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Desalination and Water Purification Research and Development Program Report No. 132

# Systems Development for Environmental Impact Assessment of Concentrate Disposal – Development of Density Current Simulation Models, Rule Base, and Graphic User Interface

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This project developed hydrodynamic models to simulate the mixing of point source concentrate discharges. The CORMIX system was modified to incorporate negatively buoyant surface (shoreline) discharge sources and models to simulate density current mixing along a sloping bottom. In addition, the CORMIX rule-base and interface was extended to include near-surface negatively buoyant single port and multiport diffuser sources. The methods and products developed by this project can be downloaded in free evaluation software from www.mixzon.com.

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**Prepared for Reclamation Under Agreement No. 04-FC-81-1061**

*by*

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# Glossary

**Actual Water Depth (HD) –** The actual water depth at the submerged discharge location. It is also called local water depth. For surface discharges, it is the water depth at the channel entry location.

**Alignment Angle (GAMMA) –** The angle measured counterclockwise from the ambient current direction to the diffuser axis.

**Allocated Impact Zone –** see mixing zone.

**Alternating Diffuser –** A multiport diffuser where the ports do not point in a nearly single horizontal direction.

**Ambient Conditions–** The geometric and dynamic characteristics of a receiving water body that impact mixing zone processes. These include plan shape, vertical cross sections, bathymetry, ambient velocity, and density distribution.

**Ambient Currents–** A velocity field within the receiving water which tends to deflect a buoyant jet into the current direction.

**Ambient Discharge (QA) –** The volumetric flow rate of the receiving water body.

**Average Diameter (D0) –** The average diameter of the discharge ports or nozzles for a multiport diffuser.

**Average Depth (HA) –** The average depth of the receiving water body determined from the equivalent cross-sectional area during schematization.

**Bottom Slope (SLOPE) –** The slope of the bottom that extends from a surface discharge into the receiving water body.

**Buoyant Jet –** A discharge where turbulent mixing is caused by a combination of initial momentum flux and buoyancy flux. It is also called a forced plume.

**Buoyant Spreading Processes –** Far-field mixing processes which arise due to the buoyant forces caused by the density difference between the mixed flow and the ambient receiving water.

**Buoyant Surface Discharge –** The release of a positively or neutrally buoyant effluent into a receiving water through a canal, channel, or near-surface pipe.

**Computer-Aided-Design (CAD) –** The use of computer-based tools that assist engineers, architects, scientists, and other design professionals in their professional design activities

**Coanda Attachment –** A dynamic interaction between the effluent plume and the water bottom that results from the entrainment demand of the effluent jet itself and is due to low-pressure effects.

**Cumulative Discharge –** Refers to the volumetric flow rate which occurs between the bank/shoreline and a given position within the water body.

**Cumulative Discharge Method –** An approach for representing transverse plume mixing in river or estuary flow by describing the plume centerline as being fixed on a line of constant cumulative discharge and by relating the plume width in terms of a cumulative discharge increment

**Darcy-Weisbach Friction Factor –** A measure of the roughness characteristics in a channel.

**Deep Conditions –** See near-field stability.

**Density Stratification –** The presence of a vertical density profile within the receiving water.

**Diffuser Length (LD) –** The distance between the first and last port of a multiport diffuser line. See diffuser line.

**Diffuser Line –** A hypothetical line between the first and last ports of a multiport diffuser.

**Discharge Velocity (U0) –** The average velocity of the effluent being discharged from the outfall structure.

**Discharge from Shore (DISTB) –** The average distance between the outfall location (or diffuser mid-point) and the shoreline. It is also specified as a cumulative ambient discharge divided by the product UA times HA.

**Distance from Shore (YB1, YB2) –** The distance from the shoreline to the first and last ports of a multiport diffuser.

**Discharge Flow Rate (Q0) –** The volumetric flow rate from the discharge structure.

**Discharge Channel Width (B0) –** The average width of a surface discharging channel.

**Discharge Channel Depth (H0) –** The average depth of a surface discharging channel.

**Discharge Conditions –** The geometric and flux characteristics of an outfall installation that effect mixing processes. These include port area, elevation above the bottom and orientation, effluent discharge flow rate, momentum flux, and buoyancy flux.

**Far-field –** The region of the receiving water where buoyant spreading motions and passive diffusion control the trajectory and dilution of the effluent discharge plume.

**Far-field Processes –** Physical mixing mechanisms that are dominated by the ambient receiving water conditions, particularly ambient current velocity and density differences between the mixed flow and the ambient receiving water.

**Flow Classification –** The process of identifying the most appropriate generic qualitative description of the discharge flow undergoing analysis. This is accomplished by examining known relationships between flow patterns and certain calculated physical parameters.

**Flux Characteristics –** The properties of effluent discharge flow rate, momentum flux, and buoyancy flux for the effluent discharge.

**Forced Plume –** See buoyant jet.

**Generic Flow Class –** A qualitative description of a discharge flow situation that is based on known relationships between flow patterns and certain physical parameters.

**GUI –** Graphic user interface.

**Height of Port (H0) –** The average distance between the bottom and the average nozzle centerline.

**High Water Slack (HWS) –** The time of tidal reversal nearest to MHW.

**Horizontal Angle (SIGMA) –** The angle measured counterclockwise from the ambient current direction to the plane projection of the port center line.

**Hydrodynamic Mixing Processes –** The physical processes that determine the fate and distribution of effluent once it is discharged.

**Input Data Tab –** A group of input forms with questions from one of six topical areas.

**Intermediate-field Affects –** Induced flows in shallow waters which extend beyond the strictly near-field region of a multiport diffuser.

**Iteration Menu –** The last menu (red panel) the user can choose after completion of a design case; allows iteration with different ambient/discharge/regulatory conditions.

**Jet –** See pure jet.

**Laterally Bounded –** A water body which is constrained on both sides by banks such as rivers, streams, estuaries, and other narrow water courses.

**Laterally Unbounded –** A water body which, for practical purposes, is constrained on, at most ,one side. This would include discharges into wide lakes, wide estuaries, and coastal areas.

**Legal Mixing Zone (LMZ) –** See regulatory mixing zone.

**Length Scale –** A dynamic measure of the relative influence of certain hydrodynamic processes on effluent mixing.

**Length Scale Analysis –** An approach which uses calculated measures of the relative influence of certain hydrodynamic processes to identify key aspects of a discharge flow so that a generic flow class can be identified.

**Local Water Depth (HD) –** See actual water depth.

**Low Water Slack (LWS) –** The time of tidal reversal nearest to MLW

**Main Menu –** The first menu (red panel) the user can choose from when entering CORMIX.

**Manning's n –** A measure of the roughness characteristics in a channel.

**Maximum Tidal Velocity (Uamax) –** The maximum velocity occurring within the tidal cycle

**Mean Ambient Velocity (UA) –** The average velocity of the receiving water body's flow.

**Mean High Water (MLW) –** The highest water level (averaged over many tidal cycles) in estuarine or coastal flows.

**Mean Low Water (MLW) –** The lowest water level (averaged over many tidal cycles) in estuarine or coastal flows.

**Merging –** The physical interaction of the discharge plumes from adjacent ports of a multiport diffuser.

**Mixing Zone –** An administrative construct which defines a limited area or volume of the receiving water where the initial dilution of a discharge is allowed to occur. In practice, it may occur within the near-field or far-field of a hydrodynamic mixing process and, therefore, depends on source, ambient, and regulatory constraints.

**Mixing Zone Regulations –** The administrative construct that intends to prevent any harmful impact of a discharged effluent on the aquatic environment and its designated uses.

**Momentum Jet –** See pure jet.

**Multiport Diffuser –** A structure with many closely spaced ports or nozzles that inject more than one buoyant jet into the ambient receiving water body.

**Near-field –** The region of a receiving water where the initial jet characteristic of momentum flux, buoyancy flux, and outfall geometry influence the jet trajectory and mixing of an effluent discharge.

**Near-Field Region (NFR) –** A term used in the CORMIX printout for describing the zone of strong initial mixing where the so called near-field processes occur. It is the region of the receiving water where outfall design conditions are most likely to have an impact on instream concentrations.

**Near-field Stability –** The amount of local recirculation and re-entrainment of already mixed water back into the buoyant jet region. Stable discharge conditions are associated with weak momentum and deep water and are also sometimes called deep water conditions. Unstable discharge conditions have localized recirculation patterns and are also called shallow water conditions.

