**AN EVALUATION OF
DILUTION MODELS FOR THE DISCHARGE OF PRODUCED
WATER INTO THE GULF OF MEXICO¹**

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Abstract: A study was performed to determine which of two mixing models (CORMIX1 or UM/PLUMES) was more appropriate for simulating the vertically downward discharge of negatively buoyant produced waters into a stratified ambient having a crossflow in Gulf of Mexico waters. For deep waters without impingement on the seafloor or gravitational collapse of the plume, UM/PLUMES is recommended because of its Lagrangian solution to the governing equations of mass, momentum, and energy. CORMIX1 is recommended if the plume interacts with the seafloor or if the plume undergoes gravitational collapse, although its results may be overly conservative at the edge of the mixing zone. These overly conservative results can be corrected by employing a post-processing technique developed by Limno-Tech, Inc. and Wright (1993). Because neither model was specifically designed to simulate the entire discharge scenario, additional work is recommended. This work includes laboratory and field studies to generate additional validation data, and code modifications to enhance the capabilities of the models and reduce uncertainty in the predicted jet behavior and potential errors in post processing model results.

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1. INTRODUCTION

All wastewater discharges to surface waters within the United States must be authorized under a National Pollutant Discharge Elimination System (NPDES) permit. Permit limitations are based on the stricter of technology-based limits (often established as national effluent limitation guidelines) or water quality-based limits. The latter limits are established to ensure protection of fresh and marine water quality standards outside of mixing zones (allocated impact zones where initial mixing takes place). Legal criteria specify the size and shape of the mixing zone and concentration values that must be met at its edge and outside of its boundaries. Within the mixing zone, water quality criteria may be exceeded as long as acutely toxic conditions are prevented (U.S. Environmental Protection Agency 1992).

U.S. Environmental Protection Agency (EPA) Region 6 has recently proposed issuing a general NPDES permit (NPDES permit number GMG290000 that covers a group of similar dischargers) that would prohibit the discharge of produced water (water and particulate matter associated with oil and gas producing formations) derived from Oil and Gas Point Source Category Facilities. As part of the rationale for establishing permit limits, dilution calculations performed using the CORMIX1 model (Cornell Mixing Zone Expert System - Doneker and Jirka 1990), indicated that water quality standards for Louisiana and Texas would be exceeded at the edge of the mixing zone for typical produced water discharges (Federal Register 1992).

The purpose of the present study is to review the use of CORMIX1 for performing the EPA dilution calculations and to present comments on the appropriateness of the CORMIX1 model for discharges of produced water to shallow, brackish, or saline environments. In addition, comments will also be presented on the applicability of using another model, UM/PLUMES (Baumgartner et al. 1993). Initially, UM/PLUMES was the preferred model of the Offshore Operators Committee (OOC) which is composed of about 93 member and associate companies that collectively account for approximately 95% of oil and gas production in the Gulf of Mexico. With a suggested post-processing technique developed by Limno-Tech, Inc. and Wright (1993), CORMIX1 is now the choice of the OOC.

The comments, conclusions, and recommendations presented in this report are made to ensure that the best available computer program for accurately modeling dilution of the produced water at the edge of the mixing zone is used in the regulatory decision-making process.

2. PRODUCED WATER CHARACTERISTICS AND PHYSICAL SETTING

In 1992, approximately 1.4 million barrels/day of produced water were discharged into Coastal Subcategory areas of Louisiana and Texas (Federal Register 1992). The produced waters are usually more saline than sea water (35 parts per thousand [ppt]), and range from 3 ppt in some restricted areas to as high as 300 ppt. In addition to high salinity, produced waters can contain high concentrations of organic compounds including entrained volatile

aromatic hydrocarbons, alkanes, metals, and radionuclides.

Using information from the OOC produced-water database (Shannon 1992) which consists of 353 discharge points (approximately one-half of all Gulf of Mexico produced water discharges), 25% of the discharges are to waters having a depth of 52 feet (ft) or less (water depths range from 1 to 1,347 ft), and 58% of the discharges occur at or above the surface of the sea. Discharge is often directed vertically downward from a single port, with rates that range from 1 to more than 100,000 barrels/day. Single port discharge pipe diameters range from 2 to 42 inches. In addition, effluent characteristics reported by Avanti (1992) vary widely, with chlorinity ranging from 20 to 30 parts per million (ppm) and temperatures ranging from 10° to 95° C.

