February 24, 1999

EPA-SAB-EC-99-011

Honorable Carol M. Browner
Administrator
U.S. Environmental Protection Agency
401 M Street, SW
Washington, DC 20460

Subject: An SAB Report: Review of the D-CORMIX Model

Dear Ms. Browner:

In response to a request from the Office of Science and Technology (OST) in EPA's Office of Water (OW), the Science Advisory Board (SAB) convened the D-CORMIX Review Subcommittee to conduct an external peer review of the D-CORMIX model. The Subcommittee met in public session on August 25-26, 1998 in Washington, DC and reviewed a number of technical aspects as well as implementation issues with the D-CORMIX model for mixing zone analysis. The Subcommittee members were given several written documents and a PC-version of the D-CORMIX model to review prior to the meeting, and then had the opportunity to interact with EPA staff, EPA Contractor staff, and staff of the US Army Corps of Engineers during the public meeting.

There were four charge questions related to the technical aspects and one charge question related to the implementation of the model with regard to use of an allocated impact zone (AIZ) for negatively buoyant wastewater discharge. These are summarized as follows:

a) **Is D-CORMIX an appropriate mixing zone model to use for continuous dredged material discharge mixing zone analysis?** D-CORMIX has the potential for the mixing zone analysis of dredged material discharges, assuming additional validation as suggested in Section 3.4 in the attached report is completed. Nevertheless, the appropriateness of D-CORMIX for intended applications will depend on the level of detail and sophistication required for the analysis. For those applications for which suspended solids are the only contaminant of interest, D-CORMIX might be said to be partially validated. However, if intended applications for predicting mixing zones include the need to predict dissolved phase contaminant distributions that originate from chemicals originally bound to the sediment, then D-CORMIX must be considered to be, at present, unvalidated. Nonetheless, it is important that an inability of D-CORMIX to handle one set of processes, such as contaminant interactions and fate, does not invalidate it as an appropriate model for cases in which mixing and sedimentation are the dominant processes.

b) **Does the model accurately capture the physics of negatively buoyant surface plumes, in particular, behavior of the density current and particle settling associated with dredged disposal plumes?** D-CORMIX shows mixed results with respect to the predicted distribution of suspended solids and associated changes in density in comparison with several laboratory data sets. D-CORMIX appears to warrant additional validation as outlined in Section 3.4 in the attached report. One of the Subcommittee members had access to several laboratory data sets and simulated these using both the CORMIX and D-CORMIX models (properly accounting for the issue associated with positive or negative buoyancy as required by the particular model). A comparison of the simulations led to the following conclusions: (1) in most situations, the models performed relatively well in predicting dilutions and plume dimensions observed in the experiments; (2) in cases where vertical density gradients were present in the ambient fluid of sufficient magnitude to trap the plume within the water column, a number of deviations were noted; and (3) comparison of data in which plumes impinge directly on a boundary indicates that the model conservatively underestimates the dilution in the initial layer spreading along the surface.

c) **What are the essential differences between the D-CORMIX and CD-FATE models and which is preferable as a mixing zone model for continuous dredged material discharge?** D-CORMIX focuses on the movement and dilution of a mixture of solids and liquids initially as a sinking jet or plume and then as a density current once the spreading elevation is attained (either the bottom for no or weak density stratification or internally at a neutrally buoyant level for a water column with significant stratification). It accounts for particle settling removing a portion of the sediment from the density current but does not account for any of this material to re-enter the water column. CD-FATE calculates a suspended sediment contribution due to two additional effects; a component stripped from the descending plume and a second component entrained from the material deposited on the bottom. These predictions are specified by empirical models. CD-FATE does not directly compute the sediment distribution in a bottom density current, but the sediment component entrained from the bottom deposits resembles the density current to some extent.

d) **Does the SAB approve of our outline for laboratory validation? What further suggestions can be offered?** As noted in Section 3.4 below, the Subcommittee recommends a staged validation process. An initial objective in the design of any validation study must be to decide whether or not the processes in D-CORMIX are to be validated or whether it is the ability of D-CORMIX to be able to represent physically important processes that is being investigated. Even if additional capabilities were developed for D-CORMIX to properly model chemical and physio-chemical processes, it is possible for a validation effort to fail if the mixing/sedimentation processes are not represented properly in the current version of the model. In light of this, it appears to be more fruitful to approach the validation effort in a staged manner.

e) **What factors should be considered in developing an AIZ that will not adversely impact the integrity of the aquatic ecosystem? How should the AIZ be sized, especially in relation to distance from the bottom (substrate), and portion of water column encompassed?** The Subcommittee supports the continued use of mixing zones as allocated impact zones (AIZs). In addition, we support Agency efforts to define and model AIZs as they may exist under different conditions. However, we note that current practices at the state level often result in designation of AIZs that are not well defined and which do not consider (measure/estimate) risk to aquatic species or humans. Therefore, the Subcommittee recommends EPA continue to develop models that can assist in setting risk-based AIZs.

The Subcommittee appreciates the opportunity to provide advice to the Agency on the technical, validation, and implementation aspects of the D-CORMIX model. We look forward to the response of the Assistant Administrator for the Office of Water to the advice contained in this report.

Sincerely,

/signed/
Dr. Joan Daisey, Chair
Science Advisory Board

/signed/
Dr. Ishwar Murarka, Chair
D-CORMIX Review Subcommittee
Science Advisory Board

NOTICE

This report has been written as part of the activities of the Science Advisory Board, a public advisory group providing extramural scientific information and advice to the Administrator and other officials of the Environmental Protection Agency. The Board is structured to provide balanced, expert assessment of scientific matters related to problems facing the Agency. This report has not been reviewed for approval by the Agency and, hence, the contents of this report do not necessarily represent the views and policies of the Environmental Protection Agency, nor of other agencies in the Executive Branch of the Federal government, nor does mention of trade names or commercial products constitute a recommendation for use.

ABSTRACT

The US EPAs Science Advisory Board (SAB) convened the D-CORMIX Review Subcommittee to conduct an external peer review of the Agency's D-CORMIX model. The Subcommittee met in public session on August 25-26, 1998 in Washington, DC and reviewed a number a technical aspects as well as implementation issues with the D-CORMIX model for mixing zone analysis.

