2-2, R = 37

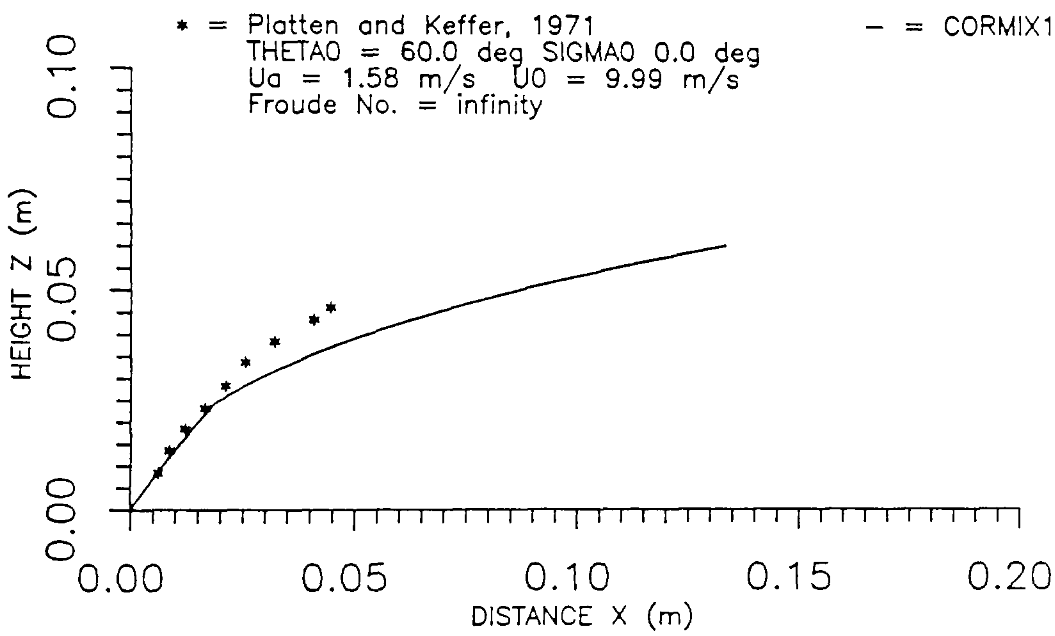


Figure 4.6 Platten and Keffer, θ_0 = 60.0

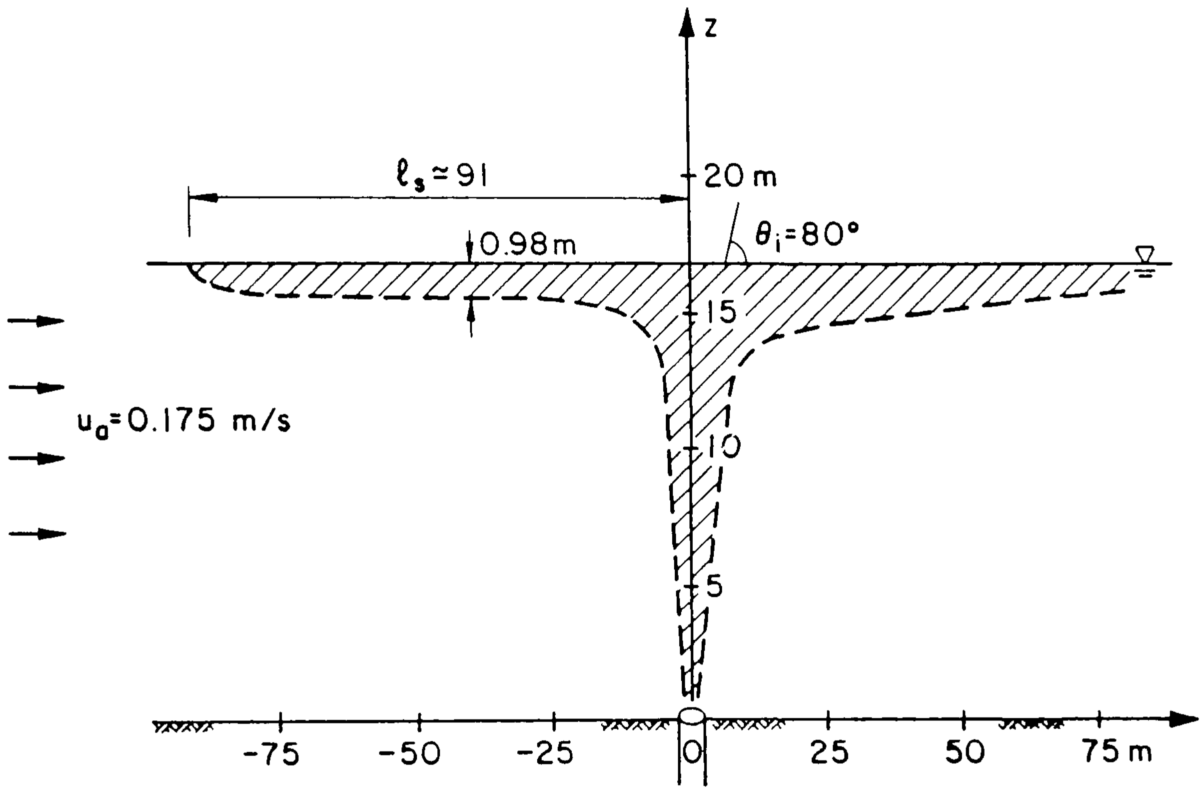


Figure 4.7a Simulation of Stable Surface Impingement/Upstream Spreading

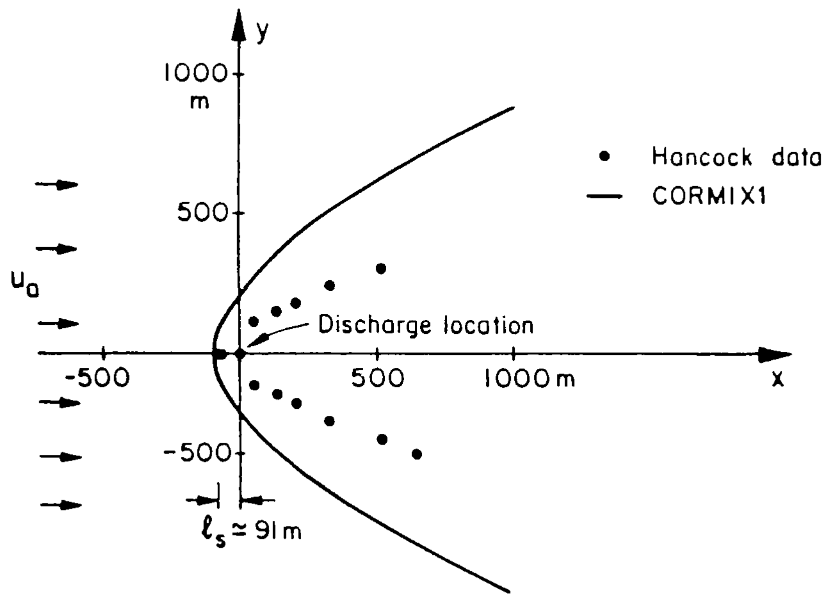


Figure 4.7b Plan View of Surface Impingement/Upstream Spreading

half width at impingement of 237 m. The actual data indicate an upstream intrusion of about 90 m and flow half-width at impingement of about 75 m. No dilution or flow depth data were available. CORMIX1 has good agreement with upstream spreading, but over predicts flow width. Possible sources of error in the prediction might be a caused by weak density gradients which can be expected in such ocean depths. Future work for CORMIX1 includes the consideration of density stratification. Overall agreement appears to be satisfactory in this test case.

4.3 Unstable Surface Impingement With Buoyant Upstream Spreading

Fischer et al. (1979), presents field data for the San Onofre nuclear power plant. The San Onofre Unit 1 discharge is a thermal discharge from a 4.3 m diameter outfall located 5.0 ^R
m below the surface water off the California coast. The ambient current in the vicinity of the outfall is about 0.14 m/s and the discharge velocity is 1.45 m/s. The temperature difference between the ambient current and the discharge is 11.1°C giving rise to a buoyant acceleration of $g_o' = 0.032$. CORMIX1 predicts a flow classification of V6, representing an unstable shallow water discharge with buoyant upstream spreading. This case is further discussed as a design example in Chapter V.

Figure 4.8 shows the CORMIX1 results compared with actual field results obtained with a scanning infrared radiometer (Figure 5.3 presents the cross-section predicted by CORMIX1). CORMIX1 predicts an upstream intrusion of 37 m with a flow half-width of 95 m at surface impingement. The data show an upstream intrusion and half-width at surface impingement of about 30 m and 85 m, respectively. The unstable near field impingement is a highly complicated hydrodynamic process, and the results of CORMIX1 appear to be in excellent agreement, although the width of the density current may be somewhat over-predicted with increasing downstream distance.

