PLUMES2.0 – Dilution Model
Model Theory and User Manual

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PLUMES2.0
Model Theory and User Manual

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Acronyms and Abbreviations

AMZ	Acute Mixing Zone
CORMIX	A dilution model originally developed by Cornell University with EPA support
CMZ	Chronic Mixing Zone
CSTR	Continuously stirred tank reactor
DKHW	A multiport dilution model in the VP package based on original technical developments by Davis, Kannberg, and Hirst in the 1970s (Windows based)
FRFIELD	Farfield dilution model in the VP package based on Brooks' Laws
FVCOM	Finite Volume Community Ocean Model – a 3D hydrodynamic model
FVCOM-ICM	Salish Sea Model biogeochemical component based on CE-QUAL-ICM
GUI	Graphical User Interface
JETLAG	A Lagrangian dilution model of Lee et. al., from the University of Hong Kong
LCV	Lagrangian Control Volume
NPDES	National Pollution Discharge Elimination System
NRFIELD	Roberts, Snyder, and Baumgartner (RSB) dilution model in VP package
ORD	Office of Research and Development
PDSW	Prych, Davis, and Shirazi 3D plume model for Windows in VP package with the ability to accommodate surface discharge.
PLUMES	US EPA recommended package of dilution models for effluent discharges.
QA	Quality assurance
QAPP	Quality Assurance Project Plan
QC	Quality control
RMZ	Regulatory Mixing Zone
SI	International System of Units
SSMC	The *Salish Sea Modeling Center* at University of Washington
UM3	Three-dimensional version of UMERGE model which is part of the VP package
UMERGE	A two-dimensional effluent dilution model with plume merging
US EPA	United States Environmental Protection Agency
VP	Visual Plumes
ZID	Zone of Initial Dilution for a typical effluent plume

1 Executive Summary

The ability to conduct effluent fate and transport using standalone public domain software with a graphical user interface (GUI) is a core need of the National Pollutant Discharge Elimination System (NPDES) program. Visual Plumes (Frick et al., 2004) was a Windows and Pascal based computer application that provided tools for analysis of effluent fate and transport. Visual Plumes had superseded the DOS and Fortran based PLUMES (Baumgartner, Frick, and Roberts, 1994) mixing zone modeling system. Visual Plumes simulated single and merging submerged plumes in arbitrarily stratified ambient flow from buoyant submerged as well as surface discharges. Among its features were multiple dilution models, tidal pollutant build-up estimation, a sensitivity analysis capability, and a multi-stressor pathogen decay model. Visual Plumes offered a suite of dilution models including DKHW and UM3 models that are based on the original UDKHDEN and UM models (Muellenhoff et al., 1985), the surface discharge model PDS (Davis, 1999), the NRFIELD model based on RSB (Roberts et al., 1989 a,b,c) and the passive farfield transport and dilution of the wastefield using Brooks' laws (Brooks, N.H., 1969). The most widely used sub-model by default was UM3. Walter E. Frick, formerly from the US Environmental Protection Agency (US EPA) Office of Research and Development (ORD), was the last lead on Visual Plumes. Dr. Frick has since retired, and the Visual Plumes software became incompatible with the current version of the Windows operating system.

As part of unrelated US EPA funded research at the Pacific Northwest National Laboratory and Salish Sea Modeling Center (SSMC) at the University of Washington, a three-dimensional Lagrangian approach-based plume model (FVCOM-plume) was developed (Premathilake and Khangaonkar, 2019). The FVCOM-plume model written in Fortran includes an initial dilution module based on UM3 formulation. That imbedded initial dilution module accommodates multiport diffusers and its performance has been confirmed against Visual Plumes (UM3).

Subsequently, the US EPA, in collaboration with SSMC scientists, initiated this effort towards developing updated model software for simulating dilution of effluent from submerged outfalls. The overall goal was to develop, test, and release the new version of dilution modeling software (renamed PLUMES2.0) along with a User's Manual to US EPA and the user community for distribution. This release and the User's Manual represent the completion of Phase 1 of the development and testing of the software. Additional features and models may be added in subsequent phases based on user community response and needs. In PLUMES2.0, the initial dilution of the effluent, consisting of jet and buoyancy induced dynamic mixing of the effluent plume in the nearfield, is computed using the UM3 methodology. PLUMES2.0 then allows for analysis of plume fate following stabilization of the wastefield at the trapping depth when it is carried away by the ambient currents and further diluted by turbulence. This farfield transport of the wastefield and dilution is computed using Brooks laws (Brooks, N.H., 1969). Specifically, PLUMES2.0 includes (a) UM3 - initial dilution model, (b) Brook's Farfield model, and (c) a graphical user interface (GUI). The associated Model Theory and User Manual (this document) provides basic theory of effluent mixing and dilution principles, concept of mixing zones, and guidance for model use which may range from NPDES permitting to wastewater outfall diffuser design. The document includes step-by-step instructions for setting up the input files and is suitable for new users. We expect that experienced Plume modelers will be able to navigate the menus directly based on prior familiarity with Visual Plumes.