The charge to the Subcommittee is summarized as follows: a) Is D-CORMIX an appropriate mixing zone model to use for continuous dredged material discharge mixing zone analysis?; b) Does the model accurately capture the physics of negatively buoyant surface plumes, in particular, behavior of the density current and particle settling associated with dredged disposal plumes?; c) What are the essential differences between the D-CORMIX and CD-FATE models and which is preferable as a mixing zone model for continuous dredged material discharge?); d) Does the SAB approve of our outline for laboratory validation? What further suggestions can be offered?; and e) What factors should be considered in developing an AIZ that will not adversely impact the integrity of the aquatic ecosystem? How should the AIZ be sized, especially in relation to distance from the bottom (substrate), and portion of water column encompassed?

In its report, the Subcommittee provided responses to the above questions, addressed several concerns over the actual model itself, and made suggestions for improvements in validation.

Keywords: D-CORMIX, CD-FATE, mixing zone, water quality, dredge discharge

U.S. Environmental Protection Agency
Science Advisory Board
Cormix Review Subcommittee

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1. EXECUTIVE SUMMARY

The Science Advisory Board (SAB) convened the CORMIX Review Subcommittee to conduct an external peer review of the US EPA Office of Water's D-CORMIX model. The Subcommittee met in public session in Washington DC on August 25-26, 1998. At the meeting the Subcommitttee discussed the model with staff of both EPA and the US Army Corps of Engineers. The Agency requested responses from the Subcommittee to four charge questions related to the technical aspects and one charge question related to the implementation of the model with regard to use of an allocated impact zone (AIZ) for negatively buoyant wastewater discharge. These charge questions and the Subcommittee's summary responses follow. More detailed responses to these questions can be found in Chapter 3.

a) Is D-CORMIX an appropriate mixing zone model to use for continuous dredged material discharge mixing zone analysis? [see section 3.1 for further details]

The appropriateness of D-CORMIX for intended applications will depend on the level of detail and sophistication required for the analysis. Limited validation studies have been undertaken thus far with mixed results with respect to the predicted distribution of suspended solids and associated changes in density in comparison with several laboratory and field data sets. Neither the hindered settling option nor contaminant decay/growth features have been tested. For those applications for which suspended solids are the only contaminant of interest, D-CORMIX might be said to be partially validated. However if intended applications for predicting mixing zones include the need to predict dissolved phase contaminant distributions that originate from chemicals originally bound to the sediment, then D-CORMIX must be considered to be, at present, unvalidated. Nonetheless, it is important that an inability of D-CORMIX to handle one set of processes, such as contaminant interactions and fate, not invalidate it as an appropriate model for cases in which mixing and sedimentation are the dominant processes.

D-CORMIX has the potential for the mixing zone analysis of dredged material discharges, assuming additional validation as suggested in Section 3.4 below is completed. In its current form, it does not account for any physico-chemical interactions between the sediment and liquid phases. Due to short transit times through the mixing zone, this may not be an important limitation for most applications. It may be appropriate to define specific applications or classes of applications where this simplification is not appropriate and to clearly identify these conditions for potential users. D-CORMIX is a modification of CORMIX that considers the presence of suspended sediment as a density-producing agent which can subsequently settle out of a density current flowing along the bottom of the receiving fluid. The deposition is handled by specification of a settling velocity which is dependent on sediment size. Whether particle settling within the density current is the only important physical process distinguishing dredged material plumes from dissolved phase ones and whether the simple settling computation can be used to estimate sediment removal from the plume needs to be subject to a more rigorous validation effort than has been conducted to date. In addition, the nature of above water discharges and their contribution to a splash component of sediment flux to the environment needs to be further investigated to determine the significance to local turbidity within the mixing zone.

b) Does the model accurately capture the physics of negatively buoyant surface plumes, in particular, behavior of the density current and particle settling associated with dredged disposal plumes? [see section 3.2 for further details]

D-CORMIX shows mixed results with respect to the predicted distribution of suspended solids and associated changes in density in comparison with several laboratory data sets. D-CORMIX appears to warrant additional validation as outlined in Section 3.4 below. One of the Subcommittee members had access to several laboratory data sets and simulated these using both the CORMIX and D-CORMIX models (properly accounting for the issue associated with positive or negative buoyancy as required by the particular model). A comparison of the simulations led to the following conclusions: (1) in most situations, the models performed relatively well in predicting dilutions and plume dimensions observed in the experiments; (2) in cases where vertical density gradients were present in the ambient fluid of sufficient magnitude to trap the plume within the water column, a number of deviations were noted; and (3) comparison of data in which plumes impinge directly on a boundary indicates that the model conservatively underestimates the dilution in the initial layer spreading along the surface.

In addition to the above mentioned issues, there are additional issues which have not been adequately explored. Concerns were expressed with regards to a number of issues that fall into this category such as the magnitudes of the various entrainment coefficients used in the density current model, involving frontal, vertical and lateral entrainment. An additional concern is that the density current is essentially a box model and thus predicts an average or “top-hat” concentration. If more detailed information on plume concentrations is required, information on the concentration distributions is required. This may be especially critical in the case where sediment particle settling will significantly distort the sediment profiles within the density current.

c) What are the essential differences between the D-CORMIX and CD-FATE models and which is preferable as a mixing zone model for continuous dredged material discharge? [see section 3.3 for further details]

D-CORMIX is a model which predicts the movement and dilution of a discharge starting with the source conditions and progressing through a near-field jet-mixing region, a plume-mixing region, a density current region, and a far-field ambient mixing region for a variety of possible configurations. CD-FATE is a model which also predicts the movement and dilution of a discharge but with several important differences from the D-CORMIX formulation. CD-FATE begins with the source conditions and utilizes the formulation in the original model CORMIX to describe the descending plume. However, it also assumes that an empirical fraction of the source sediment is stripped from the descending plume and enters the water column subject to subsequent ambient water column transport and mixing processes. Once the sinking plume reaches the bottom, the sediment load is assumed to settle directly to the bottom as opposed to being transported as a bottom density current. However, CD-FATE does allow for entrainment from the bottom deposits and an additional component of sediment is thereby introduced to the bottom of the water column to be subsequently transported and diluted by the ambient flow. CD-FATE as a model appears to be less generally formulated than D-CORMIX in that it does not handle the movement and dilution of a suspended sediment density current that may be important in some situations. However, the component of the model that accounts for entrainment from the bottom deposits does introduce a suspended sediment plume near the bottom in a fashion somewhat analogous to the density current. The processes assumed to model the bottom plume are significantly different in D-CORMIX and CD-FATE and no rigorous attempt has been made to delineate differences in the predictions of the two models for typical applications. It is, therefore, not possible to assess the relative validity of the two models without further investigation.