The median ambient current speed for the disposal sites is estimated to be 10 centimeters per second (cm/s) (U.S. Environmental Protection Agency 1993). This current speed is the median value for data recorded at the West Hackberry Brine Disposal Site, and was used for the produced water and drilling fluid dilution modeling conducted for the Ocean Discharge Criteria Evaluation when the existing permit was reissued.

The median water depth associated with the disposal structures is approximately 49 ft, with 5% of the structures in water having a depth of less than 16 ft; 90% of the structures are in water less than 215 ft deep. Ambient stratification at the West Hackberry Brine Disposal Site ranges from 0.10 to 2.97 σ_t /meter (kg/m³/m).

Modeling performed with CORMIX1 for the EPA for the newly

proposed general NPDES permit was done using produced water discharge rates of 500, 1,000, 2,000, 3,000, 4,000, ..., and 25,000 barrels/day. The model was run assuming an average water depth of 35 ft (Limno-Tech, Inc. 1992). The ambient current speed was selected as 10 cm/s; linear ambient stratification was assumed, with a gradient of $0.15 \sigma_t/m$ ($kg/m^3/m$). This gradient is the annual average for the Gulf of Mexico and was used in the regulatory impact analysis for the Offshore Subcategory guidelines. The discharge pipe was oriented vertically downward to coincide with standard operational practices. Discharge depth was set at 11.5 ft above the seafloor. Because only 1% of all dischargers in the Western Gulf of Mexico OOC are in 11.5 ft of water or less, a new approach was proposed to more properly take into account the depth difference between the seafloor and the location of the discharge port (U.S. Environmental Protection Agency 1993). This approach added a number of new tables to the permit to allow more precise evaluation of critical dilution. Effluent salinity was set at 100 ppt (28th percentile chlorinity), and the effluent temperature was assumed to be $40.5^\circ C$ (90th percentile value).

3. PLUME HYDRODYNAMICS

The hydrodynamics of a plume from continuously discharged produced water can be conceptualized as consisting of two regions. In the first region (near field), the initial jet characteristics of momentum flux, buoyancy flux, and outfall geometry influence the jet's trajectory and dilution. In the second region (far field),

the source characteristics of the jet become less important, and the conditions existing in the ambient surroundings control the trajectory and dilution of the plume through buoyant spreading and passive diffusion (Doneker and Jirka 1990).

For a single port discharging negatively buoyant fluid (more dense than the ambient water) vertically downward into a stratified ambient fluid (fluid in which density varies with depth) that has an initial velocity field (crossflow), the effluent will initially move vertically downward under the influence of the jet's momentum (Figure 1). As the effluent moves downward, surrounding water is entrained, and the plume becomes less dense. This process can be visualized as the mirror image of a positively buoyant plume discharged vertically upward, in which the effluent is less dense than the surrounding fluid and rises because of the combined actions of vertical momentum and buoyancy.

As the negatively buoyant plume moves vertically downward in the stratified receiving fluid, it loses momentum, entrains ambient fluid, and becomes less dense. If the plume does not interact with the bottom surface, a point of neutral buoyancy is reached in which the plume density is equal to its surroundings. Due to momentum, this point of neutral buoyancy may be exceeded, and the plume overshoots the equilibrium location and oscillates with a dampened motion (Figure 1). In effect, the linear stratification of the receiving water traps the flow at a given level and forms an internal density current with moderate additional mixing (Doneker and Jirka 1990). If the momentum of the plume is sufficiently high

or the receiving water is shallow, the effluent can impinge on the seafloor and spread laterally (Figure 2).

In the presence of an ambient crossflow, the plume is deflected downstream in the direction of the prevailing current because of entrainment of crossflow momentum (U.S. Environmental Protection Agency 1992). Near the discharge port, the effects of crossflow can be small if the initial momentum flux of the jet is large. At large distances from the discharge port, the horizontal momentum of the entrained ambient fluid increases sufficiently to deflect the jet (Figures 1 and 2).

For cases of spreading along the terminal level in a continuously (e.g., linearly) stratified ambient, at abrupt transitions in ambient density (pycnoclines), and along the seafloor or surface of the sea, the discharge plume may decrease in thickness into a thin but very wide layer (gravitational collapse) unless lateral boundaries are encountered (U.S. Environmental Protection Agency 1992).