2 Introduction

2.1 Background

Wastewater from industrial and municipal facilities may contain pollutants that pose an ecological and/or human health risk. In recognition of the fact that natural mixing causes the concentration of pollutants to diminish in the receiving waters, regulatory agencies allow mixing zones in evaluating water quality compliance and exposure risk. A mixing zone is defined as a small region near the outfall where certain water-quality criteria can be exceeded as long as (a) there is no lethality to the organisms passing through the mixing zone, (b) there are no significant risks to human health, and (c) the designated and existing uses of the water body are not impaired (US EPA, 1991). Effluent discharges and mixing zones are authorized through the Clean Water Act: Section 402 (40 CFR Part 122) National Pollution Elimination System (NPDES) Permits. Water quality compliance for carcinogens and highly toxic substances is typically evaluated at the end of pipe. But for many pollutants, compliance is evaluated at the mixing zone boundaries after the completion of initial rapid mixing and dilution of the effluent with the surrounding waters. The allowable dimensions of mixing zones vary from state to state based on requirements in state water quality standards.

When two fluids carrying the same constituent but at different concentrations mix, the resultant concentration of the mixture is simply the volume averaged concentration. For example, if a concentrated effluent volume V_e (m³) at a concentration C_e (mg/L) is mixed with a volume V_a of clean water, the resulting concentration C_f after mixing may be simply expressed as $C_f = C_e/D$, where D is the volumetric dilution factor expressed as $D = (V_e + V_a)/V_e$ assuming that the ambient concentration C_a is zero. The effluent concentration after mixing is therefore regarded as being reduced by the dilution factor.

In realistic settings however, the ambient concentration is rarely zero. It must be accounted for to assess compliance with regulations. To do so, the concentration of the effluent constituent of concern is compared against the applicable water quality standard(s) C$_{wqs}$, after the completion of the dilution process within the allocated mixing zone. The constituent concentration in the water outside the mixing zone must remain below C$_{wqs}$. Water quality standards for protection of aquatic life are defined based on acute and chronic effects based on duration of exposure. Aquatic organisms can endure exposure to higher concentrations or acute exposure for a short duration of time (e.g., 1 hr). Under chronic exposure (e.g., 96 hrs), lower concentrations can cause ecological impacts. Depending on the applicable water quality regulations, there may be two mixing zone boundaries to consider - (a) Acute Mixing Zone (AMZ) and (b) the Chronic Mixing Zone (CMZ), also known as the Regulatory Mixing Zone (RMZ). Dimensions of these mixing zones vary based on site specific conditions and are explicitly defined in the NPDES permit for the discharge. The estimation of effluent dilution over time and space is necessary for the application of a mixing zone in permit limit derivations and/or the design of an outfall structure/location to achieve a target dilution.

The effluent concentrations following dilution and mixing may be computed using the simple equation below.

$$C_f = \left(\frac{C_e - C_a}{D} \right) + C_a$$

(1)

Where C_f =   Final concentration (mg/L) of the effluent after dilution and mixing with the ambient water,

                  C_e =   Effluent concentration (mg/L) of the discharge or end-of-pipe concentration,

C_a = Ambient receiving water concentration (mg/L) outside of the influence of the effluent discharge, and

D = Volumetric dilution factor.

In a continuously stirred tank reactor (CSTR) laboratory setting with a known volume(s) the dilution factor D may be estimated in a straightforward manner as the ratio of total volume of the mixed fluid in the reactor to the effluent volume added. In a CSTR, the volumes are fixed and mixing of the two fluids and diffusion process is assumed to have reached completion. In a realistic setting however, computing the volumes of the respective fluids and extent of diffusion is complex and requires the assistance of numerical models or physical dye studies. The process of mixing and dilution itself occurs in the timescale order of minutes and often reaches a steady state within a short distance from the outfall. It is dependent on multiple physical parameters controlled by effluent characteristics such as flow rate, effluent density, outfall port/diffuser dimensions and depth, and receiving water stratification and currents. Upon exiting the outfall, the effluent undergoes rapid mixing due to nearfield momentum (jet) and buoyancy effects. Following this initial dilution, the plume stabilizes at the surface or at a neutrally buoyant trapping depth. The wastefield is then carried away by ambient currents over a longer timescale. The dilution continues to increase gradually during this farfield passive mixing phase from natural turbulence and currents further reducing the concentration of the effluent in the plume. Concentrations and dilution vary throughout the plume downstream of the discharge point.