In summary, D-CORMIX focuses on the movement and dilution of a mixture of solids and liquids as a jet or plume and as a density current and does not account for the distribution within the water column of a component stripped from the sinking plume or entrained from bottom deposits. CD-FATE calculates a solids concentration in the water column resulting from an ad hoc specified amount of solids stripped from the descending jet/plume and also calculates suspended sediment distributions associated with material entrained from bottom deposits. It does not predict the transport and dilution of suspended material moving along the bottom as a density current except that the material entrained from the bottom may be considered to be somewhat analogous to a density current. However, this material is not assumed to move under its own weight but is simply transported and mixed by the ambient flow.

d) Does the SAB approve of our outline for laboratory validation? What further suggestions can be offered? [see section 3.4 for further details]

As noted in Section 3.4 below, the Subcommittee recommends a staged validation process. An initial objective in the design of any validation study must be to decide whether or not the processes in D-CORMIX are to be validated or whether it is the ability of D-CORMIX to be able to represent physically important processes that is being investigated. For example, if near field turbidity within the water column is deemed to be important in a specific mixing zone application, it is likely that the splash from an above water discharge could provide a significant contribution to turbidity. However, since this process is not currently modeled by D-CORMIX, any validation effort that relies on observations of near field turbidity is likely to be unsuccessful. On the other hand, if the validation effort includes attempts to properly characterize processes that ought to be included in D-CORMIX, the investigation of near field turbidity may be a fruitful exercise.

A similar consideration arises with respect to chemical and physio-chemical processes since D-CORMIX currently does not represent these in any meaningful fashion. It may therefore be pointless to even attempt to validate the current model in systems with reactive constituents. However, if an attempt is made to determine the potential significance of reactions to mixing zone processes, a second dilemma is present. Even if additional capabilities were developed for D-CORMIX to properly model chemical and physio-chemical processes, it is possible for a validation effort to fail if the mixing/sedimentation processes are not represented properly in the current version of the model. In light of this consideration, it appears to be more fruitful to approach the validation effort in a staged manner.

e) What factors should be considered in developing an AIZ that will not adversely impact the integrity of the aquatic ecosystem? How should the AIZ be sized, especially in relation to distance from the bottom (substrate), and portion of water column encompassed? [see section 3.5 for further details]

Continued use of mixing zones as allocated impact zones (AIZs) is supported. Additionally, the Subcommittee supports Agency efforts to define and model AIZs as they may exist under different conditions. Current practices at the state level often results in designation of AIZs that are not well defined and which do not consider (measure/estimate) risk to aquatic species or humans.

2. INTRODUCTION

2.1 Background

Understanding the fate of dredged material discharged at open water sites is essential in order to predict potential effects of released contaminants on aquatic life and human health. Mathematical models of the physical processes determining the fate of the discharged material can be used to provide an estimate of concentrations in the receiving water as well as the initial deposition pattern of material on the bottom. Any evaluation of potential water column biological effects has to consider the effects of mixing and resulting dredged material/chemical correction. As defined by EPA (EPA, 1991) the mixing zone (or dilution zone) is defined as a limited area or volume of water where initial dilution of a discharge takes place; and where numeric water quality criteria can be exceeded but acutely toxic conditions are prevented from occurring. (See section 3.1.1a) for a further discussion of ‘mixing’).

The draft Inland Testing Manual (EPA, 1993) for the evaluation of dredged material under CWA Section 404, which was previously reviewed by the Science Advisory Board (SAB, 1994), contains a mathematical model for evaluating the mixing of **instantaneous** discharges from barges and hopper dredges. Following the SAB’s review, EPA has conducted an evaluation of possible modeling approaches for **continuous** dredge pipeline disposal. During that evaluation, EPA determined that continuous pipeline dredge operations were primarily conducted in relatively shallow waters, where boundary interaction between the disposal plume and the bottom would strongly influence the hydrodynamics of the mixing process. After a careful review of available EPA and U.S. Army Corps of Engineers initial mixing methodologies, EPA selected CORMIX for further development. CORMIX was chosen because it was deemed by EPA to be the only easily applied methodology which: a) accounts for plume boundary interaction in shallow waters; and b) simulates the resulting plume density current after boundary interaction.

D-CORMIX, the model which is presently being examined in this SAB review, predicts the initial dilution and mixing zone of a typical continuous dredge outfall operation such as a pipeline discharge. EPA anticipates that D-CORMIX, when fully validated, will be an important tool to evaluate potential exceedences of water quality standards due to continuous dredged material or other negatively buoyant discharges.

The CORMIX family of models consists of CORMIX1 (Doneker and Jirka, 1989) for mixing of a submerged single port discharge, CORMIX2 (Akar and Jirka, 1991), for multiport discharges, CORMIX3 (Jones et al., 1996), for discharge from channels, and most recently D-CORMIX, for mixing of continuous dredge disposal. The first three models were developed to predict mixing for buoyant plumes with little or no suspended solids present, such as for example the discharge of a treated wastewater to the ocean. D-CORMIX was developed to model mixing for negatively buoyant plumes which may contain high solids concentrations, such as occur during dredge disposal operations. It incorporates Stokes settling for up to five particle sizes, although optional use of hindered settling is possible. It also contains a first order decay/growth function for modeling contaminant reactions. The CORMIX models are structured within an expert system framework which is used to facilitate data entry, and select the type of mixing regime using a reasoning approach which mimics the way an engineer would go about solving the problem. Once the regime is identified, the model solves appropriate equations. The solution generates tabular and graphical output. The CORMIX models operate under a DOS environment, although a Windows-based version of CORMIX is being developed.

CORMIX1, CORMIX2, and CORMIX3 have, over time, established themselves as useful tools for defining mixing zones and the concentration distribution of conservative contaminants. These models are widely distributed and used throughout the engineering community. The CORMIX modeling approach has been applied to address a wide range of discharge situations, ranging from complex multiport diffusers to small toxic discharges and large cooling water outflows. A strength of the CORMIX approach is that it contains no adjustable parameters that must be estimated or found indirectly; input data consist of values measured directly for the system of interest.