At sufficiently large distance from the discharge port, passive ambient diffusion processes eventually dominate, and additional dilution of the plume occurs.

4. EVALUATION CRITERIA FOR MIXING MODELS

Based on the characteristics of the produced waters, the discharge geometries, and the ambient conditions for Gulf Coast waters, the following list summarizes capabilities that are essential for an appropriate mixing model (Limno-Tech, Inc. 1992):

- . single port discharge
- . negatively buoyant effluent
- . buoyant jet mixing
- . far field diffusion
- . stratified ambient
- . ambient crosscurrents, and
- . vertically downward discharge.

Nine computer models were briefly evaluated for applicability to the present problem: UPLUME, UMERGE, UOUTPLM, UDKHDEN, ULINE, CORMIX1, CORMIX2, UM/PLUMES, and RSB/PLUMES (Limno-Tech, Inc. 1992). Of these nine models, only two satisfy all of the above conditions: CORMIX1, and UM/PLUMES. A discussion on the capabilities of these mixing models is given in the next section.

5. MIXING MODELS

5.1 CORMIX1

The Cornell Mixing Zone Expert System (CORMIX1) software was developed to predict the dilution and trajectory of a submerged single-port discharge of arbitrary density (positive, neutral, or negative) into a stratified or uniform density ambient environment with or without crossflow (Doneker and Jirka 1990). To accomplish this objective, a systematic dimensional analysis is performed to define the problem and to provide first-order approximate, asymptotic solutions to describe the jet's characteristics (Wright 1977).

As part of the CORMIX1 package, an expert system is provided.

This expert system is designed to provide the following features:

- . assurance that the proper model has been selected for the physical application;
- . assurance that the chosen model is applied methodically, without skipping essential elements;
- . 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;
- . flagging of borderline cases for which no predictive model exists;
- . continuous updating of the knowledge base as improved models, experimental data, and field experience with particular designs become available;
- . a documented analysis listing the knowledge and decision logic that lead to solution of the problem;
- . a common framework whereby both regulators, applicants, and the scientific community can arrive at a consensus on state-of-the-art hydrodynamic mixing and pollution control;
- . pollutant concentrations at the specified regulatory mixing zones; and
- . a teaching environment whereby the initially inexperienced analyst gains physical insight and understanding about the initial mixing process (Doneker and Jirka 1990).

At the present time, CORMIX1 supports 35 flow configurations for the near field (Figures 3 through 6). These configurations

have four major categories: flows affected by linear stratification leading to internal trapping (S classes); buoyant flows in a uniform ambient layer (V and H classes); negatively buoyant flows in a uniform ambient layer (NV and NH classes); and bottom attached flows due to wake or Coanda effects (A class) (Doneker and Jirka 1990). Inspection of Figures 3 through 6 indicates that CORMIX1 does not have a flow class specifically designed for negatively buoyant discharges released from the surface. However, this flow class can be adequately simulated by using the results for positively buoyant discharges released from the bottom by invoking symmetry arguments.

For conditions relevant to the general NPDES permit proposal in which a negatively buoyant discharge is released from the surface into a stratified ambient environment that has crossflow, the most appropriate flow classes would include those of the S subclassification (trapping), and those that interact with the surface (near-horizontal flow with a surface impingement angle less than 45° , and near-vertical flow with a surface impingement angle greater than 45°).

As indicated in Figures 3 through 6, the flow classes and subclassifications depend on various length-scale combinations that arise from dimensional analyses. In general, there are six major lengths of scale: L_Q , L_M , L_b , L_w , L_M' , and L_b' , where:

$$L_Q = Q/M^{1/2} \quad = \text{discharge (geometric) scale}$$

$$L_M = M^{3/4}/J^{1/2} \quad = \text{jet/plume transition scale}$$

$$L_b = J/U_s^3 \quad = \text{plume/crossflow scale}$$

$$L_m = M^{1/2}/U_a = \text{jet/crossflow scale}$$

$$L_M = (M/\epsilon)^{1/4} = \text{jet stratification scale, and}$$

$$L_b = J^{1/4}/\epsilon^{3/8} = \text{plume stratification scale}$$

and

Q = kinematic mass flux

M = momentum

J = buoyancy

U_a = ambient crossflow velocity, and

ϵ = density stratification.