Accurate determination of D at the specified mixing zone boundary (or C_f in the plume and at the specified mixing zone location) becomes an important requirement for various regulatory needs such as (a) Reasonable Potential Analysis – to evaluate if a constituent detected in effluent has a reasonable potential to exceed water quality criteria, (b) Assessment of compliance with applicable water quality standard based on discharge monitoring data, and (c) computation of Water Quality-based Effluent Limitations (WQBELs). Similarly, the design of diffusers and siting of outfalls for existing or new discharges requires iterative dilution ratio computations as part of feasibility and final design. These assessments require a predictive dilution model.

2.2   Brief History and Overview of Dilution Models

Development of mathematical models to predict mixing and dilution of effluent from wastewater outfalls dates back to early 1950s. Researchers applied principles of continuity, momentum, and energy conservation, integrated using Gaussian principles to study the spreading of buoyant plumes in uniform and stratified but stagnant environments (Rouse et al., 1952; Priestly and Ball, 1955). Numerous studies improved on this early work through the addition of concepts, such as an entrainment function based on local length scales (Morton et al., 1956), port orientation effects (Abraham, 1963; Fan, 1967), and effects of ambient currents and cross flow (Chu, 1979; Wright, 1984). Studies of plumes from multi-port diffusers have included line diffusers (fully merged plumes) in stagnant ambient waters (Pearson, 1956), and experimental laboratory work on merging of plumes (Liseth, 1970, 1976). Subsequently in the 1970s several mathematical models were proposed to simulate buoyant plume discharges varying from single to multiport diffusers, and, mixing in uniform confined environments to stratified flowing conditions (Koh and Fan, 1970; Cederwall, 1971; Sotil, 1971; Kannberg and Davis, 1977; Roberts, 1977; Roberts, 1979 a,b). By the early 1980s, there were numerous mathematical models available from various researchers, each specializing in different aspects of the plume dilution phenomena. Although multiple literature review papers had been published by then (Davis and Shirazi, 1978; Roberts, P.J.W., 1983, 1984, 1985), consolidation of the existing research and models into practical tools along with clear instructions on their use in practice for outfall design or for regulatory analysis did not exist until the mid-1980s.

The need for such guidance became more urgent when US EPA adopted regulations implementing Section 301(h) of the Clean Water Act (PL 97-117) (US EPA, 1982). Under these rules, publicly owned municipal wastewater could be discharged using treatment levels less effective than secondary treatment, after demonstrating compliance with water quality standards at the prescribed "zone of rapid mixing" or the zone of initial dilution (ZID). The demonstrations of environmental acceptability by the NPDES applicants and review by the permit writers required the use of plume models. To ensure consistency in the use of available tools, and quality assurance, EPA provided procedures for calculating the initial dilution and for describing the zone of initial dilution near a discharge site, using five leading dilution models (Muellenhoff et al. 1985). The models were UPLUME, UOUTPLM, UMERGE, UDKHDEN, and ULINE, based on prior work by Teeter and Baumgartner (1979) and Roberts (1977, 1979b). These were codes written in Fortran with differences in their computational approaches but utilized a universal input file format and structure that offered users consistency in input parameters (effluent, diffuser, and receiving water characteristics) and results (plume characteristics including location, size, and flux averaged plume dilution as a function of distance from the outfall). These estimates were based on a Gaussian distribution of concentrations within a plume cross section. The computations stopped at the completion of initial rapid mixing phase, typically after the plume reached the surface or stabilized at a neutrally buoyant trapping depth, thereby defining the ZID.

Most plume models use simplifying assumptions in defining the discharge configuration and the mixing processes (e.g., Gaussian distribution of plume concentration across the plume width, diffusers with simple geometries, and domains with no bounding constraints). In realistic settings, the plume behavior may be affected by boundary effects (bottom or bank attachment, plume stability), and complex diffuser geometries such that simplifying assumptions in plume models may no longer be valid. Dye studies or laboratory studies involving hydraulic scale models with precise representation of the site-specific conditions may be needed to accurately estimate the initial dilution process. With an emphasis on the importance of boundary interactions on the stability of the plume and mixing processes, Cornell University with support from US EPA developed the CORMIX model. CORMIX consists of a series of software systems for the analysis, prediction, and design of discharges with emphasis on the role of boundary interaction to predict steady state mixing behavior and plume geometry. It classifies momentum and buoyancy of the discharge in relation to boundary interactions to predict mixing behavior. Boundary interactions can be surface or bottom contact or terminal layer formation in density stratified ambient waters. CORMIX was released as a knowledge and inference based expert system package consisting of CORMIX1 (Doneker and Jirka, 1990) for single port discharges, CORMIX2 (Akar and Jirka, 1992) for multiport diffusers, and subsequently CORMIX3 (Jones et al., 1996) for surface discharges.