D-CORMIX appears to have been developed in response to initiatives by the Corps of Engineers to model dredge disposal problems. The Corps approach is based on the concept that negatively buoyant surface discharges can be modeled as the mirror image of positively buoyant subsurface discharges. To this end, the CD-FATE program, ADDAMS (Automated Dredging and Disposal Alternatives Management System), was written (ADDAMS, 1994). CD-FATE incorporates the CORMIX positive buoyant models into a larger framework which contains pre- and postprocessing modules for facilitating interpretation of input and output data. D-CORMIX takes a similar approach, but as noted incorporates additional mechanisms related to particle settling, contaminant reactions, and the movement of density currents over sloping bottoms.

2.2 Charge to the Subcommittee

a) Technical aspects of D-CORMIX:

1) <u>Is D-CORMIX an appropriate water quality model to use for continuous dredged material discharge mixing zone analysis?</u> (**Charge Question #1**)

2) <u>Does the model accurately capture the physics of negatively buoyant surface plumes, in particular, behavior of the density current and particle settling associated with dredged disposal plumes?</u> (**Charge Question #2**)

3) Is D-CORMIX, a model based on conservation of mass, momentum and energy principles that provides continuous simulation of near-field, intermediate-field, and far-field physical processes, preferable to models which make empirical assumptions on the amount of suspended materials available for transport (*e.g.*, CD-FATE)? (Note - the Subcommittee revised

this charge question to the following: What are the essential differences between the D-CORMIX and CD-FATE models and which is preferable as a mixing zone model for continuous dredged material discharge?) (**Charge Question #3**)

4) Does the SAB approve of our outline for laboratory validation? What further suggestions can be offered? (**Charge Question #4**)

b) Implementation of model with regard to use of an allocated impact zone for negatively buoyant wastewater discharges (not dredged material discharges):

1) EPA's current policy addresses mixing zones as allocated impact zones (AIZs) where certain numeric water quality criteria may be exceeded as long as: there is no lethality to organisms passing through the mixing zone; there are no significant risks to human health; and the integrity of the water body as a whole is not impaired as a result of these exceedences. These AIZs, if disproportionately large, could potentially adversely impact the integrity of the aquatic ecosystem and have unanticipated ecological consequences.

(a) D-CORMIX predicts the 3-dimensional characteristics and mixing behavior of a negatively buoyant discharge plume. What factors should be considered in developing an AIZ that will not adversely impact the integrity of the aquatic ecosystem? How should the AIZ be sized, especially in relation to distance from the bottom (substrate), and portion of water column encompassed? (**Charge Question #5**) We realize that this will be influenced by site-specific ambient characteristics, but seek general (or specific, if appropriate) guidance.

3. RESPONSE TO THE CHARGE

3.1 Charge Question #1 - Is D-CORMIX an appropriate water quality model to use for continuous dredged material discharge mixing zone analysis?

Before commenting on the appropriateness of D-CORMIX, it is important to identify three very general categories of processes that affect the constituents in a dredged material discharge:

3.1.1 Definitions

a) Mixing: the physical mixing (or dilution) of the discharged material (water, sediment, and all constituents of interest) with water from the receiving water body will generally tend to reduce the concentrations of suspended sediment and constituents in the discharge jet or plume. In many applications, mixing will be the most important mechanism for concentration reduction as the jet or plume falls (or rises) within the water column and reaches an equilibrium position (often the surface or bottom), and, in some cases, as the discharge is transported as a density current or dispersed by ambient turbulence. The time scale for this mixing to occur within the limits of typical mixing zones is usually on the order of seconds to minutes.

b) Sedimentation: suspended sediment in the discharge will affect the density of the discharge and, as a result, will influence the movement of the discharge within the receiving water. In addition, suspended sediment in the discharge will settle downward under the action of gravity. This settling may cause the sediment ultimately to move differently from the liquid phase of the discharge, resulting in phase separation in the jet, plume, or density current region.

c) Chemical and physio-chemical reactions: both the constituents and the suspended solids in the discharge may undergo transformations of a chemical or physio-chemical nature. Constituents in the discharge may react with each other or with constituents in the receiving water. Dissolved constituents may become associated with solid material and constituents initially associated with solids may become dissolved. Finally, suspended solids may interact with each other, resulting in a change in the size distribution of solid material. Although some important reactions may occur within seconds or minutes, many of these reactions occur on a time scale of tens of minutes to hours, or even days.

The appropriateness of D-CORMIX will depend upon which of these processes are important in a given mixing zone analysis. It is likely that, by definition, mixing will always be important. For dredged material the presence of sediment will almost always affect the density, but sedimentation and related phase separation may or may not be important. In many mixing zone analyses the effect of reactions is neglected by assuming that the mixing time is small compared to the reaction time. Because of these potential differences in importance, the Subcommittee responses to this and subsequent questions will, where appropriate, address the capability of D-CORMIX to handle each of these three processes separately. It is important that an inability of D-CORMIX to handle one set of processes, such as reactions, not invalidate it as an appropriate model for cases in which mixing and sedimentation are the dominant processes.

3.1.2 Appropriateness of D-CORMIX as a Mixing Model

D-CORMIX is a derivative of CORMIX which was developed for analyzing the characteristics of the mixing zone for positively (upwards) buoyant, dissolved phase continuous discharges under a variety of different ambient and discharge configurations. CORMIX is, however, restricted to certain configurations and simulations may not be performed for various scenarios mainly involving highly irregular receiving water geometries. The structure of CORMIX involves the use of a number of different simulation modules, depending on the combination of discharge and ambient conditions, and this feature allows for simulation of a wider variety of scenarios than other currently available models. There are separate models (CORMIX 1, 2, and 3) for the simulation of single port, multiport, and surface discharges respectively. Although CORMIX allows the specification of a first order coefficient for pollutant removal/generation, in general, the model presently does not consider chemical/biological interactions and should be considered to be most applicable for the simulation of a conservative pollutant.