**Negative Buoyancy –** The measure of the tendency of an effluent discharge to sink in a receiving water.

**Nonbuoyant Jet –** See pure jet.

**NPDES –** National Pollutant Discharge Elimination System.

**Open Format –** Data input which does not require precise placement of numerical values in fixed fields and which allows character strings to be entered in either upper or lower case letters.

**Passive Ambient Diffusion Processes –** Far-field mixing processes which arise due to existing turbulence in the ambient receiving water flow.

**Plume –** See buoyant jet.

**Positive Buoyancy –** The measure of the tendency of an effluent discharge to rise in the receiving water.

**Post-Processor –** Several options available within CORMIX (main menu or iteration menu) for additional computation or data display, including a graphics package, a near-field buoyant jet model, and a far-field plume delineator.

**Pure Jet –** A discharge where only the initial momentum flux in the form of a high velocity injection causes turbulent mixing. It is also called momentum jet or nonbuoyant jet.

**Pure Plume –** A discharge where only the initial buoyancy flux leads to local vertical accelerations which then lead to turbulent mixing.

**Pycnocline –** A horizontal layer in the receiving water where a rapid density change occurs.

**Pycnocline Height (HINT) –** The average distance between the bottom and a horizontal layer in the receiving water body where a rapid density change occurs.

**Region of Interest (ROI) –** A user defined region of the receiving water body where mixing conditions are to be analyzed.

**Regulatory Mixing Zone (RMZ) –** The region of the receiving water where mixing zone regulations are applied. It is sometimes referred to as the legal mixing zone.

**Relative Orientation Angle (BETA) –** The angle measured either clockwise or counterclockwise from the average plan projection of the port centerline to the nearest diffuser axis.

**Schematization –** The process of describing a receiving water body's actual geometry with a rectangular cross section.

**Shallow Water Conditions –** See near-field stability.

**Stable Discharge –** See near-field stability.

**Staged Diffuser –** A multiport diffuser where all ports point in one direction, generally following the diffuser line.

**Stagnant Conditions –** The absence of ambient receiving water flow. A condition which rarely occurs in actual receiving water bodies.

**Submerged Multiport Diffuser –** An effluent discharge structure with more than one efflux opening that is located substantially below the receiving water surface.

**Submerged Single Port Discharge – An** effluent discharge structure with a single efflux opening that is located substantially below the receiving water surface.

**Surface Buoyant Jets –** Positively or neutrally buoyant effluent discharges occurring horizontally at the water surface from a latterly entering channel or pipe.

**Surface Width (BS) –** The equivalent average surface width of the receiving water body determined from the equivalent rectangular cross-sectional area during schematization.

**Tidal Cycle –** The variation of ambient water depth and velocity as a function of time occurring due to tidal (lunar and solar) influences.

**Tidal Period (PERIOD) –** The duration of the tidal cycle (on average 12.4 hours).

**Tidal Reversal –** The two instances in the tidal cycle when the ambient velocity reverses its direction.

**Toxic Dilution Zone (TDZ) –** The region of the receiving water where the concentration of a toxic chemical may exceed the acute effects concentration.

**Unidirectional Diffuser –** A multiport diffuser with all ports pointing to one side of the diffuser line and all ports oriented more or less normally to the diffuser line.

**Unstable Discharge –** See near-field stability.

**Vertical Angle (THETA) –** The angle between the port centerline and the horizontal plane.

**Wake Attachment –** A dynamic interaction of the effluent plume with the bottom that is forced by the receiving water crossflow.

**Zone of Initial Dilution –** A term sometimes used to describe the mixing zone for the discharge of municipal wastewater into the coastal ocean, limited to the extent of near-field mixing processes.

**Zone of Flow Establishment (ZOFE)** – The region after discharge where the velocity distribution of the discharge changes from an internal flow velocity flow profile (logarithmic) distribution to a free jet flow (Gaussian).

# List of Symbols (All Units M-K-S)

$b_h$ = plume horizontal half-width (m)

$b_v$ = plume vertical thickness (m)

$c_c$ = plume centerline concentration at downstream location

$c_0$ = initial discharge concentration

$C_D$ = drag coefficient

D = discharge opening diameter (m)

E = total plume entrainment ($m^3$)

$E_f$ = frontal entrainment from perpendicular advancement of plume edge ($m^3$)

$E_h$ = horizontal entrainment due to forward plume motion ($m^3$)

$E_i$ =I nterfacial entrainment from combined velocity sources ($m^3$)

$E_p$ = advected puff entrainment rate ($m^3$)

$E_v$ = vertical entrainment due to forward plume motion ($m^3$)

$f_1$ = near shore Darcy friction factor

$f_2$ = far-field Darcy friction factor

$f_b$ = density current bottom Darcy friction factor

$f_u$ = distribution function of axial velocity

$f_s$ = distribution function of scalar tracer

$F_B$ = buoyancy force per unit length ($kg/s^2$)

$F_D$ = drag force per unit length ($kg/s^2$)

$F_e$ = entrainment force per unit length ($kg/s^2$)

$F_p$ = pressure force acting in axial direction ($kg/s^2$)

$F_r$ = Froude number

$F_t$ = bottom friction shear stress per unit length

g = gravitational acceleration

g' = reduced gravitational acceleration due to density difference = $g(\rho_a - \rho_o)/ \rho_a$ ($m/s^2$)

$g_c$' = reduced gravitational acceleration due to density difference at centerline ($m/s^2$)

$\eta_h$ = normalized horizontal width (m)

$\eta_v$ = normalized vertical thickness

J = discharge buoyancy flux ($m^4/t^3$)

M = discharge momentum flux ($m^4/t^2$)

Q = total discharge volume flux ($m^3/t$)

$R_i$ = flux Richardson number

$r_h$ = horizontal radius (m)

$r_v$ = vertical radius (m)

s = centerline trajectory distance (m)

S = dilution

$s_1$ = near shore bottom slope (deg)

$s_2$ = far-field bottom slope (deg)

$v_B$ = lateral velocity of density current front (m/s)

$v_f$ = frontal spreading velocity (m/s)

$u_1$ = near-shore ambient velocity (m/s)

$u_2$ = far-field ambient velocity(m/s)

$u_a$ = ambient velocity (m/s)

$u_c$ = plume centerline velocity (m/s)

$u_{*w}$ = wind shear velocity (m/s)

$w_j$ = settling velocity for particle size j (m/s)

x = downstream coordinate (m)

y = lateral coordinate (m)

z = vertical coordinate (m)

$\alpha_{Q1}$ = integration constant for discharge

$\alpha_{Q2}$ = integration constant for discharge

$\alpha_{M1}$ = integration constant for momentum

$\alpha_{M2}$ = integration constant for momentum

$\alpha_{S1}$ = integration constant for scalar

$\alpha_{S2}$ = integration constant for scalar

$\alpha_h$ = horizontal plume entrainment coefficient

$\alpha_v$ = vertical plume entrainment coefficient

$\beta$ = frontal plume entrainment coefficient

$\theta_0$ = discharge vertical angle between port centerline and horizontal plane (deg)

$\theta_b$ = angle of ambient bottom slope (deg)

$\rho_a$ = ambient density at discharge level ($kg/m^3$)

$\rho_o$ = discharge density ($kg/m^3$)

$\rho_{as}$ = ambient density at water surface ($kg/m^3$)

$\rho_{a1}$ = ambient density at 1st submerged level ($kg/m^3$)

$\rho_{a2}$ = ambient density at 2nd submerged level ($kg/m^3$)

$\rho_{ab}$ = ambient density at channel bottom ($kg/m^3$)

$\sigma_0$ = discharge horizontal angle, plan projection of plume centerline with the horizontal plane (deg)

# 1. Executive Summary

This report details development of CORMIX desktop computer-aided-design (CAD) system to address the hydrodynamic, ecological, and regulatory issues associated with the fate and transport of desalination facility concentrate discharged into surface waters. The information systems described here improve the ecological impact assessment, regulatory management, and scientific prediction of concentrate behavior within the mixing zone, a limited region where the initial mixing and dilution of a concentrate discharge occurs.

In this project, the ***DHYDRO*** hydrodynamic simulation models, hydrodynamic classification rule base, and graphic user interface (GUI) were developed to enhance prediction and communication of environmental impacts associated within the hydrodynamic mixing zone to scientists, engineers, regulators, industry, and the public. This report describes state-of-the-art systems for hydrodynamic mixing process simulation, environmental impact visualization, regulatory risk assessment, and infrastructure design.