While six length scales were identified, only four are required for characterizing the system because of functional interdependencies (Doneker and Jirka 1990). These scales, in turn, depend on the discharge's kinematic mass flux, momentum, buoyancy, and the ambient velocity. These length scales interact with the geometric properties of the ambient water body, its depth, stratification, and orientation angle of the discharge port. Additional details on the functional forms for the length scales can be found in Doneker and Jirka (1990).

The flow classifications depicted in Figures 3 through 6 are implemented in CORMIX1 using a 13-step procedure. This procedure begins by testing the input variables to determine the presence of dynamically impossible conditions with a flux Richardson criterion (ratio of buoyant energy flux to the shear energy production) (Doneker and Jirka 1990). Steps 2 through 8 determine the effect of ambient density stratification (if present) on the flow. Step 9 is used to determine the detailed flow classification for those

flow classes whose dynamics are directly affected by linear ambient stratification. Steps 10 through 12 are used to examine the flow behavior for those classes in which the ambient layer can be assumed to be uniform. The last step of the procedure checks for dynamic bottom attachment (wake or Coanda effect). Branching conditions for flow regimes are determined by precisely defined conditional tests.

Once the appropriate flow classification has been made, the trajectory and dilution of the discharge are calculated using relationships from dimensional arguments and mass conservation (Doneker and Jirka 1990). Inherent in all of these relationships are a large number of constants that require definition. These constants are estimated using a combination of theoretical analyses, literature values, adaptations of literature values, and engineering judgment.

If the negatively buoyant discharge interacts with the bottom surface, lateral spreading is assumed to occur. In the present version of CORMIX1, bottom spreading is assumed to behave the same as spreading on the surface of the waterbody (Doneker and Jirka 1990). Effects from the formation of a mean-flow boundary layer, bottom friction, and wave-induced shear stresses are not included (Flow Science 1993).

In the case of a near-horizontal surface (bottom) approach (Figure 7), the concentration distribution for a two-dimensional flow is assumed to change from Gaussian to a top-hat or uniform distribution. Mixing is modeled as a bulk process, and the exiting

dilution is assumed to be 1.5 to 2 times the initial dilution.

In addition to the near-surface approach illustrated in Figure 7, two other lateral spreading models are considered in CORMIX1: a near-vertical surface impingement with buoyant upstream spreading; and near-vertical surface impingement with full vertical mixing. These processes are illustrated in Figures 8 and 9. For the case of near-vertical surface impingement with buoyant upstream spreading, flow spreads more or less radially along the surface as a density current after impingement (Doneker and Jirka 1990). The lateral spreading of the flow is driven by both flow momentum and buoyancy. In the second case, a recirculation region is established by the impinging flow, and a portion of the entrained fluid originates in the flow that is spreading radially outward along the surface, thereby reducing the final dilution (Doneker and Jirka 1990). The final dilution ranges from 1.0 to 4.0 times the initial value.

In the far field, one or two mixing processes can occur, depending on the characteristics of the discharge (Doneker and Jirka 1990). In the general case, the discharge will contain sufficient buoyancy to create buoyant spreading followed by a passive diffusion region. The region of buoyant spreading is characterized by dynamic horizontal spreading and gradual vertical thinning while the flow is advected by the ambient current. In the passive diffusion region, dilution is controlled by turbulent mixing caused by the ambient water. In CORMIX1, the region of passive diffusion uses the "4/3 diffusion law" characterized by

Fischer et al. (1979) to obtain average plume dilutions.

5.2 UM/PLUMES

The UM/PLUMES model is a revision of the original EPA sponsored programs UMERGE, UPLUME, and UDKHDEN which are a suite of programs developed to analyze the dilution of municipal wastewater discharges (Flow Science 1993). The UM portion of the package is an enhancement of the UMERGE model, and runs as part of the PLUMES interface. Specific enhancements added to UMERGE include treatment of negatively buoyant plumes, non-zero background pollutant concentrations, and far field diffusion using the "4/3 Power Law" and constant eddy diffusion (Limno-Tech, Inc. 1992).