3.1.3 Appropriateness of D-CORMIX as a Sedimentation Model

D-CORMIX involves the re-configuration of CORMIX from a buoyant dissolved phase discharge to describe a negatively (downwards) buoyant particle laden discharge in order to simulate the condition associated with typical dredged material discharge. Analogues to CORMIX I and III have been developed. A number of specific modifications to CORMIX have been implemented. The modification from positive to negative buoyancy is trivial and no discussion of this is required. A further modification is required because of this change since a positively buoyant discharge will tend to rise up to a horizontal water surface and subsequently spread along it. In contrast, a negatively buoyant discharge will sink down to and spread along a bottom. Since the bottom topography can generally be quite complex, this provides an additional degree of difficulty in specifying a discharge condition. D-CORMIX restricts simulations to a constant slope in one direction although it does allow for two different zones with different slopes. The effects of any deviation of the actual bathymetry from this idealized geometry cannot be described with the current version of D-CORMIX. An additional modification to D-CORMIX was to describe the effect of separate phase sediment particles contained within the flow. During the descent phase of the discharged plume, relative motion (sedimentation) of the sediment is not considered but settling is allowed once the plume reaches the terminal level and begins to spread as a density current. The model considers sediment to be composed of five discrete size classes (clay, silt, etc.) with prescribed settling velocities. Deposition of the sediment is computed on the basis of these settling velocities and the removal of this sediment is used to establish a reduction in buoyancy within the density current. Finally, actual dredged materials may involve discharges from above water pipelines, often with deflectors in front of the discharge to spread the material over a wider surface area than would occur with a simple submerged discharge. D-CORMIX considers a number of different above water discharge configurations to establish an "equivalent" discharge diameter and angle to be used in subsequent submerged jet analyses.

During the Subcommittee meeting, concerns were expressed regarding the computational capabilities of D-CORMIX. Two specific items included: a) the stripping of a small fraction of the discharge (including suspended sediment) from the sinking plume which is subsequently transported with the prevailing ambient current; and b) phase separation within the density current portion of the discharge involving zone settling which is observed at high suspended solids concentrations. Whether or not this second phenomenon has been observed in open water dredge spoil disposal was unclear, but it is the basis for the design and operation of confined disposal facilities as well as a number of industrial processes. The stripping process may be a function of above water discharge (splash from deflected discharges, for example) and possibly low levels of temperature stratification (leading to trapping of low momentum splash near the water surface). Although D-CORMIX does not consider either one of these two processes, there are possibilities for future modifications to the model that could incorporate these or other processes.

With specific regards to the two processes described above, the nature of the required changes would be substantially different. The "splash" or stripping into the water column is not a natural feature of the flow physics of D-CORMIX. The nature of this process is apparently poorly understood at present and is probably strongly correlated with the nature of the discharge (above water, type of deflector, etc.). With regards to dissolved phase contaminant concentrations, splash is probably unimportant, but it may provide a significant contribution to local turbidity, which may be important in some mixing zone applications. It is difficult to visualize how the incorporation of the splash component into D-CORMIX could be achieved in a mechanistic fashion comparable with the remainder of the model, but it is conceivable that an *ad-hoc* formulation could be developed from observations at field sites and incorporated into the model. The remaining process of phase separation could probably be incorporated into relevant simulation modules of D-CORMIX if it is assessed to be an important factor in sediment plume flows.

3.1.4 Appropriateness of D-CORMIX as a Model of Non-Conservative Reacting Constituents

The extension of CORMIX to negative buoyancy, high solids, nonconservative reactant problems raises several fundamental issues which will ultimately impact the level of resources needed for development and the way in which experimental validation studies will be carried out. First, one of the principal strengths of CORMIX, the lack of any adjustable coefficients, is compromised. Parameters describing particle interactions (agglomeration, shearing) and contaminant reactivity must be estimated from ancillary experiments, or adapted from the literature. Second, although the hydrodynamic portion of CORMIX is relatively sophisticated, the contaminant and particle behavior portions are less so. Five particle size classes are unlikely to sufficiently capture the interactions that grow and shrink particle masses, and there is essentially no consideration of how contaminants distribute themselves between the solid and solution phases, and how this is in turn affected by particle size changes. Third, these factors will significantly affect the conduct of laboratory and/or field validation experiments. It may not be sufficient to measure merely the spatial distribution of a few size fractions of suspended solids and sample densities if reactive contaminant distribution is sought as the guiding factor in defining the mixing zone. Rather, it may become necessary to measure a specific contaminant(s), to establish a greater number of particle size classifications, and to obtain direct evidence of the nature of particle aggregation states. Such determinations would be in addition to separate experiments related to contaminant partitioning and other reactions.

3.1.5 Summary

The appropriateness of D-CORMIX for intended applications will depend on the level of detail and sophistication required for the analysis. Limited validation studies have been undertaken thus far with mixed results with respect to the predicted distribution of suspended solids and associated changes in density in comparison with several laboratory and a field data set. Neither the hindered settling option nor contaminant decay/growth features have been tested. For those applications for which suspended solids are the only contaminant of interest, D-CORMIX might be said to be partially validated. However if intended applications for predicting mixing zones include the need to predict dissolved phase contaminant distributions that originate from chemicals originally bound to the sediment, then D-CORMIX must be considered to be, at present, unvalidated. It is important to recognize, however, that an inability of D-CORMIX to describe one set of processes, such as reactions, does not invalidate it as an appropriate model for cases in which mixing and sedimentation are the dominant processes.

In summary, D-CORMIX appears to have the potential for the mixing zone analysis of dredged material discharges. In its current form, it does not account for any physico-chemical interactions between the sediment and liquid phases. Due to short transit times through the mixing zone, this may not be an important limitation for most applications. It may be appropriate to define specific applications or classes of applications where this simplification is not appropriate and to clearly identify these conditions for potential users. D-CORMIX is a modification of CORMIX that considers the presence of suspended sediment as a density-producing agent which can subsequently settle out of a density current flowing along the bottom of the receiving fluid. The deposition is handled by specification of a settling velocity which is dependent on sediment size. Whether particle settling within the density current is the only important physical process distinguishing dredged material plumes from dissolved phase ones and whether the simple settling computation can be used to estimate sediment removal from the plume needs to be subject to a more rigorous validation effort than has been conducted to date. In addition, the nature of above water discharges and there contribution to a splash component of sediment flux to the environment needs to be further investigated to determine the significance to local turbidity within the mixing zone.

3.2 Charge Question #2 - Does the model accurately capture the physics of negatively buoyant surface plumes, in particular, behavior of the density current and particle settling associated with dredged disposal plumes?

3.2.1 Potential Deficiencies in original CORMIX Model that are incorporated into D-CORMIX

The Subcommittee expressed concerns with regards to a number of issues that fall into this category such as the magnitudes of the various entrainment coefficients used in the density current model, involving frontal, vertical and lateral entrainment. An additional concern is that the density current is essentially a box model and thus predicts an average or "top-hat" concentration. If more detailed information on plume concentrations is required, information on the concentration distributions is required. This may be especially critical in the case where sediment particle settling will significant distort the sediment profiles within the density current.