4.4 Summary

Overall CORMIX1 predictions appear to be in good first order agreement with available observations in the field and laboratory. CORMIX1 can predict buoyant upstream spreading, where other available models (e.g. PLUME) would have failed entirely.

Although limited data are available for both field and laboratory experiments, further efforts will be made to compare model predictions and adjust parameters in the flow classification system.

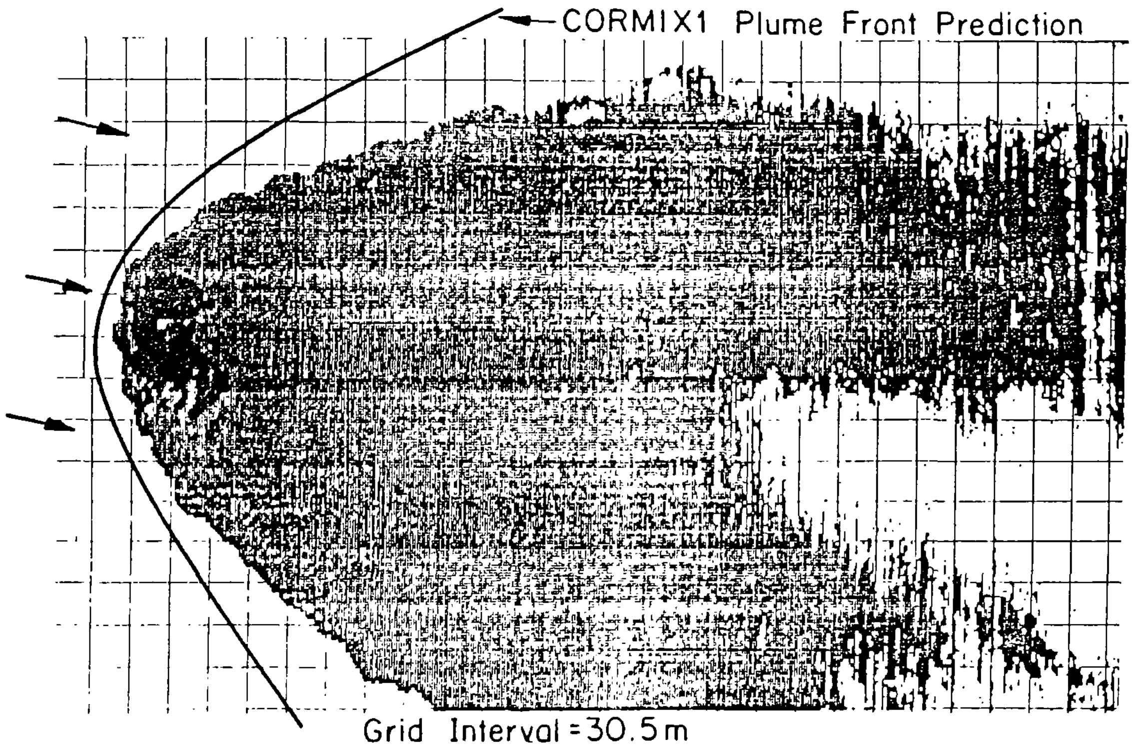


Figure 4.8 Plan View Comparison of San Onofre Prediction and Field Data (Corresponding cross-section in Figure 5.3)

Chapter V
Design Case Studies

The purpose of this chapter is twofold; i) to give an overview of the significant features of CORMIX1 in discharge evaluation and design, and ii) to illustrate the flexibility of CORMIX1 in highly divergent design conditions. The first case presented represents a small hypothetical industrial discharge into a slowly flowing river, and the second case is an actual large cooling water discharge into the ocean.

5.A Case 1: AB CHEMICAL CORP., WEST VIRGINIA

This is a hypothetical example of a discharge in a bounded section. The CORMIX1 output appears in Appendix B.1. This buoyant discharge represents a complex 3-D trajectory subject to three legal mixing criteria; a toxic dilution zone, a plume cross-sectional area criteria on a legal mixing zone, and a downstream region of interest. The analyst seeks pollutant concentrations at these locations.