In the UM/PLUMES model, a Lagrangian formulation of the governing equations for a deflected jet in a crossflow is used to predict the motion of the discharged effluent; entrainment is modeled using a combination of the Projected Area Hypothesis (PAE) (Cheung 1991) and the traditional Taylor hypothesis (Morton et al. 1956). Overall, the following entrainment processes are incorporated in the model: aspiration (shear or Taylor entrainment which is present even in the absence of current), forced entrainment (mass invected into the plume due to the presence of current), and turbulent or eddy diffusion (only important beyond the zone of initial dilution).

The model includes statements of conservation of mass, momentum, and energy. In modeling the expanding jet, the element mass is incremented by the amount of fluid that flows over the

outside boundary of the plume element in a given time. The PAE methodology guarantees that excessive or inadequate amounts of entrainment are not inadvertently introduced into the solution (Baumgartner et al. 1993).

In a similar fashion, horizontal momentum is conserved. Vertical momentum is not conserved, in general, because it is changed by buoyancy effects. Energy is conserved by adding an amount of energy equal to the product of a constant specific heat, the entrained mass, and the ambient temperature. Results from energy conservation are used with an equation-of-state to obtain densities of fresh and sea water in salinity and temperature ranges that are representative of terrestrial and coastal waters. The algorithm for calculating density from salinity and temperature may not be accurate for conditions existing in the produced discharges (Flow Science 1993). However, the inaccuracy has a maximum value of approximately 7% over ranges that extend to 260 ppt and 100° C (Brandsma 1993b). As a practical matter, this difference in density would have little effect on plume dynamics, especially once the plume has been diluted by a factor of 2 or 3, which would typically occur within seconds after discharge from the port.

For the UM/PLUMES model, the range of densimetric Froude numbers, F , is from 0 to 30, consistent with municipal wastes (Teeter and Baumgartner 1979). The densimetric Froude number relates inertial to buoyancy forces within the plume (Fischer et al. 1979). That is:

$$F = \frac{Q}{A((\delta\rho/\rho)gd)^{1/2}} \quad (1)$$

where Q is the volumetric rate of produced water discharge, A is the cross-sectional area of the discharge port, $\delta\rho$ is the density difference between the produced-water discharge and the ambient water, g is the gravitational constant, ρ is the density of the produced water, and d is the mean depth of the water. For high values of F , inertial forces dominate buoyancy. A pure plume (buoyancy only) has an F value of zero; a pure jet (no buoyancy - density in the produced water is equal to the density of the ambient) has an F value of infinity (Doneker and Jirka 1990). For the range of densimetric Froude numbers encountered in the produced-water discharges, the plumes can be described as buoyant jets or forced plumes, reflecting the fact that buoyancy and inertia both play an important role in plume dynamics. Because the densimetric Froude number for the produced waters rarely exceeds 30 (Brandsma 1993b), the applicability of the model is ensured.

In the far field, minimum dilution is estimated using the method of Brooks (Fischer et al. 1979). This method is well established and is usually referred to as the "4/3 Power Law." In functional form, the dilution factor, C_i/C , is given by the following expression (U.S. Environmental Protection Agency 1993):

$$\frac{C_i}{C} = \left(\operatorname{erf} \left(\left(\frac{1.5}{(1+8AH^{4/3} \frac{t}{H^2})^3 - 1} \right)^{0.5} \right) \right)^{-1} \quad (2)$$

where:

H = width of the collapsed plume

A = 4/3 Power Law dispersion coefficient = 0.000453 m^{2/3}/s

t = travel time from the end of impingement zone to 100 m

and

erf = the error function given by Abramowitz and Stegun (1972)
as:

$$\text{erf}(\gamma) = \frac{2}{\sqrt{\pi}} \int_0^{\gamma} e^{-\lambda^2} d\lambda \quad (3)$$

If the discharge impinges on a surface (either free water or seafloor), the calculation is terminated; the governing equations do not include this process. A warning message is, however, printed indicating that the calculation was incomplete.

6. Discussion

Single-port discharges of produced water into Gulf Coast waters create unique modeling conditions including negatively buoyant discharges into a stratified ambient with crossflow, produced discharge water having potentially high temperature and density, impingement on the seafloor or pycnocline, gravitational collapse, buoyant spreading, and passive diffusion. To date, only a limited quantity of reliable experimental data is available to validate either of the existing numerical mixing models, CORMIX1 and UM/PLUMES. However, even without validating data, it is clear that neither model was specifically designed to simulate all of the important processes associated with the discharges.