One Subcommittee member used some personally available data sets to simulate these two models. Information concerning this individual analysis is included in Appendix A.

3.2.2 Restrictions on the Situations that D-CORMIX can Analyze

There are a number of physical processes within a sediment plume that may potentially affect the distribution of dissolved phase constituents or suspended solids. Many of these will be restricted to specific classes of problems and may not be general restrictions as to the use of D-CORMIX. Further assessment may be required to determine the significance to applications typically encountered within the mixing zone of a dredged material disposal.

a) D-CORMIX makes fairly restrictive specifications on the specification of the bathymetry. Actual applications may involve bottom irregularities that have a significant impact on the density current motion.

b) D-CORMIX does not allow for flocculation of fine-grained sediments to occur within the mixing zone and therefore cannot account for possible changes in settling velocities.

c) D-CORMIX does not allow for resuspension/bottom scour as a source of sediment to the density current.

d) Except in a fairly simplistic way, D-CORMIX does not allow for the far-field build-up to influence the plume dynamics. An allowance is made for the possible re-entrainment of material from a previous tidal cycle but only insofar as it may impact the dilution. The build-up of previously discharged fluid may also influence the dynamics of the density current as well.

e) D-CORMIX does not provide estimates of suspended solids from top to bottom of the water column, i.e., represents the density current plume with a top-hat profile within the water column, and the plume is represented with a gaussian vertical profile in the passive diffusion region.

3.2.3 Possible Deficiencies in D-CORMIX

a) There is a body of knowledge that indicates whenever suspended sediment concentrations exceed something on the order of 10 g/l, sediment interactions become more complex than can be described by a simple settling model. Discharge concentrations of suspended sediment are generally above this limit and the possibility exist that these processes may become operative in at least some cases. Even in cases in which the sinking plume dilutes the flow below the threshold level, settling within the density current will redistribute sediment near the bottom of the plume; the bulk density computed by CORMIX would not be capable of detecting this situation. The assumptions used by D-CORMIX to represent the density current behavior need to be further validated.

b) There are some fundamental differences between dissolved phase plumes and two-phase plumes such as air bubble plumes and presumably sediment plumes. These differences become more pronounced in stratified receiving fluids.

c) The source description for D-CORMIX simulations (*e.g.*, the CORJET module) requires the specification of a discharge diameter and angle. D-CORMIX allows the general description of above water discharges and converts them into the required input. The accuracy of such a conversion has not been demonstrated at present. In particular, the use of a deflector plate may spread the discharge over an area comparable with the water depth and the application of a plume model to this discharge configuration is questionable. In addition, these above water discharges may contribute a “splash” component which could have a significant contribution on near field turbidity which is ignored by the present formulation of D-CORMIX.

d) The preliminary validation efforts on D-CORMIX indicated that simulations became more reliable on steeper slopes and less satisfactory on smaller slopes. Flows on shallow slopes are more influenced by far-field influence and may be more difficult to simulate accurately even when only dissolved phase plumes are considered. The existing validation effort is insufficient to conclude that the model adequately simulates the density current, in particular on mild slopes.

3.3 Charge Question #3 - What are the essential differences between the D-CORMIX and CD-FATE models and which is preferable as a mixing zone model for continuous dredged material discharge?

The answer to this question will consist of a brief description of the essential differences between the two models followed by a discussion of their relative merits as mixing zone models for continuous dredged material discharge. Additional characteristics of D-CORMIX are discussed in the answers to Charge Questions #1 and #2 (Sections 3.1 and 3.2 of this report).

D-CORMIX is a model which predicts the movement and dilution of a discharge starting with the source conditions and progressing through a near-field jet-mixing region, a plume-mixing region, a density current region, and a far-field ambient mixing region for a variety of possible configurations. As discussed in the answers to Charge Questions #1 and #2, the algorithms used by D-CORMIX in calculating the movement and dilution are based upon a body of theoretical and empirical information applicable to these configurations and are not adapted to site specific conditions or fit to a particular set of field observations.

In predicting the movement and dilution of the discharged material, D-CORMIX treats the liquid and solids in the discharge as combined phases that follow the same trajectory and experience the same dilution. The only exception to this is that, beyond the near-field jet mixing region, the solid material is removed according to specified settling velocities. Remaining solids and liquids are still assumed to move and dilute together. Furthermore, the model assumes that settled solids are deposited on the bottom immediately. Consequently, the present form of D-CORMIX will never predict that solid or liquid material leaves the original mixture and enters the water column. More specifically, D-CORMIX will not predict that solid material is 'stripped' off the jet or plume as it descends through the water column and will not predict that liquid leaves the bottom layer as a result of consolidation of the solids. The solids concentrations predicted by D-CORMIX can only become more dilute and can not increase as would be the case if consolidation were considered.

CD-FATE is a model which also predicts the movement and dilution of a discharge starting with the source conditions, a jet/plume mixing region and a far-field mixing region for a variety of different discharge configurations. CD-FATE relies on CORMIX whenever possible in predicting the characteristics of these regions, but makes different assumptions about how these regions are linked together. These assumptions are based on the general experience of the Army Corps of Engineers with open water and confined dredged material disposal operations. The resulting CD-FATE model has a more limited empirical basis compared to D-CORMIX, but is more closely linked to observations of actual dredged material disposal. [Note: the Subcommittee's evaluation of CD-FATE is based upon material contained in Attachments 12, 14, and 15 (COE, 1994a; 1994b; 1995) of the information provided to the Subcommittee in advance, as well as a verbal summary provided by Dr. Paul Schroeder of the US Army Corps of Engineers at the Subcommittee meeting. The Subcommittee notes that the description of CD-FATE in the Attachments is very sketchy and, with respect to some of the aspects of CD-FATE described by

Dr. Schroeder, incomplete. The Subcommittee recommends that, if CD-FATE is to be routinely used for mixing zone analysis, better documentation should be prepared.]

In predicting the movement and dilution of the discharged material, CD-FATE uses a linked set of CORMIX calculations, each of which assumes that the liquid and solid material in the discharge move and dilute in a similar manner. However, CD-FATE assumes that a fraction of the suspended sediment will be lost to the water column as the jet or plume descends to the bottom. This fraction is specified in an ad-hoc basis as an upper limit on that observed at actual dredged disposal sites. This solid material is assumed to remain in suspension and is accounted for in predicting the turbidity in the water column downstream from the discharge, but above any density current which may form. The calculation of solids concentration in the water column resulting from the stripping of material uses a CORMIX module starting from a surface source of solids. Solid material that is not stripped from the descending jet or plume and all of the original liquid in the discharge ultimately reach the bottom and are assumed to form an unmoving layer of consolidating solids from which liquid is ejected into the overlying water column at a rate determined by specified consolidation rates. The subsequent transport and dilution of the ejected liquid phase in the water column is predicted by a CORMIX module whose source conditions are related to the estimated size of the consolidating layer. The concentration of the solids in the consolidating layer is predicted to be greater than that of the material reaching the bottom.