This 2-year project was completed at Portland State University. The project objective was to develop the CORMIX user interface, rule base classification, and hydrodynamic simulation models of the mixing zones specific to desalination facility concentrate discharges. This project continued and enhanced work previously completed on development of visualization tools for outfall design and mixing zone management.

# 2. Background

## 2.1 Problem Scenario and our Vision

A persistent drought grips a coastal community. A water utility seeks a permit to construct a desalination facility. However, the local fishing industry strongly objects. Most vocal are the oystermen, who fear that the concentrate waste disposed from the facility will adversely affect centuries-old harvest beds. However, regulators, plant designers, and the public have access to validated computer models and advanced visualization techniques. Simulations show that the saline discharge plunges quickly into a derelict shipping channel, and then is rapidly dispersed by a strong ambient current. Visualizations of the advanced multiport diffuser system designed for the facility illustrate the behavior of the concentrate plume to the public with easily understood graphic animations. These visualizations show in detail the plume first rising and then sinking to the bottom where it is quickly diluted to background levels long before contact with sensitive oyster beds. After the fishermen withdraw their objections, opposition soon eases and the desalination facility is permitted. Expanded freshwater supplies attract new business and industries to the area, strengthening the local economy.

This project expands the functionality of CORMIX. CORMIX is an U.S. Environmental Protection Agency (USEPA) approved simulation and decision support system for environmental impact assessment of mixing zones resulting from continuous point source discharges [1-29]. The enhancements to CORMIX developed in this project includes new methods for modeling the behavior of dense saline discharges. Desalination facilities typically produce dense concentrate discharges which are twice the salinity of the intake water.


Figure 1. Example of a wastewater outfall and shoreline plume boundary interaction. The wastewater plume contacts the shoreline and exhibits upstream density current buoyant spreading. Due to the shallow water discharge location, near-field instabilities with significant benthic and shoreline impacts are likely. (Photo by I. Wood).

The CORMIX system emphasizes the role of boundary interaction to predict mixing behavior and plume geometry. The methodology contains systems to model submerged single-port and multiport diffuser discharges as well as surface discharge sources. Effluents considered may be conservative, nonconservative, heated, or contain suspended sediments.

This project developed the advanced CORMIX hydrodynamic simulation systems specific to desalination concentrate disposal water quality modeling, regulatory decision support, and techniques for outfall specification and design optimization. Specifically, the surface negatively buoyant jet discharge model, the bottom density current simulation model, hydrodynamic rule base classification, and graphic user interface (GUI) were developed specifically to address issues associated with concentration disposal.

The user manual and free trial version of CORMIX is available from MixZon Inc. for Internet download after completing a site registration. After registration, a username and password is sent by e-mail reply. The first step to installing CORMIX on a computer is to install the free evaluation version. The latest software release contains new tools for mixing zone analysis, updated hydrodynamics, and mixing zone decision support. To print and save files, a commercial use license must be obtained. Licensing and pricing information is available at the MixZon Web site.

## 2.2 Project Objectives

The project objective was to develop the *graphical user interface*, *rule base flow classification system*, and *hydrodynamic simulation models and simulation tools* for mixing zone processes associated with concentrate disposal plumes.

Previous versions of CORMIX limited surface discharge sources to positively buoyant or neutrally buoyant discharges. This project extends the surface shoreline discharge option of CORMIX to include negatively buoyant sources like concentrate disposal. In addition, previous versions of CORMIX assumed a flat bottom in far-field density current behavior. The models developed by this project include the effect of a sloping bottom on density current far-field plume trajectory and mixing.

## 2.3 Technical Approach

The technical approach to concentrate disposal management focused on the development of desktop computer information systems for environmental impact assessment, regulatory compliance, and decision support for outfall design optimization. The CORMIX system uses the artificial intelligence technology of rule-based expert systems to provide a rigorous and comprehensive assessment of the initial mixing process to users who may possess only a limited background in physical science.

# 3. Conclusions and Recommendations

The result of this project is improved environmental management achieved by technology transfer through interactive simulation and decision support software. CORMIX can now simulate negatively buoyant surface discharges. The density current model developed in this project also can simulate negatively buoyant far-field plume behavior on a sloping bottom for single port, multiport, and surface discharge sources. This additional capability should be of great use to scientists, regulators, and engineers studying the environmental impacts of concentrate discharges.

Systems developed can be used by scientists to improve prediction techniques; by regulators to assess and manage risk; and finally by consultants, engineers, and the public to analyze impacts and optimize outfall design. The systems developed can have immediate and widespread application to several thousand desalination concentrate discharges worldwide. Developed techniques improve scientific prediction of mixing zone. Regulators can obtain enhanced scientific methods to analyze water quality impacts of mixing zones. The public benefits from the new techniques the system uses to simulate mixing from concentrate disposal. Since the same integrated software analysis tools can be used by all of these groups, communication among them about mixing phenomena, risk assessment, regulatory requirements, and design optimization will be improved.

A new user manual for CORMIX v5.0, which includes the enhancements described in this document, is available. The User Manual is free to the public and available for download at http://www.mixzon.com.

To further enhance the CORMIX system as a CAD tool, an internal multiport diffuser discharge hydraulic calculation program needs to be added to the system. Multiport diffusers are the current best practice to mitigate point source near-field impacts from wastewater disposal. Currently, CORMIX assumes a uniform line source for all multiport diffusers. CORMIX gives no details on pipe sizes, number of ports needed, or head losses within the diffuser outfall structure. New tools are needed to properly size pipes in multiport diffuser outfall structures to ensure that an even flow distribution is maintained across the diffuser line and to keep pipe material costs to a minimum.

This project produced improved decision support to almost 4,000 CORMIX mixing zone model users worldwide. The developed techniques provide regulators and the public with the tools to understand mixing processes and to mitigate impacts of concentrate disposal.

In summary, this project:

- Enables scientists to improve hydrodynamic mixing zone prediction of concentrate waste disposal.
- Supports regulators in management of concentrate discharges within the NPDES permit system.
- Produces new methods which enhance the ability of regulators to communicate with the public about environmental impacts associated with concentrate disposal.

# 4. Characterization of Concentrate Mixture

The concentrate or reject will be treated as a single-phase liquid for mixing zone simulation. Desalination reject may contain twice the concentration in the original feedwater of dissolved metals. The reject may also contain dissolved chemicals used in the pretreatment of the feed water, including low concentrations of anti-scalants, surfactants, and acid. Constituents of the concentrate can be specified as conventional, nonconventional, or toxic under National Pollutant Discharge Elimination System (NPDES) permit regulations. Characterization of three types of pollutant constituents within the concentrate is considered for simulation systems development:

**(a) Conservative Pollutant:** The pollutant does not undergo any decay/growth processes within the mixing zone.

**(b) Nonconservative Pollutant:** The pollutant undergoes a first order decay or growth process within the mixing zone. One needs to specify the coefficient of decay *k* (positive number) or growth (negative number) in units of $day^{-1}$ (per day) and elapsed time *t* since discharge as:

$$c = c_0 e^{-kt} \qquad \text{(Eq. 1)}$$

**(c) Heated Discharge:** The discharge experiences heat loss to the atmosphere in cases where the plume contacts the water surface. It is necessary to specify the discharge condition in terms of excess temperature ("delta T") above ambient in units degrees Celsius ($^oC$), and the surface heat exchange coefficient in units $W/m^2$ per $^oC$. Values of the heat exchange coefficient depend on ambient water temperature and wind speed and will be supplied to the user at data entry time.

The hydrodynamic simulation models and graphics provide a prediction of the physical dilution S defined as

$$S = \frac{c_0}{c} \qquad \text{(Eq. 2)}$$

where $c_0$ is the initial constituent concentration and c is the concentration within the plume at a given point downstream.

## 4.1 Development of Integral Modeling Methods for Shoreline Concentrate Disposal

For coastal desalination, typically concentrate will be disposed as a shoreline surface discharge. Therefore, to improve the simulation modeling of mixing concentrate discharges, new jet integral techniques were developed for shoreline concentrate disposal as a negatively buoyant surface jet.

The objective of any surface jet analysis is the determination of the jet trajectory x(s), y(s), the local angle $\sigma(s)$, along with the distributions $f_u(r_h, r_v)$ for the local axial velocity *u* and $f_s(r_h, r_v)$ for the local scalar quantities $g'$ and *c*, respectively (*s* is the distance along the trajectory, and $r_h, r_v$ are local transverse and vertical coordinates). The classical jet integral method goes a step further: the distribution functions $f_u$ and $f_s$ are specified *a priori* and cease to be an object of analysis (see Jirka, 2004).