In 1991, US EPA issued technical guidance for assessing and regulating discharge of toxic substances to the waters of the United States in NPDES permits. This *Technical Support Document for Water Quality Based Toxics Control* (US EPA 1991) was comprehensive and included language about regulatory mixing zones. The guidance was then adopted by various states to develop their own standard procedures for conducting Mixing Zone Studies including the use of dilution models for conducting water quality compliance evaluations. In response to a growing demand and adapting to PC based computing platforms, US EPA released DOS Plumes (Baumgartner et al., 1994) which only included the UM model, an updated version of UMERGE, and RSB, an updated version of ULINE based on experimental studies on multiple 'T' shaped port diffusers (Roberts et al. 1989 a,b,c). DOS Plumes also incorporated the flow classification scheme of the CORMIX model (Jirka and Hinton, 1992), with recommendations for model usage. DOS Plumes and CORMIX then became the two US EPA-supported models for dilution modeling and mixing zone analyses.

DOS Plumes was subsequently upgraded to Visual Plumes (Frick et al., 2004), a Windows-based application that included graphics, time-series input files, user specified units, a conservative tidal

background-pollutant build-up capability, a sensitivity analysis capability, and a multi-stressor pathogen decay model that predicts coliform mortality based on temperature, salinity, solar insolation, and water column light absorption. It also included DKHW model that is based on UDKHDEN (Muellenhoff et al., 1985), the surface discharge model PDS (Davis, 1998), the three-dimensional UM3 model based on UM, and the NRFIELD model based on RSB. Visual Plumes was distributed by US EPA. Similarly, the DOS-based CORMIX suite of models were upgraded to a Windows-based application, licensed and distributed by MixZon, Inc. For nearly 15 years since their release, Visual Plumes and CORMIX were the two leading modeling systems that were used extensively by the community for outfall design, siting studies, and mixing zone analyses. Following the release of Windows 10, however, Visual Plumes lost its compatibility with the PC operating system. The community has since primarily relied on CORMIX as the only model readily available to the plume modeling community. The PLUMES2.0 project provides renewed access to key sub-models of the Visual Plumes model suite.

3   Theory and Model Formulation

3.1   Approach and Conceptual Framework

PLUMES2.0 directly adopts the analytical modeling framework that was used in the UM3 model. UM3 in turn is based on the most recent and established theoretical treatment of effluent plumes developed over several decades of research described in Section 1.2 (e.g., Akar and Jirka, 1991; Baumgartner et al., 1994; Brooks, 1960; Fan, 1967; Fischer et al., 1979; Muellenhoff et al., 1985). The conceptual model of a buoyant effluent plume consists of three phases or regimes of physical mixing of two fluids, as shown in Figure 1. The plume dynamics in the immediate vicinity of the diffuser are controlled by jet mixing where effluent is discharged to the ambient waterbody under hydraulic pressure. The jet mixing occurs through momentum flux and turbulent shear accompanied by a drop in pressure. This is followed by a buoyancy-induced transition phase including interaction with ambient currents. The final phase is the farfield passive transport phase where stabilized wastefield is carried away by ambient currents and further mixed with surrounding waters through spreading due to combination of remnant buoyancy and natural turbulence in the receiving water.
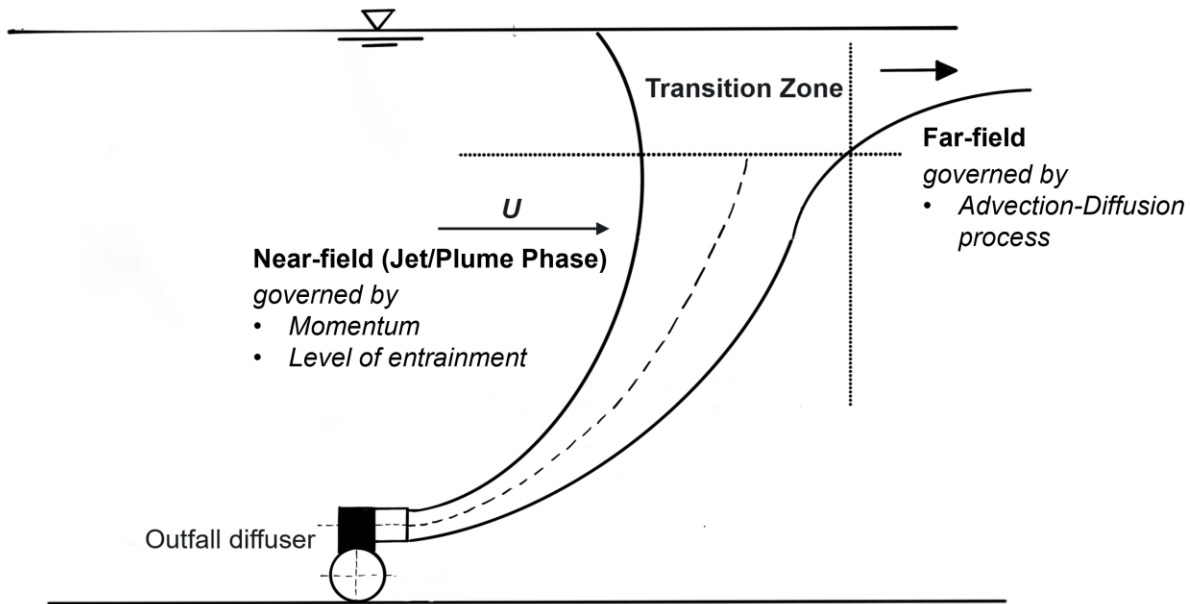
Figure 1: Schematic representation of the conceptual model for a typical buoyant effluent discharge.