CORMIX1 is a collection of systematically applied dimensional analyses coupled with an expert system to provide order-of-magnitude estimates for jet characteristics. Because the results of the dimensional analyses are only valid at the limits of the dimensionless analyses, and in general practice the dimensionless parameters of the system frequently do not approach these values, the plume calculations are inherently uncertain. The closer the system's dimensionless parameters come to the limiting values, the less the degree of uncertainty.

In CORMIX1, flow classes are differentiated by conditional testing on single system parameters. Small differences in a system's characteristics can, potentially, have a large impact on dilution if flow regimes change abruptly and there is no smoothing algorithm across the transition. In addition, while a test is performed in CORMIX1 to determine if the discharge port is flowing full, a brief diagnostic is printed in the output file, and the calculation then proceeds normally. This procedure can lead to incorrect characterization of the discharge port (flooded or partially flooded ports may not be recognized) and improper evaluation of the discharge jet, especially in the near field, may occur.

While a large number of flow classes are available in CORMIX1, it is unclear which of them have been validated with field data. The analyst may, therefore, be performing calculations in modules that have not been fully developed and tested. In addition, the present version of CORMIX1 does not have a specific flow class for

negatively buoyant effluent discharged from the surface or for effluent discharged more than one-third the length of the water column from the seafloor. However, mirror-imaging techniques can be used to simulate these processes adequately if care and caution are used by the analyst. Coefficients required for predicting the plume's trajectory and dilution should correspond fairly well with those established for positively buoyant discharges.

In the case of impingement with the seafloor, CORMIX1 treats the interaction the same as spreading of the plume on the surface of the sea; bottom friction, boundary layer development, and shear flows are not incorporated. Calculations performed by Flow Science (1993) indicate that the buoyant jet can get into a region of gravitational collapse (vertical thinning), and stay within these constraints well beyond the 100-meter mixing zone without much additional dilution. For these conditions, CORMIX1 predictions may significantly underestimate the dilution, and the plume can become unrealistically thin.

To reconcile the above underestimated dilution with CORMIX1, a method was developed by Limno-Tech, Inc. and Wright (1993). The following three steps are implemented for this procedure:

1. CORMIX1 is run for the conditions in the area for the permit, and the average dilution at the end of the impingement region (S), the calculated plume width (H), and the downstream distance where the impingement area ends (x) are found.

2. The far-field dilution factor, C_i/C , is evaluated using the "4/3 Power Law" (Equation 2).

3. The total dilution at 100 m is defined as the product of the near-field dilution factor, S , found in Step 1 and the far-field dilution factor, C_i/C , calculated in Step 2.

With this revision to the CORMIX1 output, model results from the first phase of mixing calculated with CORMIX1 are incorporated in the "4/3 Power Law" (Equation 2) to calculate the dilution at the edge of the mixing zone. The underestimation of dilution is corrected because the portion of CORMIX1 that overpredicts gravitational collapse of the plume is not used (U.S. Environmental Protection Agency 1993).

The second mixing model, UM/PLUMES, solves the governing equations for mass, momentum, and energy for a deflected jet in a crossflow using a Lagrangian approach; less empiricism is required than in CORMIX1. In addition, with connection to PLUMES, rapid analytical evaluations of plumes can be performed for probabilistic assessments.

A number of problems face the analyst when using UM/PLUMES for simulating the discharge of produced water. First, the density of the calculated plume may be incorrect near the discharge port because the salinity/temperature algorithm incorporated in the model has a limited range of applicability. This problem is not important once the plume has been diluted by a factor of 2 or 3, usually within the first few seconds after discharge from the port.

The second problem with employing UM/PLUMES occurs if the plume impinges on the seafloor; the code terminates its calculations with a warning message. At this point, hand

calculations can be performed to extrapolate the results to the 100-meter boundary of the mixing zone (Brandsma 1993a). These additional calculations require care and familiarity with plume hydrodynamics to produce a defensible value at the boundary of the mixing zone.

Finally, the UM/PLUMES model does not have a capability for predicting gravitational collapse of the plume, thus the potential dilution can be overestimated.