Here, a modified approach is used that describes the gradual evolution of the normalized distribution functions

$$u = u_c f_u(\eta_h, \eta_v) + u_a \cos\sigma,\; g' = g'_c f_s(\eta_h, \eta_v),\; c = c_c f_s(\eta_h, \eta_v) \qquad \text{(Eq. 3)}$$

in which $u_c$ is the excess axial velocity, $g'_c$ the buoyancy, and $c_c$ the concentration, all on the carline, $\eta_h = r_h / b_h$, $\eta_v = r_v / b_v$, and $b_h$ and $b_v$ are the horizontal jet half-width and vertical jet width (depth), respectively. Following the basic transition model of Jirka (1982) the local influence of the buoyant perturbation mechanism on these functions is given by a local Froude number, or its squared inverse, a local bulk Richardson number

$$F_l = \frac{u_c + u_a \cos\sigma}{(g'_c b_v \cos\theta)^{1/2}}, \quad R_i = \frac{g'_c b_v \cos\theta}{(u_c + u_a \cos\sigma)} \qquad \text{(Eq. 4)}$$

in which $u_c + u_a \cos\sigma$ is the total velocity along the jet trajectory. The functional transition is such that the profiles undergo a full change from Gaussian profiles for jet-like $Ri \to 0$, to top-hat profiles for plume-like, $Ri \to \infty$, conditions, respectively. An exponential decay term, as suggested by Jirka (1982), is used here.

The jet integral method proceeds by using the boundary-layer nature of the flow and by integrating all terms ( ) of the governing turbulent Reynolds equations of motion (not stated herein) across the cross-sectional plane, $\iint (\;)\, dr_h dr_v$. A system of simple ordinary differential equations is the resulting major advantage of this procedure. The same convention as in Jirka (2004) is used as regarding the limits of integration, namely for the jet-like stage that the crossflow contribution in the Gaussian profiles is limited by $\sqrt{2}b_h$ and $\sqrt{2}b_v$, respectively.

The following integral quantities (bulk variables) result from this integration: the total volume flux within the turbulent zone Q, axial momentum flux M, buoyancy flux J, and tracer mass flux $Q_c$,

$$Q = 2b_h b_v (a_{Q1}u_c + a_{Q2}u_a \cos\sigma) \qquad \text{(Eq. 5)}$$

$$M = 2b_h b_v (a_{M1}u_c + a_{M2}u_a \cos\sigma)^2 \qquad \text{(Eq. 6)}$$

$$J = 2b_h b_v (a_{S1}u_c + a_{S2}u_a \cos\sigma)g_c' \qquad \text{(Eq. 7)}$$

$$Q_c = 2b_h b_v (a_{S1}u_c + a_{S2}u_a \cos\sigma)c_c \qquad \text{(Eq. 8)}$$

in which coefficients $a_{Q1}$ and $a_{Q2}$, $a_{M1}$ and $a_{M2}$, and $a_{S1}$ and $a_{S2}$, are the integration constants for discharge, momentum and scalars, respectively. These coefficients all contain an exponential dependence on the local Richardson number, equation (Eq.) 4, following the theoretical analysis of Jirka (1982). This has the result that, for the jet-like cases, the coefficients correspond to the values for Gaussian profiles; while for plume-like conditions, the values for top-hat profiles are attained. As an example, the coefficient $a_{Q1}$ with the jet profiles $(f_u = e^{-\eta_h \eta_v})$ takes on the value $\pi/4$, and the plume profiles ($f_u$ =1, for $\eta_h, \eta_v \le 1$; $f_u$ = 0, for $\eta_h, \eta_v > 1$) the value of 1. The Richardson number dependence, thus, simulates a gradual approach to a turbulent stratified equilibrium flow (Turner, 1972), even though that equilibrium is reached only asymptotically.

### 4.1.1 Conservation Equations and Turbulence Closure

Conservation equations for the flux quantities defined by equations 5 to 8 are formulated for a jet element of length *ds* centered on the trajectory. The usual assumptions are made (Jirka, 2004): 1) Turbulent pressure deviations from hydrostatic within the jet are neglected consistent with the boundary layer nature of the flow, 2) acceleration effects due to jet curvature are neglected, and 3) turbulent momentum and scalar fluxes can be considered proportional to the mean flux values.

The conservation principles for volume (continuity), momentum components in the global directions x and y, buoyancy, and scalar mass lead to the following equations

$$\frac{dQ}{ds} = E \qquad \text{(Eq. 9)}$$

$$\frac{d}{ds}\left[(M\cos\theta+F_p)\cos\sigma\right]=Eu_a+F_d\sqrt{1-\cos^2\theta\cos^2\sigma}-F_t\cos\theta\cos\sigma$$
(Eq. 10)

$$\frac{d}{ds}\left[(M\cos\theta+F_p)\sin\sigma\right]=-F_D\cos\sigma\frac{\cos^2\theta\sin\sigma}{\sqrt{1-\cos^2\theta\cos^2\sigma}}-F_t\sqrt{1-\cos^2\theta\cos^2\sigma}+F_b$$
(Eq. 11)

where θ = angle of bottom slope (a negative quantity)

$$\frac{dJ}{ds}=-k_s 2b_h g_c'$$
(Eq. 12)

$$\frac{dQ_c}{ds}=-k_D C_c$$
(Eq. 13)

The geometry of the trajectory is defined by:

$$\frac{dx}{ds}=\cos\sigma,\frac{dy}{ds}=\sin\sigma$$
(Eq. 14)

Another dynamic equation describes the global buoyant collapse of the jet cross-section as:

$$\frac{db_h}{ds}=k_{j,w}+\frac{v_f}{u_c}$$
(Eq. 15)

The buoyant pressure force $F_p$ term in the two momentum equations results from the cross-sectional integration over the buoyancy distribution

$$F_p=a_F b_h b_v^2 g_c'\cos\theta$$
(Eq. 16)

with the coefficient $a_F$ based on values from Jirka, 2005.

The above set of governing equations, 9 to 15 (with the supplemental Eq. 16) contains several terms that all relate to turbulent processes acting on the buoyant surface jet.

$$F_t=\frac{t_o}{4}b_h u_c\sqrt{u_c^{\,2}+u_a^{\,2}}$$

Note: $g_c'$ is negative, but θ is also negative!

(Eq. 17)

$$\mathrm{F_B}=2b_v b_h g_c'\sin\theta$$
(Eq. 18)

These are the rate of entrainment E, the ambient drag force $F_D$, and the frontal spreading velocity $v_f$. The force term $Eu_a$ in Eq. 10 is the entrainment of ambient momentum into the jet. The specification of these turbulent processes constitutes the "turbulence closer problem" in the integral formulation.

Turbulent entrainment E into the buoyant surface jet consists of several contributions $E = E_h + E_v + E_p + E_f + E_i$ that are modeled separately and become significant under specific flow conditions. The horizontal entrainment rate $E_h$ at the lateral jet periphery is given by:

$$E_h = 2a_1 b_v u_c \left( a_1 + a_3 \frac{u_a \cos\sigma}{u_c + u_a} \right) \qquad \text{(Eq. 19)}$$

where the two terms represent the nonbuoyant jet ($a_1$) and wake ($a_3$) mixing rates, defined by Jirka (2004), with $a_1 = a_3 = 0.055$. The vertical entrainment rate $E_v$ at the jet top reads similarly:

$$E_h = 2a_1 b_v u_c \left( a_1 + a_3 \frac{u_a \cos\sigma}{u_c + u_a} \right) \frac{1}{(1 + k_{Ri} Ri^{2.4})^{1/2}} \qquad \text{(Eq. 20)}$$

but includes a buoyant damping term with dependence on Ri. This damping formulation follows the model of Parker et al. (1987) for density current motions, with $k_{Ri}$ = 720. The advected puff entrainment rate $E_p$ in the strongly bent stage is another purely nonbuoyant entrainment mechanism:

$$E_p = 4a_{Q1} b_v u_a a_4 \left|\sin\sigma \cos\sigma\right| (b_v / b_h) \qquad \text{(Eq. 21)}$$

with the puff coefficient ($a_4$ = 0.5), given by Jirka (2004). The additional factor $(b_v / b_h)$ indicates its diminished importance in the collapsed plume stage. The frontal entrainment rate $E_f$ at the plume boundaries is a purely buoyant mechanism scaling with the front velocity $v_f$

$$E_f = 2\beta_f b_v v_f \left( 1 + \frac{u_a}{u_c} \cos\sigma \right) \qquad \text{(Eq. 22)}$$

taken from the model of Akar and Jirka (1994), with $\beta_f$ = 0.20. The latter work also gives the interfacial entrainment rate $E_i$ at the plume base as another buoyant mechanism that depends on wind-induced shear velocity $u_{*w}$, on an interfacial shear induced by the ambient flow component $u_a \sin\theta$, and on an interfacial shear induced by the front velocity $v_f$

$$E_i = 2\beta_I b_h \frac{1}{g_c' b_v} \left( \left( \frac{f_0 + f_a}{8} \right)^{3/2} (u_a (u_c + u_a \cos\theta \cos\sigma)^3 \sin\sigma)^3 + \frac{1}{4} \left( \frac{f_1}{8} \right)^{3/2} (1 + \frac{u_a}{u_c} \cos\sigma)^3 v_f^3 \right)$$

(Eq. 23)

in which $f_1$ is a quadratic-law interfacial friction factor and the coefficient $\beta_I$ = 0.23.