5.A.1 The Problem Statement

AB Chemical discharges an industrial effluent into the Ohio River through a submerged pipe outfall. The discharge flow is 0.2 m**3/s and contains 0.5 miCi/m**3 of Cesium 134. Cesium is considered toxic, and has a criterion maximum concentration (CMC) value of 0.0005 miCi/m**3 (hypothetical). For the critical summer conditions the discharge temperature is 35.0°C.

At the discharge site the Ohio River is dammed as a run-of-the-river reservoir. The cross-section is approximately trapezoidal with a bottom width of 240 m and bank slopes of 1 in 3. The river depth is 8.5 m. Due to gate operation at the dam the river velocity varies between 0.1 m/s (near-stagnant) and 0.6 m/s. Typical summer temperatures are 22.0°C. The river roughness conditions are given by a Manning's n of 0.024.

The outfall is located 50 m from the berm line near the left bank. The right bank is under the jurisdiction of the State of Ohio. The port is pointing directly offshore (normal to the ambient flow) and is angled 20° upward above the horizontal. The round port has a diameter of 30 cm and its center lies 0.5 m above the river bottom.

The mixing zone limitations of the State of West Virginia have to be considered. These stipulate that the mixing zone have a maximum dimension of 33% of the cross-sectional area and a length equal to 10 times the stream width.

5.A.2 CORMIX1 Analysis

The first step in the analysis would be to schematize the bounded cross-section as shown in Figure 5.1. Stream cross-sections are usually highly irregular; the trapezoidal cross-section represents an initial approximation of the actual stream cross-section. CORMIX1 assumes an equivalent rectangular cross-section as shown in Figure 5.1, which the analyst would approximate.

Using DATIN, the site parameters are specified. One of the advantages of logic programming is the "transparency" of the rule base to the user. For example, DATIN seeks information concerning the distance from the outfall to the nearest shore. During the session, DATIN prompts:

What is the distance from the nearest bank or shore to the effluent discharge point (m)? [1]

If the user wants to know why this information is needed, he could determine the rule in the knowledge base that DATIN is trying to evaluate simply typing "why", to which DATIN responds:

```
M.1 is trying to determine whether the following rule is
applicable in this consultation:

kb-33:
     if bounded_section = 1 and
     distance_bank = YB and
     stream_width = BS and
     BS*0.5 >= YB and
     location_bank = NBANK
then nearest_bank = found

The following entries are also under consideration:

     kb-29 (a rule)
     kb-4  (an initialdata)                                 [2]
```

The user can conclude that the question in expression [1] is asked because DATIN is seeking a valuation for the expression