Within a short distance from the ports, the flow entrains fluid and transitions from a jet to a plume. The buoyancy effects take over causing the plume to rise in the water column. As the plume ascends, it further entrains ambient water, diluting it and decreasing the plume buoyancy. When the buoyant plume is in a stratified water column, it stabilizes at a depth where its density approaches that of the surrounding water (the neutral buoyancy depth), trapping the plume below the water surface (also referred to as the trapping depth). In unstratified conditions, the plume often reaches the water's surface without being trapped. This region from the diffuser port to the stabilized wastefield is referred to as the zone of initial dilution (ZID) in secondary treatment regulations, or the region of rapid initial mixing in the scientific literature (Baumgartner et al., 1994; Roberts, 1990). For well-designed outfalls, the jet mixing is highly energetic near the outfall, resulting in rapid mixing and reduction in pollutant concentrations within the plume. The completion of the initial dilution phase, including jet and

buoyancy effects, is typically constrained to a spatial scale of 10–1000 meters (m) and occurs over time scales of 1-10 minutes. After the initial dilution is complete, the effluent is spread by ambient currents and diffusion by natural turbulence. The farfield mixing phase is governed by advection-diffusion and occurs over a much larger spatial scale of 100–10,000 m and time scales of 1-20 hours (Roberts, 1990).

3.2   Model Architecture

PLUMES2.0 follows the Visual Plumes approach to capture the nearfield plume characteristics while providing the option to continue the computations to farfield transport within a common computational framework. To facilitate this, the initial dilution component of PLUMES2.0 uses the Lagrangian Control Volume (LCV) method, as in the UM3 model (Baumgartner et al., 1994), including the entrainment and integrated features of plume merging. The farfield computations are conducted using the Brooks (1968) principles.

The architecture of PLUMES2.0 is also based on the mathematical and numerical approaches that were implemented in the UM3 model in Pascal code. In PLUMES2.0, each phase of the conceptual model was developed independently in Fortran 90 and includes the transfer of data from one phase to the next phase. Figure 2 shows a high-level representation of model design with data flow between different phases and processes. The model requires input related to (a) discharge characteristics such as diffuser layout, port orientation, diameter, flow rates, and (b) receiving water characteristics such as ambient stratification (temperature and salinity) and current velocity profile data. The jet/plume phase is numerically simulated using the LCV method. Upon the completion of nearfield computations, major plume parameters (i.e., plume diameter and dilutions) are revised/adjusted to match the wastefield dimensions (total width) during the transition stage prior to initiation of farfield calculations.
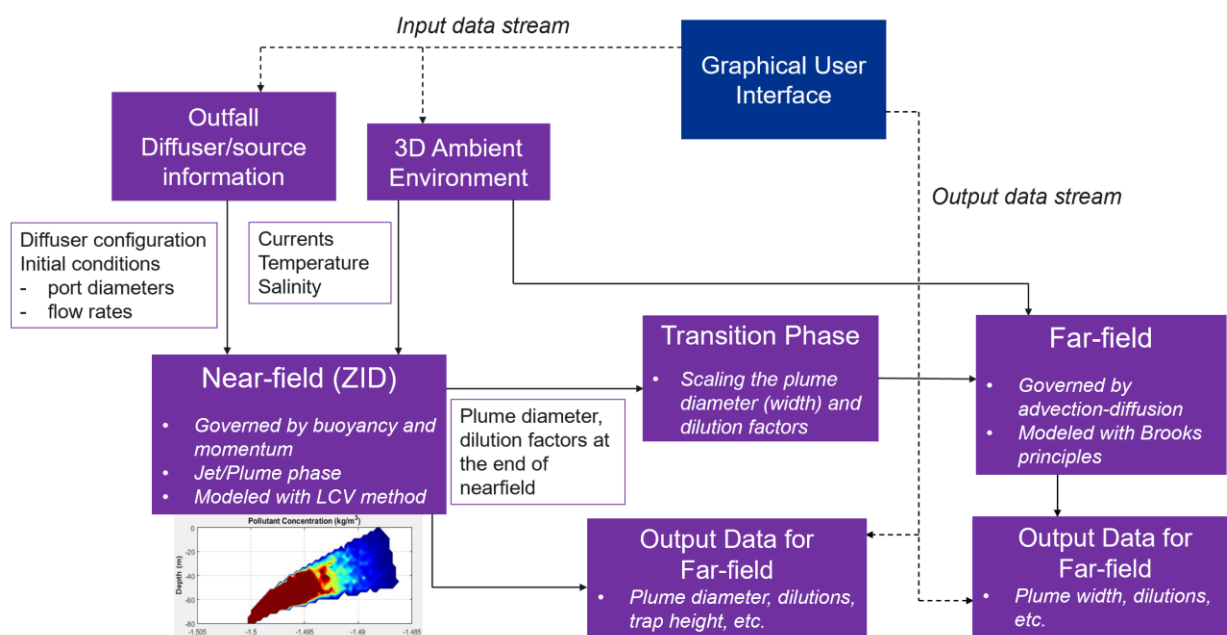
Figure 2: Schematic representation of the model architecture.