The ambient drag force $F_D$ is parameterized as a quadratic law force mechanism

$$F_D = c_D \sqrt{2} b_v \frac{u_a^2 \sin^2 \sigma}{2}$$

(Eq. 24)

in which $u_a \sin\sigma$ is the significant velocity component and $c_D$ the drag coefficient, with $c_D$ = 1.3 based on Jirka's (2004) detailed data analysis. The frontal spreading velocity $v_f$ is specified by the model of Akar and Jirka (1994)

$$v_f = u_c Ri \left( \frac{6b_v}{6c_{Df} b_v + (f_1 + f) b_h} \right)$$

(Eq. 25)

where $c_{Df} \cong 1.0$ is the frontal drag coefficient.

### 4.1.2 Solution Method and Initial Conditions: Zone of Flow Establishment (ZOFE)

The eight governing equations for flux conservation and jet geometry, Eqs. 9 to 16, together with the supplemental equations, Eqs. 20 to 25, describe the evolution of the eight jet variables, Q, M, J, $Q_c$, $b_h$, $\sigma$, x, y. The numerical solution of the equation system is carried out with a fourth-order Runge-Kutta algorithm within the program CorSurf that, in turn, is embedded in the expert system DHYDRO within CORMIX in-/output interfaces. The formulation given above uses essentially a flux-conservative formulation that minimizes the effect of potential singularities. The use of some of the local variables, such as $b_v$, $u_c$, and $g_c'$, cannot be avoided altogether. Supplemental relationships for these variables can be derived from the flux definitions.

Initial flow conditions are usually known at the channel efflux. The transition from that more or less uniform efflux section to a fully established jet flow that can be characterized by the approximately self-similar distribution functions, given by Eq. 3, takes place in the ZOFE. Considerable care must be taken for the ZOFE treatment of surface jets because of the large dimensions and/or low Froude number conditions of the discharge, that can cause major changes, especially when interacting with a cross-current. The following treatment uses modifications of the round jet ZOFE analysis [13, 14]. The ZOFE length $L_e$ and its final transverse angle $\sigma_e$ are

$$L_e = 8.0 L_Q (1 - 3.22 \sin\sigma_e / R) e^{-5/Fr_o^2} \quad \text{(Eq. 26)}$$

$$\sigma_e = \tan^{-1}\left(\frac{\sin\sigma_e}{\cos\sigma_e - (\sqrt{2}-1)/R}\right) \quad \text{(Eq. 27)}$$

in which the factor $e^{-5/Fr_o^2}$ describes the slumping effect of a low Froude number discharge. Furthermore, the initial slumping also affects the lateral width at the end of the ZOFE

$$b_{he} = 0.5 b_o + 0.5 L_e / Fr_{ch} \quad \text{(Eq. 28)}$$

in which the channel Froude number $Fr_{ch} = U_o / (g'_c h_c)^{1/2}$ is based on channel depth.

In summary, the eight starting values at the end of the ZOFE for the solution of the surface jet equation system are, for the geometry

$$\sigma_e, \quad x_e = L_e \cos\sigma_{ave} \ \ and \ \ y_e = L_e \sin\sigma_{ave} \quad \text{(Eq. 29)}$$

in which $\sigma_{ave} = (\sigma_o + \sigma_\varepsilon)/2$, and for the dynamic variables,

$$Q_e = \sqrt{2} Q_o, \quad M_e = M_o, \quad J_e = J_o, \quad Q_{ce} = Q_{co} \quad and \quad b_{he} \quad \text{(Eq. 30)}$$

respectively.

## 4.2 Software Design

The interactive and fully integrated software delivered employs object-oriented code for visual display, structured procedural code for hydrodynamic simulation, and rule-base logic code for model selection, simulation interpretation, regulatory assessment, and design optimization. The new GUI forms for data entry for concentrated are shown in appendix A.

The code developed in this project was developed with 32-bit Windows NT running on Pentium-IV engineering graphic workstations. Careful selection of graphic development tool libraries were undertaken to assure portability to Pentium based personal computers (PCs) as the intended runtime platform.

## 4.3 Significant Deliverables

A new CORMIX forms-based GUI for data entry of shoreline and near-surface concentrate discharges was developed by this project. Examples of the new GUI are shown in appendix A. The fully functional user GUI interface is contained in the CORMIX v5.0 software release. A fully functional free evaluation version of CORMIX and users manual can be downloaded at: http://www.mixzon.com/downloads/.

The free trial version does not print or save files; only commercial versions of CORMIX can print and save files in documented analysis. Licensing fees for software are published at the MixZon Web site, discounts are available for government and academic use.

A new rule-based hydrodynamic classification system for model selection of dense concentrate discharges was also developed in this project. The new rule base expands the CORMIX rule base from near-bottom single port and multiport diffuser discharges and extends it to include near-surface discharge configurations. Examples of the new rule base classification appear in appendix B.

Finally, a new DHYDRO FORTRAN simulation code based upon the surface negatively buoyant jet model development described previously herein, along with the bottom density current formulation given by Doneker (2004), was incorporated into the software delivered by this project.

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# Appendix A: CORMIX v5.0 Graphical User Interface