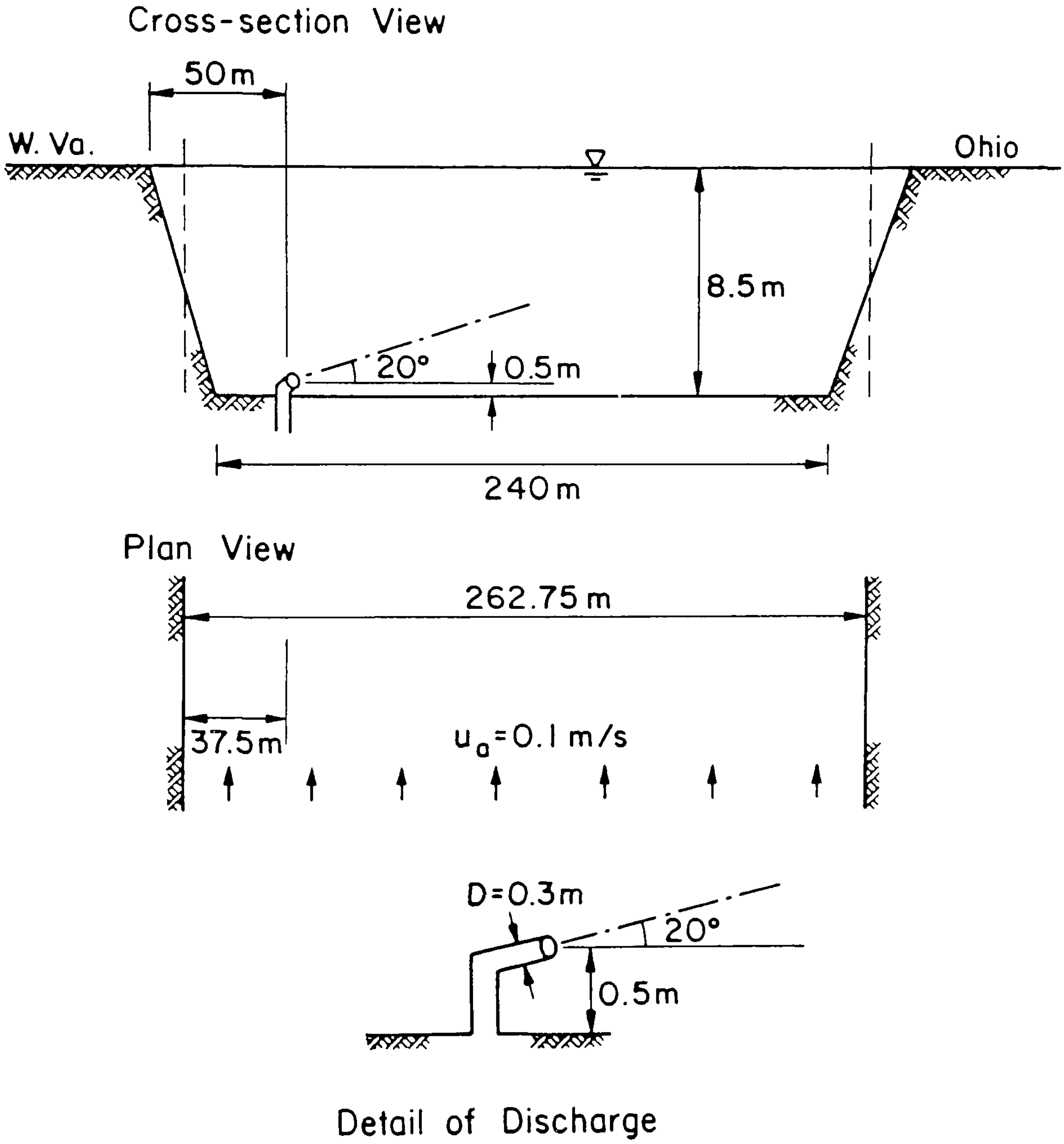


Figure 5.1 Schematization of Cross-section

"nearest_bank" in "kb-33". The flag "kb-33" is a label created by DATIN for this rule.

If the user is interested in why DATIN is seeking a valuation for "nearest_bank" in kb-33, expression [2] also lists that kb-29 and kb-4 are also under consideration. Thus the user can conclude that kb-33 was invoked by another rule, kb-29; and kb-29 was invoked by kb-4 an "initialdata" (similar to a "goal") statement. The user can see kb-29 by typing "list kb-29" to which DATIN responds (simplified here, for full printout, see appendix B.1)

```
kb-29:if  depth_at_discharge = H and
          nearest_bank = found and
          ambient_velocity_field = found and
     then ambient_conditions = found                    [3]
```

to which the user can conclude that "ambient_conditions" for the discharge were being sought, when the rule in expression [2] for "nearest_bank" was invoked.

Another advantage to logic programming is in error handling. It is simple to write rules that reject contradictory data. For example, when schematized as a rectangular cross-section, the stream width is 262.75 m and the distance to the nearest bank (W. Va.) is 37.5 m. If the user made an error and responded to expression [1] by entering the distance to the Ohio shore of 225.25 m, DATIN would respond:

```
The distance to nearest bank is in error.
The value must be less than half the stream width.
Recheck and re-enter a value less than or equal
to 131.375 (m).                                       [4]
```

and the user is given another chance to enter the correct value of 37.5 m. This result can be explained as follows. The rule kb-33 in expression [2] would fail when evaluating the "BS*0.5 >= YB" clause (stream width = BS = 226.75) in the premise. Since kb-33 failed when DATIN was seeking a valuation for the expression "nearest_bank" it will automatically seek another rule in the knowledge base with "nearest_bank" in its conclusion. Error handling advice is placed in the next rule that has "nearest_bank" in its conclusion. Thus the message shown in expression [4] comes from the next rule in the knowledge base with "nearest_bank" in its conclusion.

After completing DATIN, the analyst executes PARAM, followed by CLASS. In CLASS the analyst is advised of the intermediate conclusions reached; i.e. the discharge is a near horizontal "H" case, l_m/h = 0.885 indicating deep water with weak momentum, l_b/H = 0.923 showing weak buoyancy, and finally l_M/h =0.864 concluding that buoyancy dominates at surface impingement. CLASS assigns a flow classification of H1, specifying the flow simulation will consist of mdnf -> bdnf -> bdff -> surface approach -> buoyant surface spreading -> passive diffusion.