PLUMES2.0 was developed using Fortran 90 standards. Building and testing were conducted using Intel Fortran compilers. For the graphical user interface (GUI) development, several options were explored. Typical graphic libraries, application programming interfaces (APIs), and other tools are based

on C++, Python, and Java. Using such tools for GUI development creates coupling challenges with Fortran. To avoid the complexities and incompatibilities associated with coupling multiple programing languages, a Fortran 90 based GUI toolset was selected for the PLUMES2.0 GUI development. The commercially distributed third-party application – *Winteracter* (https://www.winteracter.com/) provided Fortran-based GUI libraries and development toolset for this effort.

3.3   Model Derivation

3.3.1   Nearfield Dilution

The plume behavior in the nearfield is simulated using the LCV method, adopting the approach that has been used previously in models such as UM3 and JETLAG (Baumgartner et al., 1994; Lee and Cheung, 1990). In the LCV method, the physical properties (i.e., velocities, concentration, salinity, etc.) of an LCV over a cross-section are assumed to be distributed uniformly using a Top-Hat profile structure. In other words, all properties at a specific plume cross-section are uniformly distributed and drop sharply to ambient values outside of the plume boundary. Figure 3 shows a schematic representation of selected LCVs of the plume, and the numerical integration of all LCVs produces the expected plume structure for the nearfield. The kinematic equations of the plume dynamics are derived by applying basic governing equations to each LCV of the plume. The continuity equation (Equation 2) describes the change in liquid mass in the LCV (dm) during a small-time increment (dt) is equal to the net ambient liquid entrainment. Total ambient entrainment is computed as the summation of forced entrainment and Taylor-induced entrainment (shear entrainment).

$$\frac{dm}{dt} = -\rho_a \boldsymbol{A_p}.\boldsymbol{U_a} + \rho_a A_T \beta_T \tag{2}$$

In Equation 2, ρ_a is the density of the ambient liquid $\boldsymbol{A_p}$ is the projected area vector for forced entrainment computation while $\boldsymbol{U_a}$ is the ambient velocity vector (vector variables indicated in bold). A_T is the area of the LCV in contact with ambient fluid for Taylor entrainment and wraps completely around the element is not expressed as a vector and computed as an area of a cylindrical element assuming an infinitesimal thickness of Lagrangian element (Baumgartner et al., 1994). β_T is the Taylor aspiration velocity, which can be defined as $\beta_T = \alpha|\boldsymbol{U_j}|$, where α is the Taylor entrainment coefficient and $\boldsymbol{U_j}$ is the average plume velocity of the LCV. $\boldsymbol{A_p}$ lies in a vertical plane containing the velocity vector and points upstream out of the element. $\boldsymbol{A_p}$ and $\boldsymbol{U_j}$ point in opposite directions so that their dot product is negative. To estimate the projected area, it is necessary to express mathematically how the length of the element changes in response to changes in other plume properties. Further details on the mathematical estimation of A_p can be found in Frick (1984) and Frick et al. (1995).