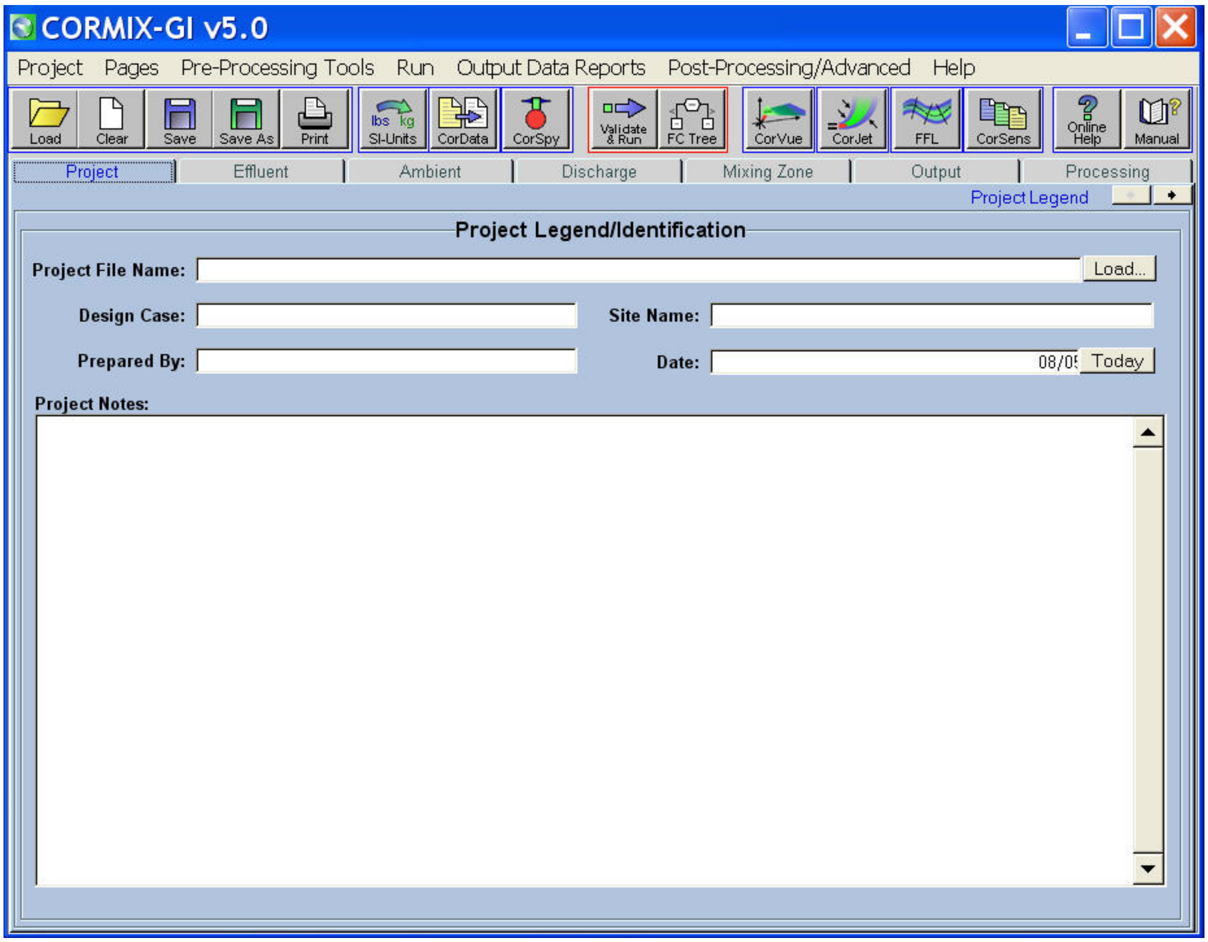


Figure A-1. The CORMIX v5.0 Graphical User Interface (GUI). In this version, the order of the input tabs is modified for a more logical specification of the discharge source. The "Effluent" tab now follows the "Project" tab because the specification of ambient and discharge properties is dependent on source characteristics.

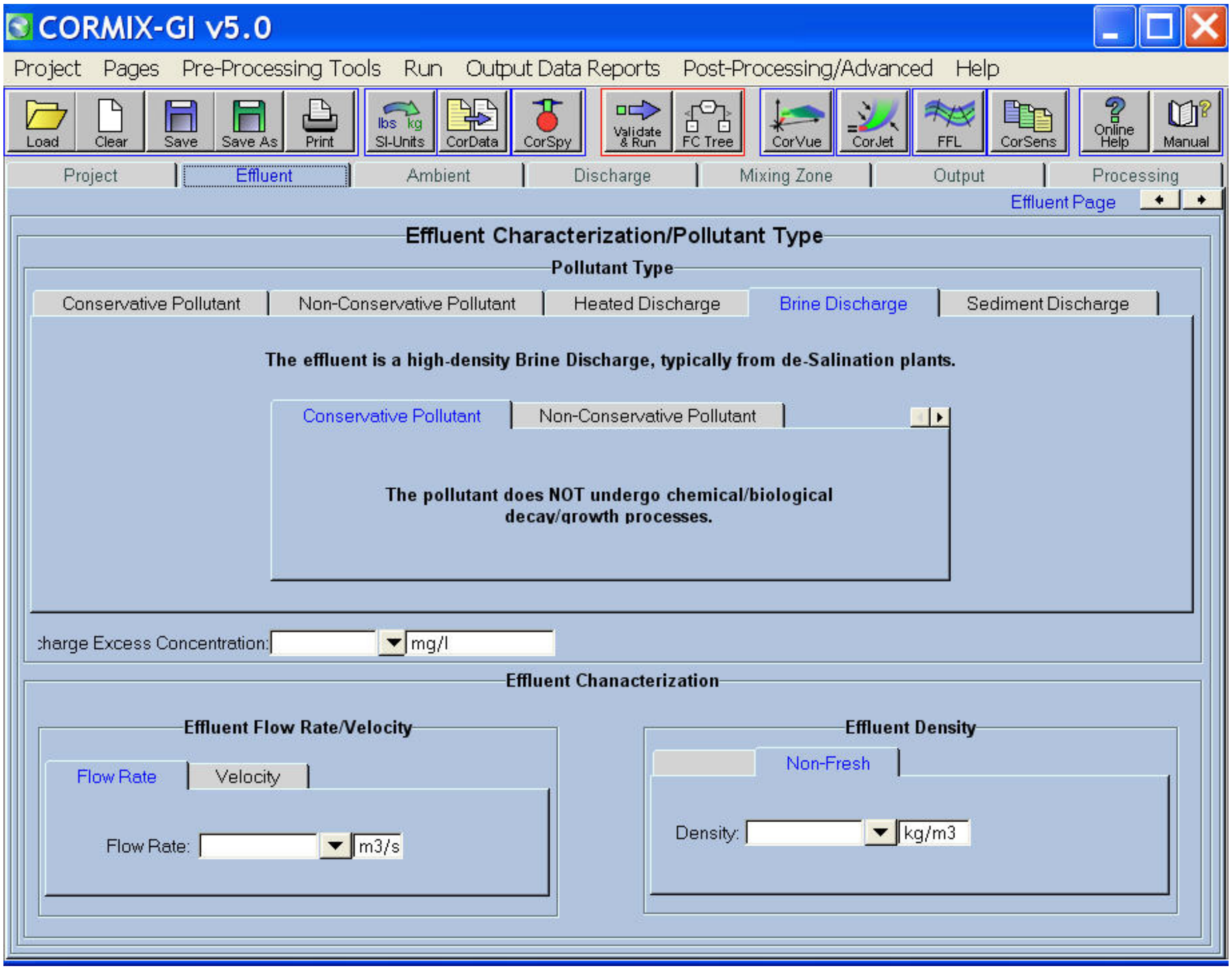


Figure A-2. The CORMIX v5.0 Effluent Tab. In this version, if a brine discharge is specified, then the input forms for ambient and discharge are modified to account for bottom density current behavior.

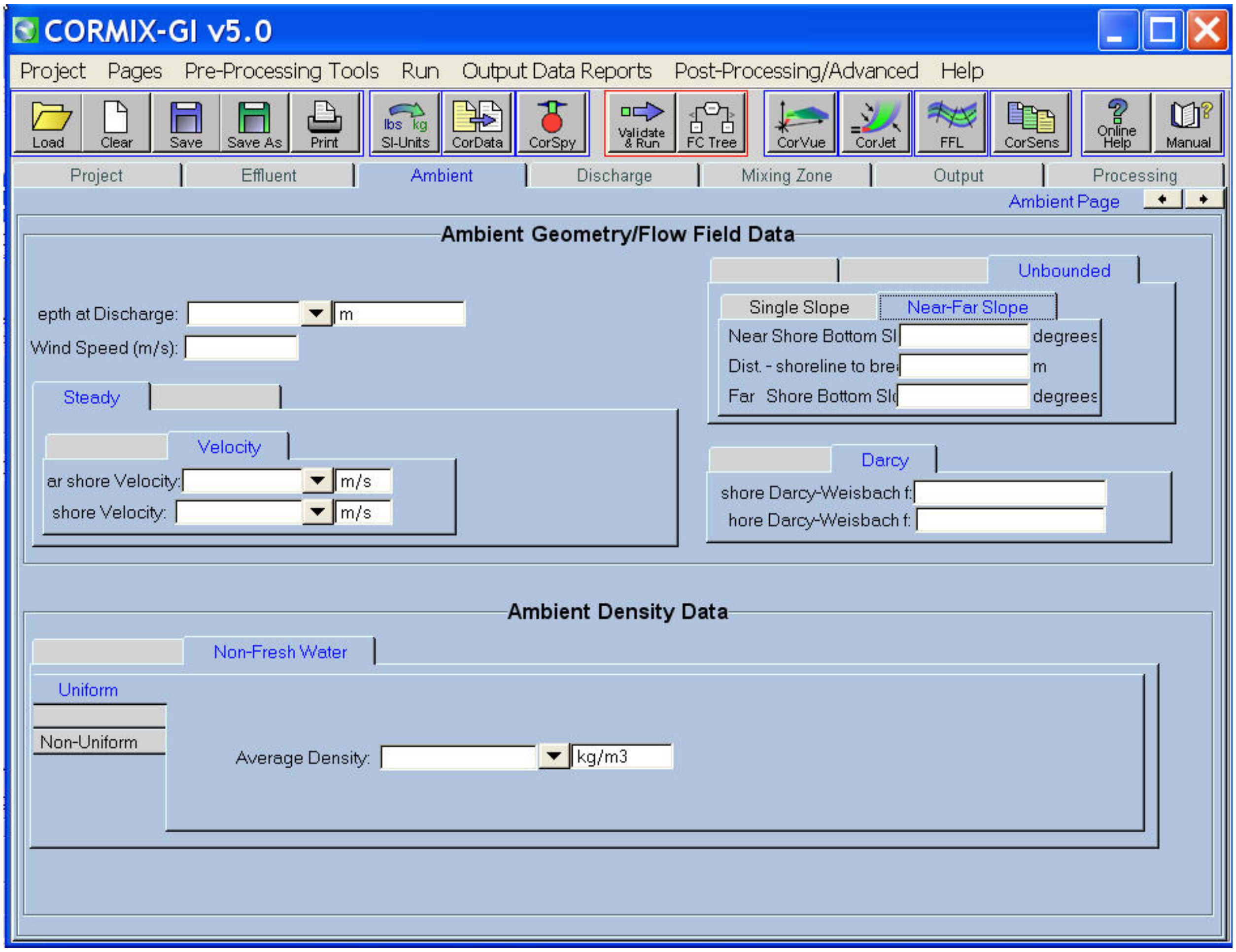


Figure A-3. The CORMIX v5.0 Ambient Tab. In this version, the ambient collects data about bottom bathymetry (local bottom slope) that will influence mixing zone behavior of concentrate discharges.