Viewing the output of HYDRO shown in Figure 5.2, the plume attaches to the left bank at x ≅ 650 m downstream. The plume meets the legal criteria of 33% of the stream cross-sectional area at x ≅ 850 m downstream of the orifice, S = 395, c = 0.0014 miCi/m**3. At x = 1200 m the effluent is fully mixed within the cross section with c = 0.00053 miCi/m**3.

In SUM, the analyst is alerted that the assumed criterion maximum concentration (CMC) value for the toxic discharge is not met within the legal restrictions. The user is advised to improve dilution by changing the exit velocity, decreasing the discharge angle θ_0, locating the port in a deeper section of the cross-section, or by orienting the discharge so it does not attach to the left bank first.

5.B Case 2: SAN ONOFRE UNIT 1

While the previous case represented a hypothetical small stable deepwater discharge, San Onofre is an existing large cooling water outfall located on the coast of California. Large cooling water outfalls are typically unstable, characterized by strong momentum and relatively weak buoyancy. The CORMIX1 session appears in Appendix B.2. The output includes all available help a user could request during the consultation.

5.B.1 The Problem Statement

The San Onofre Nuclear Generating Station, Unit 1, is operated by Southern California Edison Company. It has a power output of 450 MW. The cooling water from unit 1 is discharged about 1000 m offshore at a local water depth of 5.0 m. The bathymetry is sloping approximately linearly from the shoreline.

The discharge port is round with a diameter of 4.3 m and extends about 0.2 m above the surrounding bottom. The cooling water is discharged vertically at a flowrate of 21 m**3/s. The design ambient temperature is 24.0°C and the condenser temperature rise is 11.1°C (20°F).