Equation 3 represents the change of momentum in an LCV due to the momentum passed by the entrained ambient mass and the momentum induced by the buoyancy force acting on the LCV.
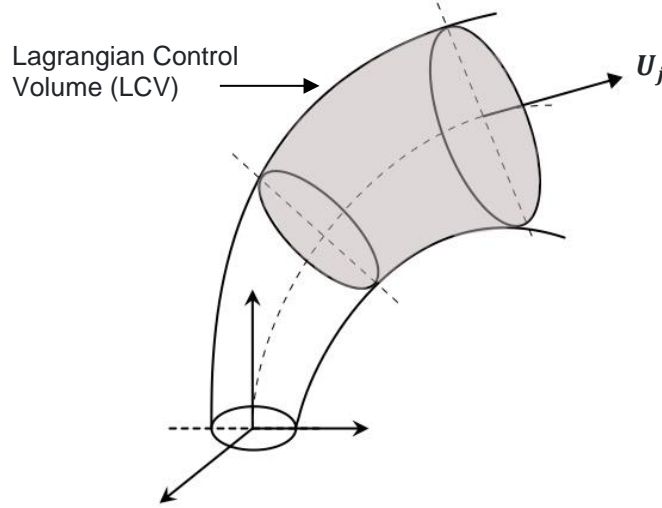
Figure 3: Lagrangian Control Volume representation (Premathilake and Khangaonkar, 2019).

Because the physical properties at the outer surface of the LCV are assumed to match the properties of ambient fluid, the drag force acting on the LCV is assumed to be zero, which is consistent with the approach of Baumgartner et al. (1994).

$$\frac{d(m\boldsymbol{U_j})}{dt} = \boldsymbol{U_a}\frac{dm}{dt} - m\frac{(\rho_a - \rho_j)}{\rho_j}g \qquad (3)$$

In Equation 3, g is the gravitational vector and ρ_j is the plume density of the LCV, which is a function of plume temperature and salinity. The plume temperature can be determined by applying the conservation of energy equation considering the heat exchange between the LCV and the ambient fluid. A simplified version of the energy equation has been used to compute the plume temperature in the dynamic phase of the plume, which is given by Equation 4,

$$\frac{d(mT_j)}{dt} = T_a\frac{dm}{dt} \qquad (4)$$

where T_j and T_a denote the average plume temperature and temperature of ambient liquid, respectively. Equation 4 was derived by assuming temporally constant specific heat at constant pressure, which is consistent with the approach followed in UM3 model formulation. Similarly, conservation of salinity is shown in Equation 5, in which S_j and S_a are the average salinity of the LCV and ambient salinity, respectively.

$$\frac{d(mS_j)}{dt} = S_a\frac{dm}{dt} \qquad (5)$$

Both ambient and plume densities are computed from the equation of state for the sea water density (Sigma-t function) (Fofonoff, 1985). Numerical integration of the equations from Equation 2 to 5 generates the spatial and temporal variation of the buoyant jet/plume properties.

To enhance rapid mixing and dilution of the effluent within the mixing zone, rather than releasing the effluent through an open-ended pipe, many outfall pipes include a diffuser section. The diffuser section of a typical ocean outfall is usually the most seaward section. The outfall pipe flow is

blocked off with an end-flange, and the effluent is released through a series of ports. The ports may be simple holes directly on the outfall pipe, or they may be designed with riser pipes normal to the diffuser axis. The ports may be fitted with nozzles with a port diameter that is relatively small and oriented at specific vertical angles, allowing the effluent to exit the outfall as a strong jet resulting in rapid entrainment and mixing. When the effluent is released from multiple ports, the individual plumes often merge with each other as the plumes rise in the water column, thereby affecting the individual plume dynamics. A schematic of a typical effluent plume from a multiport diffuser with plume merging is shown in Figure 4. Specifically, the merging processes affect the entrainment mechanism significantly as the individual plume area is reduced. This also results in a loss of dilution efficiency.

The merging of plumes causes a reduction in the effective plume area due to overlapping plume sections. The reduction in plume area reduces the overall entrainment causing changes to plume dynamics. Implementation of plume merging processes requires specific factors in the computation of the effective entrainment area. Figure 4 shows the reduction of plume areas in the overlapping plume sections. The mathematical formulation of UM3 introduced a geometry-based correction to calculate the entrainment area of merged plumes (Baumgartner et al., 1994). The same approach is adopted in the mathematical model of PLUMES2.0.
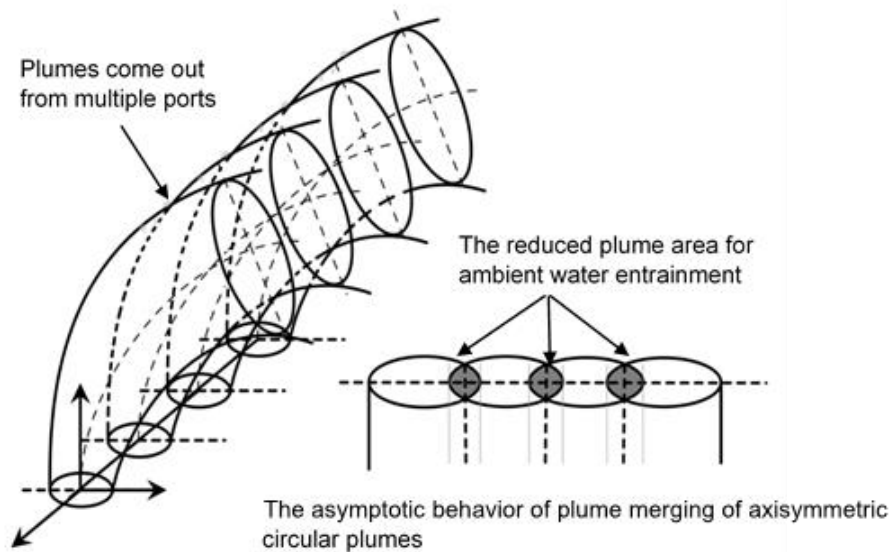
Figure 4: Typical merging model for a vertically released effluent discharges.