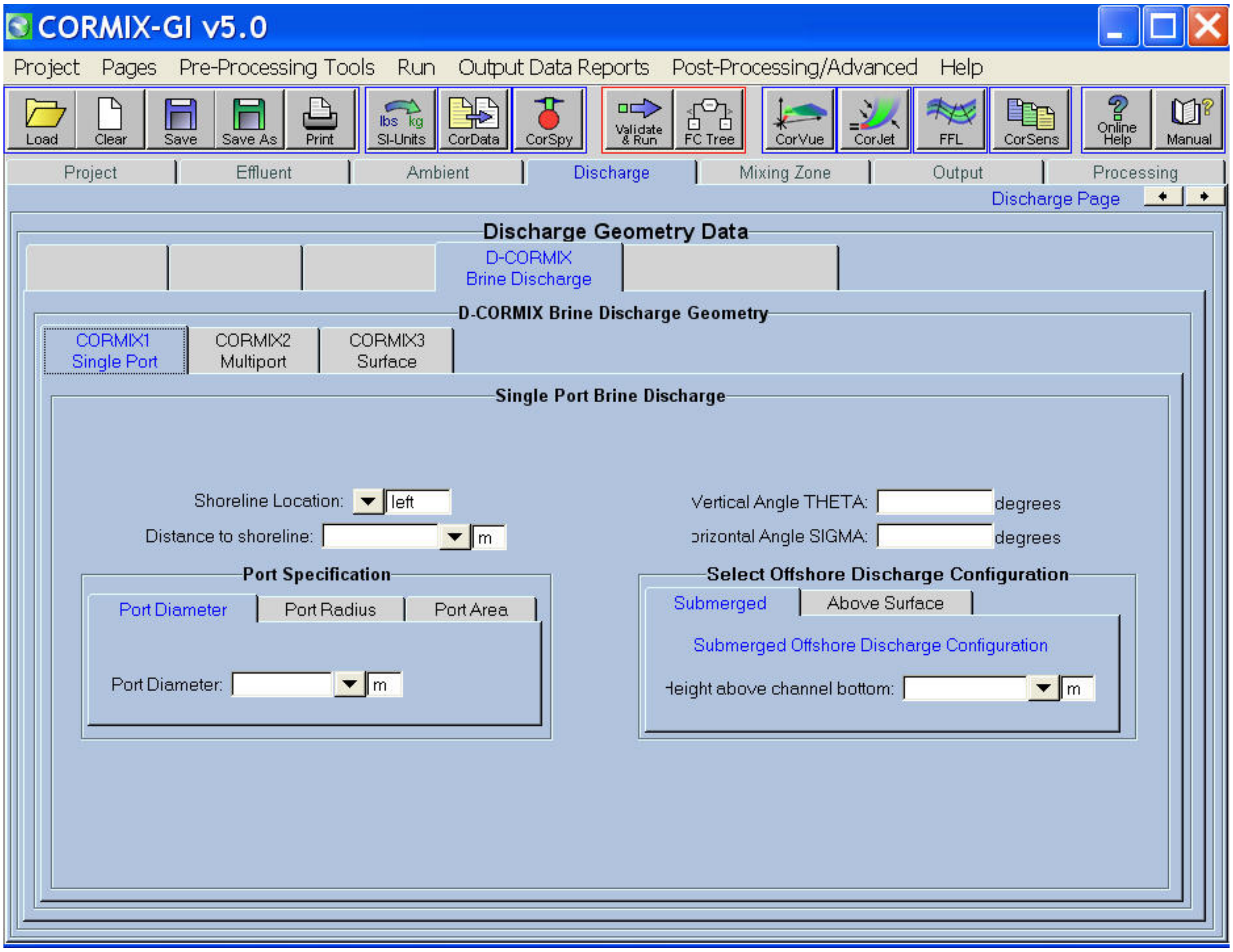


Figure A-4. The CORMIX v5.0 Discharge Tab. In this version, the discharge data includes both near-surface, above surface, and near-bottom discharge locations.

# Appendix B: CORMIX v5.0 Brine Classification System

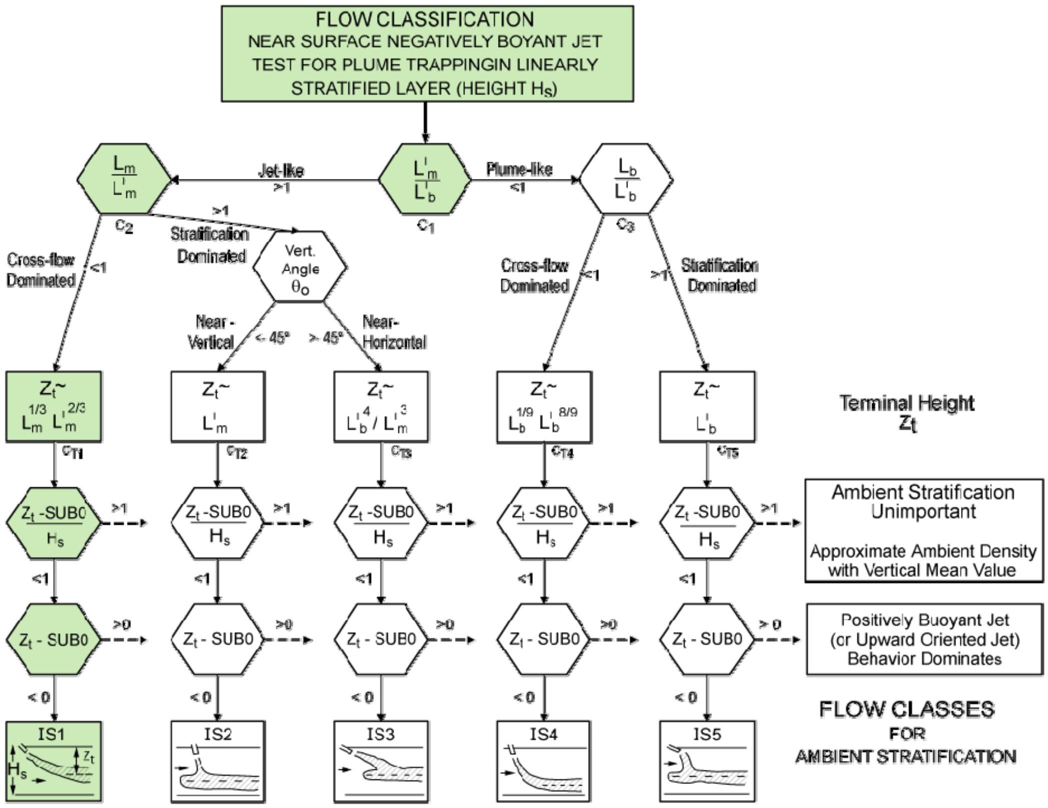


Figure B-1. The CORMIX v5.0 classification system for single-port, near-surface, negatively buoyant discharges into stratified ambient layers.