The site is characterized by weak currents along the shore

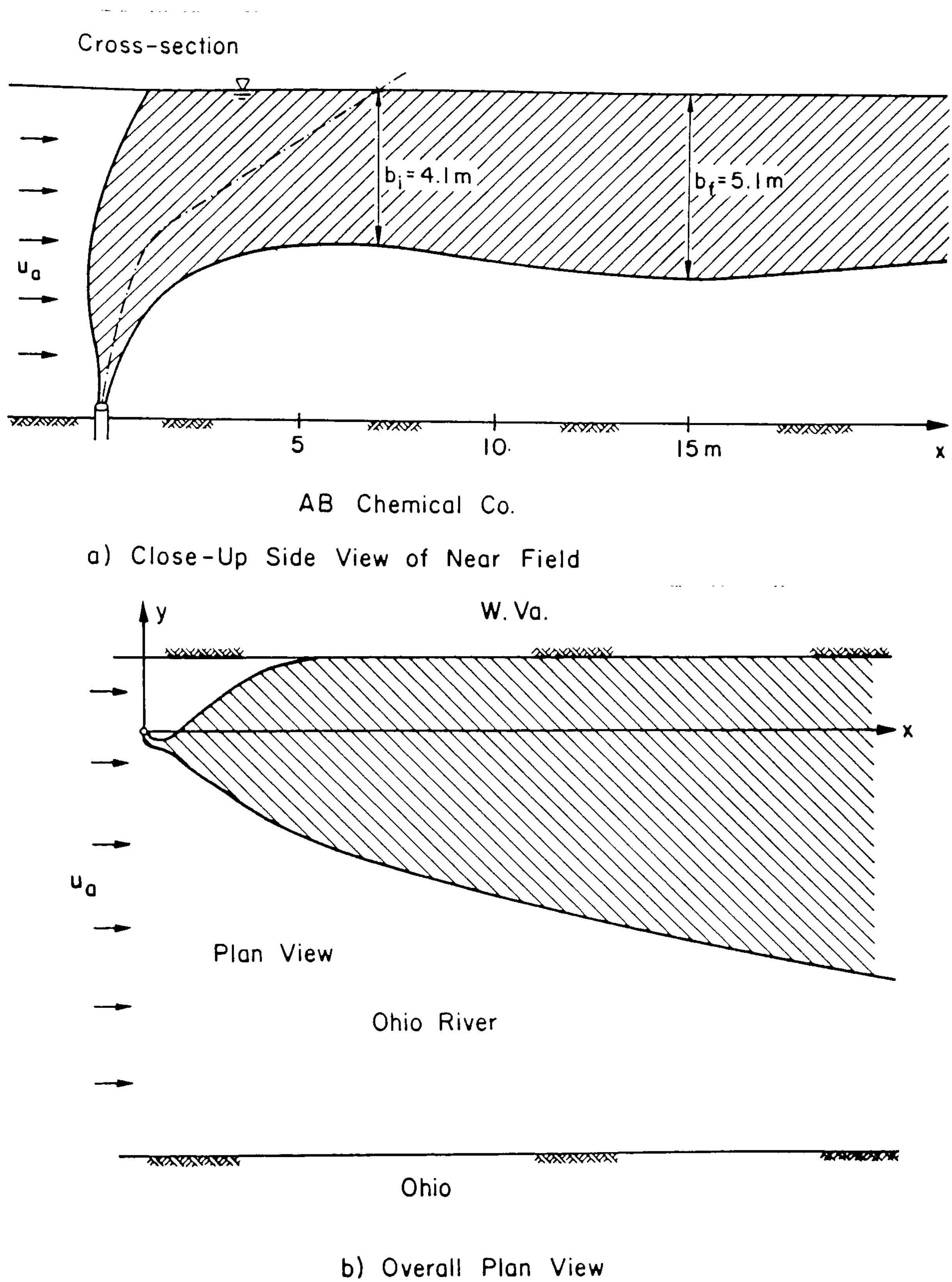


Figure 5.2 Plot of CORMIX1 AB Chemical Co. Predictions

of 6 cm/s in the southerly direction. The bottom is smooth and sandy with an estimated Darcy-Weisbach friction factor of 0.015 (Fischer et al., 1979, Lee and Jirka, 1981).

5.B.2 CORMIX1 Analysis

The representative cross-section in this case would place the discharge 500 m from shore in 5.0 m of water.

Class assigns a flow classification of V6, indicating an unstable discharge, characterized by strong momentum and relatively weak buoyancy. The interactive session of CORMIX1 appears in Appendix B.2.

Figure 5.3 plots the cross-section of the CORMIX1 predictions. The plan view of this simulation is shown in Figure 4.8.

SUM alerts the analyst to the upstream buoyant intrusion, and the possible plume bank attachment. Again the analyst is advised to improve dilution by some of the same options outlined in section 5.A.2..

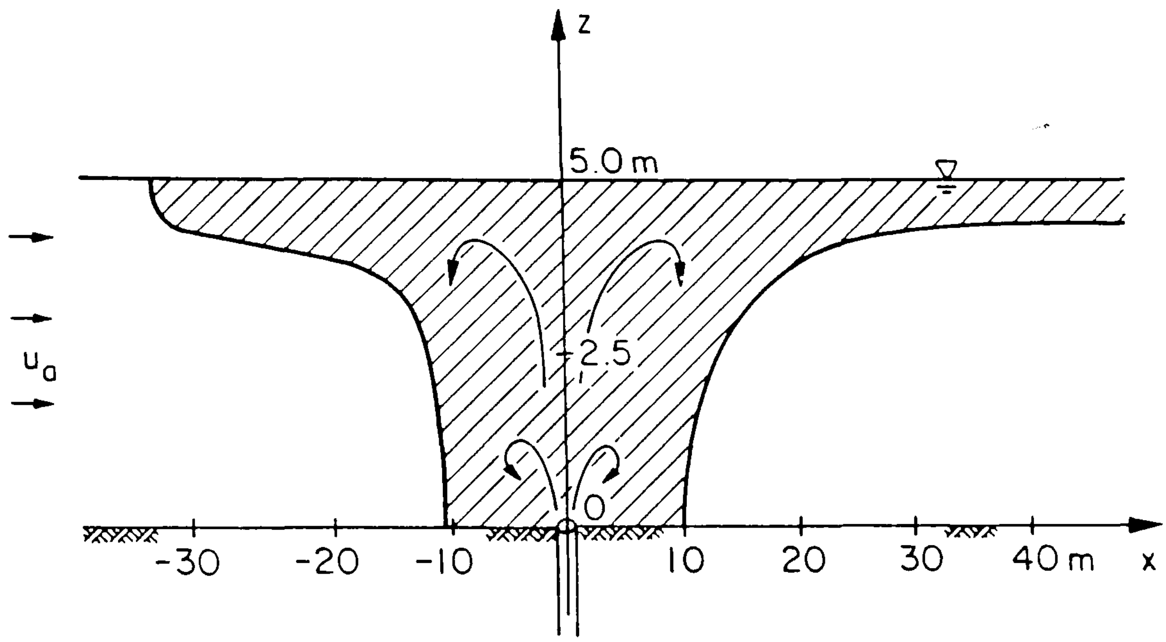


Figure 5.3 San Onofre Longitudinal Cross-Section (Vertical Distortion = 6, See Corresponding Plan View in Figure 4.8)