In summary, D-CORMIX focuses on the movement and dilution of a mixture of solids and liquids as a jet or plume and as a density current and does not account for the distribution within the water column of a component stripped from the sinking plume or entrained from bottom deposits. CD-FATE calculates a solids concentration in the water column resulting from an ad hoc specified amount of solids stripped from the descending jet/plume and also calculates suspended sediment distributions associated with material entrained from bottom deposits. It does not predict the transport and dilution of suspended material moving along the bottom as a density current except that the material entrained from the bottom may be considered to be somewhat analogous to a density current. However, this material is not assumed to move under its own weight but is simply transported and mixed by the ambient flow.

The adequacy with which D-CORMIX represents physical processes associated with discharges containing high solids concentrations has been identified as a concern in the answers to Charge Questions #1 and #2, and as an area in need of experimental study in the answer to Charge Question #4 (Section 3.4 of this report). If the processes of solids stripping and consolidation are found to be important for such discharges, D-CORMIX as presently formulated would be incapable of predicting accurately the behavior of the liquid and solid material stripped out of the plume and the consolidation of the suspended sediment into a bottom deposit with the attendant ejection of water from the deposit. These aspects may be important if regulatory focus is on the water column above the density current.

CD-FATE as a model appears to be less generally formulated than D-CORMIX in that it does not handle the movement and dilution of a suspended sediment density current that may be important in some situations. For this reason, CD-FATE may not be an appropriate model if regulatory focus is on the concentrations within the density current region. CD-FATE does however, account for suspended sediment components stripped from the descending plume and entrained from bottom deposits, and does make predictions of the results of these processes on water column sediment concentrations. CD-FATE, if validated, may be an appropriate model if the regulatory focus is on the water column outside of the density current.

3.4 Charge Question #4 - Does the SAB approve of our outline for laboratory validation? What further suggestions can be offered?

D-CORMIX appears to warrant additional validation as suggested by the staged approach outlined below. An initial objective in the design of any validation study must be to decide whether or not the processes in D-CORMIX are to be validated or whether it is the ability of D-CORMIX to be able to represent physically important processes that is being investigated. For example, if near field turbidity within the water column is deemed to be important in a specific mixing zone application, it is likely that the splash from an above water discharge could provide a significant contribution to turbidity. However, since this process is not currently modeled by D-CORMIX, any validation effort that relies on observations of near field turbidity is likely to be unsuccessful. On the other hand, if the validation effort includes attempts to properly characterize processes that ought to be included in D-CORMIX, the investigation of near field turbidity may be a fruitful exercise.

A similar issue arises with respect to chemical and physio-chemical processes since D-CORMIX currently does not represent these in any meaningful fashion. It may therefore be pointless to even attempt to validate the current model in systems with reactive constituents. However, if an attempt is made to determine the potential significance of reactions to mixing zone processes, a second dilemma is present. Even if changes were made to D-CORMIX to properly model chemical and physio-chemical processes, it is possible for a validation effort to fail if the mixing/sedimentation processes are not represented properly in the current version of the model. In light of this consideration, it appears to be more fruitful to approach the validation effort in a staged manner. Such an effort could be structured along the lines of the effort listed below.

3.4.1 Validation of Mixing Processes

Jet/plume mixing processes are reasonably well understood and major validation efforts are probably not required on these. However, a well designed study could also focus on these to some extent. One of the more important changes in D-CORMIX relative to CORMIX is the extension to above water surface discharges. A laboratory study that investigates the near field mixing associated with above water discharges including discharges impinging on deflector plates would allow the assessment of the below surface mixing associated with some generic configurations. An additional advantage is that these same experiments could be used to assess the splash problem and the nature of its contribution to near field turbidity. Finally, if these discharges are allowed to impinge on a bottom (probably a sloping one but this would not be an absolute necessity), the nature of bottom impingement contributions to mixing that are not presently incorporated into CORMIX or D-CORMIX could also be investigated. It would also be fruitful to examine typical discharge configurations and determine by application of the current model whether or not ambient water column stratification is likely to be of any consequence in these circumstances. If so, then it would also be worthwhile to conduct a separate laboratory study to investigate this effect.

3.4.2 Validation of Sedimentation Processes

Efforts at multiple levels may be the best approach to this problem. At a laboratory scale, a careful investigation of the dynamics of density currents spreading on a slopping bottom should be undertaken. These experiments should be at as large a scale as is feasible in order to minimize Reynolds number effects. They should also incorporate sediment as the density producing agent and at concentrations that are realistic of dredged disposal application . The discharge configuration should be simple in order to minimize confounding issues addressed above. Different bottom slopes from "mild" to "steep" should be considered and should be of sufficient length that a significant amount of sediment deposition will occur. A key issue is to determine whether the current sedimentation model of D-CORMIX is adequate or whether phase separation processes are important.

One possible investigation at the field scale, but with more controlled ambient conditions, would be the investigation of flows in confined disposal facilities. Initially, a review of existing data sets could determine whether or not there is existing information that could be utilized in a model validation effort. If no such data sets are available, a properly designed experiment in an existing facility might be arranged. Although such an approach would necessarily not include all processes in place at open water disposal sites, the advantages of more control over system variables will allow a more detailed set of observations against which to compare D-CORMIX predictions.

3.4.3 Validation for Non-Conservative Reacting Constituents

The Subcommittee suggests that some consideration be given at this stage of model development to the specific uses intended for D-CORMIX. Are there certain classes of contaminants that are generally found in dredge materials for which water quality standards are well established (*e.g.*, PAHs, PCBs, heavy metals)? Are there certain common physical and chemical features of dredge particles that will tend to define particle-particle interactions and particle-contaminant interactions (size distributions, organic matter content, pH, etc.)? If these questions are answerable, it may be possible to build a degree of sophistication into D-CORMIX for reactive contaminants and particle interactions which is appropriate for a large number of intended uses, but not so complex that much of the value of the CORMIX approach is lost.