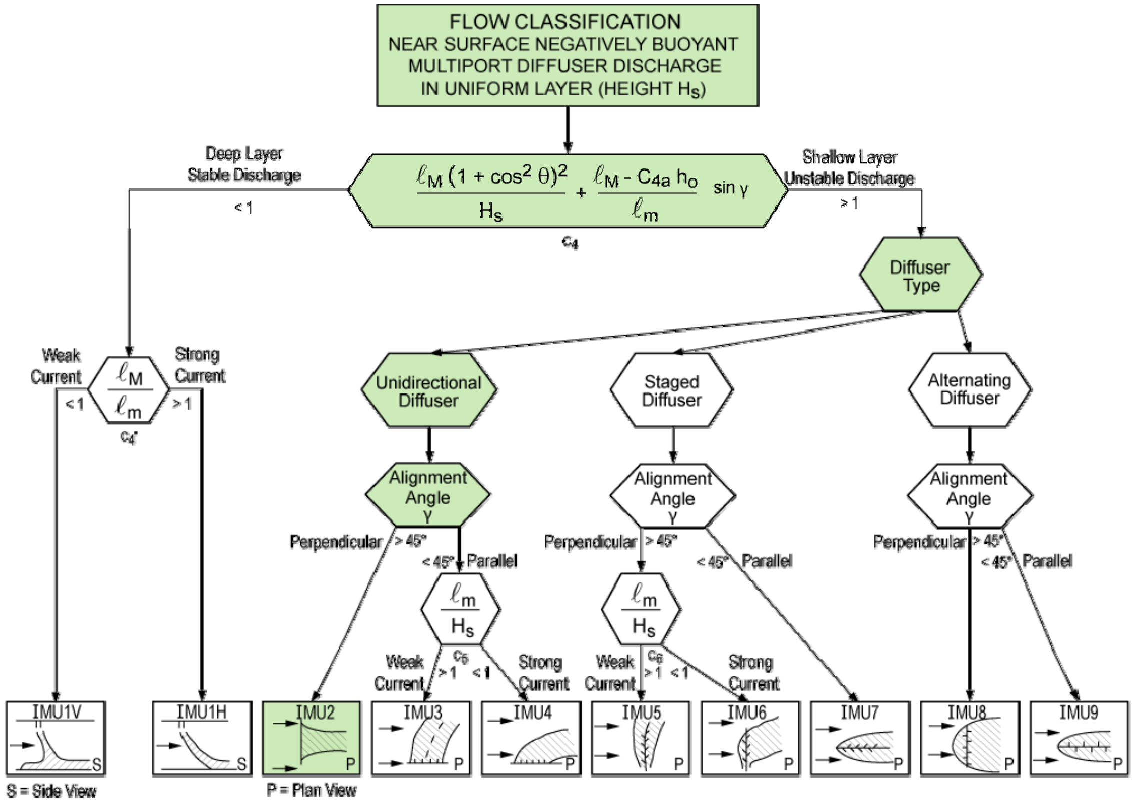


Figure B-2. The CORMIX v5.0 classification system for multiport, near-surface, negatively buoyant discharges into uniform ambient layers.

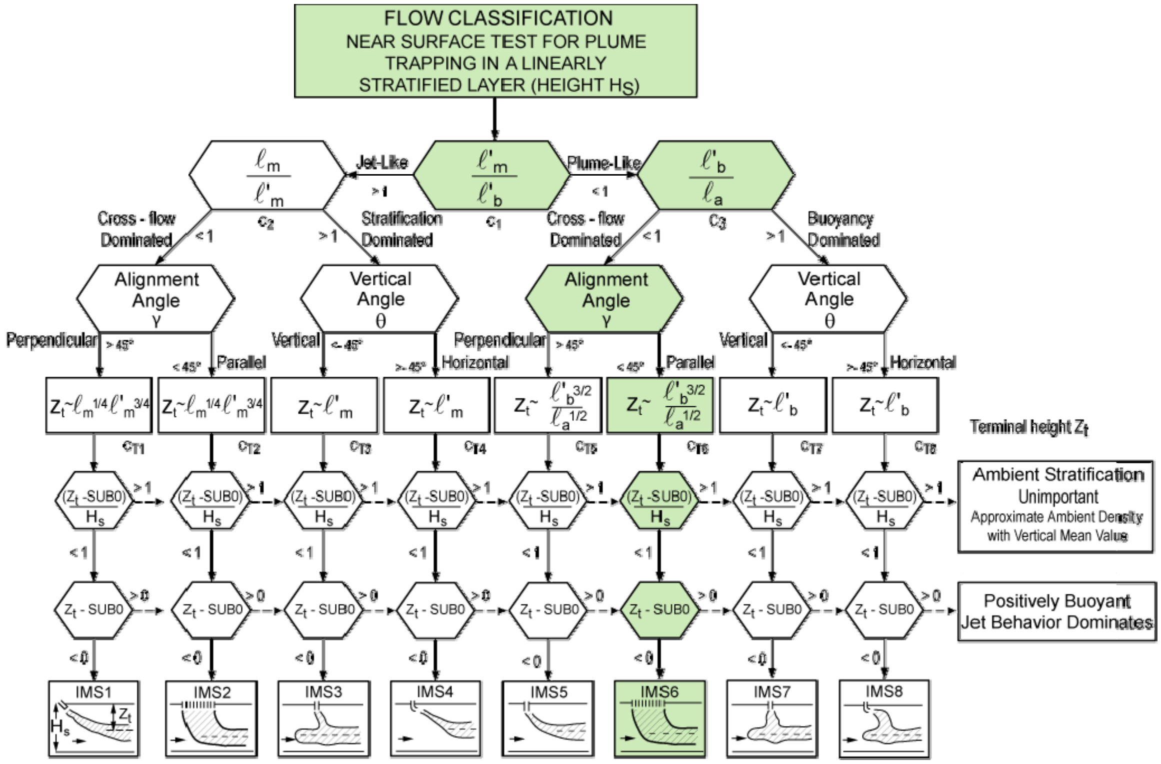


Figure B-3. The CORMIX v5.0 classification system for multiport, near-surface, negatively buoyant discharges into stratified ambient layers.

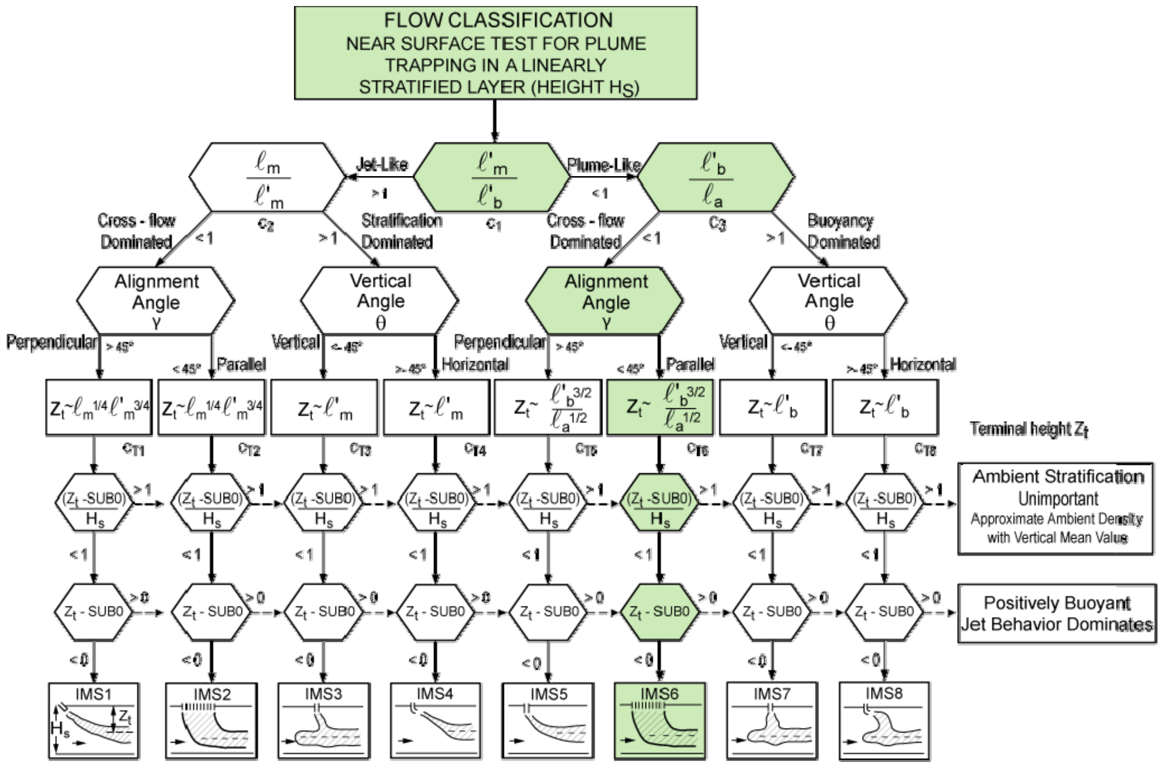


Figure B-4. The CORMIX v5.0 classification system for multiport, near-surface, negatively buoyant discharges into stratified ambient layers.