Chapter VI
Conclusions and Recommendations

U.S. water quality policy allows for a mixing zone as a limited area or volume of water where the initial dilution of a discharge occurs. Water quality standards apply at the edge and outside of the mixing zone. Toxic discharges have additional regulatory restrictions, which require additional dilution analysis. The implementation of this policy in the National Pollution Discharge Elimination System (NPDES) permitting process places the burden of prediction of initial dilution on both regulators and dischargers. Given a myriad of possible discharge configurations, ambient environments, and mixing zone definitions, the analyst needs considerable training and expertise to conduct accurate and reliable mixing zone analysis. An expert system, CORMIX1, was developed as an analysis tool for regulators and dischargers.

CORMIX1 predicts the dilution and trajectory of a single buoyant discharge into a unstratified ambient environment with or without crossflow. CORMIX1 uses knowledge and inference rules obtained from hydrodynamic experts to classify and predict buoyant jet mixing. CORMIX1 gathers the necessary data, checks for data consistency, assembles and executes the appropriate hydrodynamic simulation models, interprets the results of the simulation in terms of the legal requirements including toxic discharge criteria, and suggests design alternatives to improve dilution characteristics.

The results of the hydrodynamic simulation are in good to excellent agreement with field and laboratory data. In particular, CORMIX1 correctly predicts highly complex discharge situations involving boundary interactions and buoyant intrusions, a result not predicted by other currently available initial mixing models.

However, simulation models of complex phenomena, such as the hydrodynamics of jet and plumes described here, should always be given with a caveat. The analyst is forced to make many assumptions when modeling the complex mechanisms controlling buoyant jet flow.

In reality, many physical processes which occur in the environment are difficult to simulate or control for in laboratory experiments. If the basic assumptions within the methodology are violated in the analysis of a discharge, the resulting analysis will be tenuous at best. For example, CORMIX1 assumes a uniform velocity field in a uniform cross-section. This is a good first order approximation for many simple discharges. But the extreme case represented by a discharge into a cross-section that is highly variable with downstream distance, characterized by strong velocity fluctuations within the flowfield (such as a discharge into stream section with rapids), would be beyond the scope of CORMIX1.

What has been attempted here is to place a modestly complex hydrodynamic simulation methodology within the framework of a rule based expert system. Many of the common pitfalls to model use - incomplete or contradictory data, choice of appropriate simulation model, and faulty interpretation of results - appear to be mitigated within the context of an expert system methodology.

CORMIX1 educates the user to the important hydrodynamic processes controlling the flow. It will give 3-D discharge trajectory and dilution. It will alert the user to where significant legal criteria apply to the discharge. It predicts buoyant upstream spreading, which presently no other model can simulate. It allows for a rapid evaluation of design alternatives, and gives the user suggestions for improving dilution characteristics of the discharge. Overall CORMIX1 appears to be an excellent first cut tool for the analyst.

As stated in Chapter IV, further work should be done to determine the constants in the flow classification system and all other constants within the model. More research should be devoted to the concepts involved in the design recommendations in SUM. The existing data base is limited for conducting rigorous validation studies indicating a need for additional field and laboratory data.

The problem domain of CORMIX1, single port positively buoyant discharges into a uniform density field, should be extended to include near field boundary attachments, negatively buoyant discharges, and density stratified environments. The application of computer generated graphics to plot simulation results would enhance user understanding of simulation results.

Future work plans for CORMIX1 are: further calibration of model constants, consideration of dynamic jet boundary attachment, analysis of negatively buoyant discharges, and the effects of density stratified environments.

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APPENDIX A

Appendix A contains the code listing for all programs within CORMIX1. The M.1 programs are presented first followed by the Fortran programs. Section A.1 has the listing for DATIN, the M.1 data entry module. Section A.2 shows the M.1 listing for CLASS, the flow classification program. Section A.3 lists SUM, the M.1 program that summarizes the hydrodynamic simulation output. Section A.4 is the Fortran program PARAM which computes the length scales used in the flow classification system. Section A.5 contains the Fortran listing for the hydrodynamic simulation program HYDRO.