Validation studies should address issues related to selected cases of contaminant partitioning, consistent with the important sediment, water, and contaminant characteristics identified above. In so doing, it is not necessary that these studies be exhaustive, but should include enough experimental data to provide confidence that the model adequately captures the physics and chemistry that are relevant to evaluating the distribution of contaminants within the mixing zone. In general, validation studies can be designed to measure various particulate distribution patterns, but incorporate contaminants into the source and fate aspects of the experiments. It is anticipated that the inclusion of actual contaminants in validation studies will entail some degree of modification to D-CORMIX. However, it should be possible to accomplish this with a limited number of added "modules", each containing process and reaction-level mechanisms relevant to the contaminant/sediment/water classes of interest. In this way, the 'rule-based' classification approach of D-CORMIX can be used to include contaminant partitioning behavior classes.

3.4.4 Need for Field Validation

It must be remembered that without adequate calibration during development and subsequent real-world validation, all models remain as cartoons of reality subject to speculation and challenge. Validation against laboratory systems is an important step but it does not carry the full validation that comparison with a real-world receiving water ecosystem would afford. To be effective, any model must be calibrated during its development using real-world data to ensure that all inputs are realistic and based on actual performance of natural systems. Once the model is assembled, its outputs must then be validated against real-world ecosystem behavior to ensure the accuracy of its calculated outputs. A small-scale field program with intensive monitoring of sediment behavior and plume dynamics is needed to validate the D-CORMIX model.

3.5 Charge Question #5 - What factors should be considered in developing an allocated impact zone (AIZ) that will not adversely impact the integrity of the aquatic ecosystem? How should the AIZ be sized, especially in relation to distance from the bottom (substrate), and portion of water column encompassed?

CORMIX model objectives clearly state the desire to model the behavior of dissolved and particulate components within discharge plumes. However there is no provision to model the all important sorption kinetics of organics or other dissolved chemicals which are essential to properly define mixing zones. There is little value in considering merely the physical transport of particles if we have no means to consider the sorption kinetics and effects on bioavailability of the sorbed chemicals on the particle surface. Provisions must be incorporated to model this key aspect of environmental partitioning before results of CORMIX models can be extrapolated to real-world ecosystems.

Continued use of mixing zones as allocated impact zones (AIZs) is supported. Additionally, the Subcommittee supports Agency efforts to define and model AIZs as they may exist under different conditions. Current practices at the state level often results in designation of AIZs that are not well defined and which do not consider (measure/estimate) risk to aquatic species or humans.

Looking to the future, the Subcommittee recommends that Agency guidance on mixing zones be developed using a risk based approach consistent with EPA risk assessment guidelines. Additionally, the development and application of the CORMIX models for the delineation of mixing zones needs to consider how the resultant data would ultimately be used to reach or support conclusions from a human or ecological risk assessment. Currently the program reads as though "we will expend all these resources to develop a model and then we'll give it to the risk assessors and see if they can use it." Obviously this is not a productive sequence and the modelers would be well served to incorporate risk assessment experts into the model development phase to maximize the ultimate application of the results. Additionally, we recommend that the following be considered in developing AIZs/AIZ guidance:

a) dynamics of site conditions;

b) organisms of interest at a given site with emphasis on keystone species, commercial species, and endangered species; and

c) physical/chemical properties (sorption, hydrolysis, volatilization, etc.) of the chemical under review.

Generalizations on AIZs are difficult because site specific conditions often dominate. Some generalizations include the following: the AIZ should be relatively small to avoid population effects, and the AIZ should not limit migratory species (zone of passage should be protected). Generalizations about the AIZ in relation to the distance above the bottom is difficult. Important considerations include aerial extent, species present, and depth and width of the negatively buoyant zone. The particular species that are potentially effected by a negatively buoyant effluent should be considered. As a general rule, organisms with a short reproductive cycles (amphipods, oligochaetes, polychaetes, etc.) will recolonize an area much more rapidly than those with longer reproductive cycles (clams, mussels, bottom fish) and therefore, would require less protection. Additionally, consideration should be given to the potential for avoidance of the chemical(s) in the negatively buoyant effluent by mobile organisms such as bottom fish

Appendix A - Potential Deficiencies in original CORMIX Model that are incorporated into D-CORMIX

One of the Subcommittee members had access to several laboratory data sets (See end of this appendix for references) and simulated these using both the CORMIX and D-CORMIX models (properly accounting for the issue associated with positive or negative buoyancy as required by the particular model). A comparison of the simulations led to the following conclusions:

a) In most situations, the models performed relatively well in predicting dilutions and plume dimensions observed in the experiments. In general, the models appeared to under-predict the observed dilution, but the differences were not generally significant.

b) In cases where vertical density gradients were present in the ambient fluid of sufficient magnitude to trap the plume within the water column, a number of discrepancies were noted. The models generally predicted dilution within the jet/plume region fairly well with a tendency to slightly under-predict the dilution as noted above. However, the plume then spreads as an internal density current. Early versions of CORMIX tended to severely over-estimate the collapse of the density current plume resulting in an layer that was much thinner and wider than observed in experiments. Subsequent versions of CORMIX rectified this problem to some extent by introducing wind and bottom shear induced mixing. The subsequent dilution reduced the lateral spreading forces and therefore the plume collapse. However, the laboratory experiments involved stagnant ambient fluids with no wind or shear induced turbulence and inclusion of these mechanisms to improve model agreement is not appropriate (Wright, 1977). It appears that the magnitude of lateral spreading forces has been over-estimated in the models and therefore CORMIX or D-CORMIX may not provide accurate simulations for these cases.

c) Comparison of data in which plumes impinge directly on a boundary indicates that the model underestimates the dilution in the initial layer spreading along the surface. The reasons for this are clear; the study of Wright et al. (1991) indicate a significant dilution associated with the initial phase of the horizontal spread of the impinging flow while CORMIX and D-CORMIX do not generally consider any mixing within this region. This is more significant in the case of weak ambient current and/or shallow water depths where the sinking plume impinges nearly normal to the bounding surface. Differences between model predictions and experimental observations can be several hundred percent in this cases. The significance of these deviations within the context of an entire mixing zone analysis has yet to be determined.

Appendix A - Data Source References:

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AN SAB REPORT: REVIEW OF THE D-CORMIX MODEL

PREPARED BY THE D-CORMIX REVIEW SUBCOMMITTEE OF THE SCIENCE ADVISORY BOARD