7. RECOMMENDATIONS

The following section summarizes recommendations based on the analyses and discussion presented in this report. The recommendations are in three categories: recommendations for approaches for modeling the process, recommendations for additional model development, and recommendations for additional field or laboratory studies.

7.1 Recommended Approaches for Modeling

.. For deep-water conditions or territorial seas in which the effluent plume behaves like a deflected jet in crossflow and does not intercept the seafloor or undergo gravitational collapse, UM/PLUMES should be used to predict plume trajectories and dilutions. This recommendation is primarily based on the Lagrangian solution to the governing equations incorporated in the model.

.. For the most conservative results (least amount of

dilution), CORMIX1 should be used for calculating the characteristics of jets that have impinged on the seafloor or have undergone gravitational collapse. This recommendation is primarily based on the inability of UM/PLUMES to predict plume behavior after impingement with the seafloor or gravitational collapse.

- . To avoid overly conservative dilution calculations with the CORMIX1 model, the post-processing procedure developed by Limno-Tech, Inc. and Wright (1993) should be implemented.

7.2 Recommended Additional Model Development

Because neither of the two mixing models was specifically designed to simulate vertically downward negatively buoyant discharge into a stratified ambient with crossflow, gravitational collapse, and impingement on the seafloor, a number of code modifications could significantly enhance their capabilities and reduce uncertainties in predicted plume behavior. These modifications are discussed below.

7.2.1 CORMIX1

The following additional work should be performed for CORMIX1:

- . Incorporate a methodology for dealing with discharges that result in flow conditions that are less than full at the port.
- . Incorporate a flow class capable of directly simulating vertically downward discharge of a negatively buoyant effluent.
- . Incorporate smooth transitions between potential flow regimes. This modification can include techniques associated with

fuzzy composite programming (Kaufmann and Gupta 1988).

- . Incorporate the effects of boundary-layer formation, bottom friction, and shear stress on lateral jet spreading after impingement with the seafloor.

- . Incorporate the post-processing methodology developed by Limno-Tech, Inc. and Wright (1993).

- . Provide additional documentation on validation studies for the flow classes included in the model.

7.2.2 UM/PLUMES

The following additional work should be performed for UM/PLUMES:

- . Modify the salinity/temperature algorithm in UM/PLUMES to include a larger range for conditions in and near the discharge port.

- . Incorporate logic to extrapolate plume characteristics to the boundary of the mixing zone once the jet has impinged on the seafloor.

- . Incorporate logic to account for gravitational collapse of the plume.

7.3 Recommended Additional Field or Laboratory Studies

Because there is only a limited amount of data for performing model validation, additional laboratory or field studies are recommended, especially for plumes that impinge on the seafloor or undergo gravitational collapse.

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FIGURE 1. NEGATIVELY BUOYANT PLUME IN A STRATIFIED AMBIENT WITH CROSSFLOW AND INTERNAL TRAPPING

FIGURE 2. NEGATIVELY BUOYANT PLUME IN A STRATIFIED AMBIENT WITH CROSSFLOW AND IMPINGEMENT ON THE SEAFLOOR

FIGURE 3. SUBCLASSIFICATION: ASSESSMENT OF AMBIENT DENSITY STRATIFICATION AND DIFFERENT FLOW CLASSES FOR INTERNALLY TRAPPED DISCHARGES (SOURCE: DONEKER AND JIRKA 1990)

FIGURE 4. SUBCLASSIFICATION: BEHAVIOR OF POSITIVELY BUOYANT DISCHARGES IN UNIFORM AMBIENT LAYER (SOURCE: DONEKER AND JIRKA 1990)

FIGURE 5: SUBCLASSIFICATION: NEGATIVELY BUOYANT DISCHARGES IN UNIFORM AMBIENT LAYER
(SOURCE: DONEKER AND JIRKA 1990)

FIGURE 6. SUBCLASSIFICATION: DYNAMIC BOTTOM ATTACHMENT OF DISCHARGE DUE TO WAKE OR COANDA EFFECTS (SOURCE: DONEKER AND JIRKA 1990)

FIGURE 7. FLOW INTERACTION PROCESS FOR NEAR-HORIZONTAL SURFACE APPROACH
(SOURCE: DONEKER AND JIRKA 1990)

FIGURE 9. SURFACE IMPINGEMENT WITH FULL VERTICAL MIXING
(SOURCE: DONEKER AND JIRKA 1990)