The model development presented above is based on average motion of the plume element with properties averaged over the element. The plume trajectory is traced by the center-of-mass of the plume element. The plume element expands with time as it moves away from the source, affected by buoyancy and entrainment of ambient water, with widely varying properties in between the element boundaries. The concentration of the effluent mass averaged over the Lagrangian element (C_{ave}) is computed by the model in each step based on volume of water entrained in the element. The assumption is that the effluent mass in the Lagrangian element at each time step remains constant. Of importance is the calculation of difference in concentration between the plume and the ambient (C_{ave}-C_a), where C_a is the ambient concentration. Dilution in the plume relative to initial effluent concentration at the end-of-the pipe C_e is given by $D = (C_e - C_a)/(C_{ave} - C_a)$, as in Equation 1 after rearranging the terms. Here, C_{ave} computed by the model in each model step replaces C_f at the end of initial dilution process (in Equation 1).

In the model, the concentrations are assumed to be distributed over the cross section of the plume element following the 3/2 power profile (Kannberg and Davis, 1976), which closely matches a Gaussian profile but is constrained to the plume geometry. The 3/2 power profile is expressed by the following:

$$\Phi = \left[1 - \left(\frac{r}{b}\right)^{\frac{3}{2}}\right]^2$$

(6)

where, as described in Baumgartner et al. (1994), Φ is an instantaneous scaling factor relating difference between the plume and the ambient of any appropriate property, such as the concentration of some pollutant or velocity, b is the plume radius, and r is the distance from the center of the plume to the point within the plume at which Φ is measured. In other words, $C(r)=C_{max}\Phi$. This distribution ensures that the maximum concentration is at r = 0, at the plume element centerline and approaches 0 for r = b at the radial plume boundary.

The average concentration, C_{ave}, provided by the model may also be expressed as flux-averaged concentration.

$$C_{ave} = \frac{\int C \cdot v \cdot dA}{\int v \cdot dA}$$

(7)

where C and v are the instantaneous concentration and velocity in the plume element at a radial location r distance from the centerline, A is the cross-sectional area, and dA is the corresponding infinitesimal area. For large dilutions and currents, the velocity may be approximated to follow a top-hat distribution and assumed constant. This simplification along with 3/2 profile for concentrations (substituting C with $C_{max}\Phi$) can be used to derive the relationship C_{max}/C_{ave} = 3.89 for round plumes and 2.22 for fully merged line plumes. However, as described in Baumgartner et al. (1994), the ratios can vary. In much of the plume, the peak-to-mean ratios are considerably smaller than these limiting values, approaching 1.0 at the source. Therefore, the centerline concentration prediction is approximate and occasionally deviates from the expected trend when vertically varying background pollutant concentrations are present. The dilution value D computed by the model by default is the flux-averaged dilution, based on flux-averaged concentration C_{ave}. The centerline dilution (an output provided by the model) corresponds to C_{max}.

The termination of the plume dynamic phase is decided by four benchmarks based on the plume properties. The first criterion, which decides the termination of the nearfield mixing, is the stage in which the plume density is equal to the ambient density. This also can be defined as the plume-trapping stage, and the depth at which the plume reaches neutral buoyancy, designated as the trapping depth. The second criterion for terminating the nearfield mixing is when the plume vertical velocity becomes reversed, causing the plume that has overshot the trapping depth to fall back. Once the plume reaches this stage, the plume structure collapses, and subsequent effluent transport continues as an advection-diffusion process. Other criteria for the termination of jet/plume behavior of the effluent plume include instances such as when the plume encounters boundaries, including the water surface, the shoreline, or the seabed.

3.3.2 Farfield Dilution

Once the momentum-driven plume reaches the terminal criterion of nearfield dilution, the plume structure is no longer sustainable and is dispersed as a passive effluent field by the ambient currents. Here, the effluent (which exited with an initial end-of-pipe concentration of C_e) is already partially mixed in the ambient environment after completion of initial dilution process (dilution ratio D) with a resulting wastefield concentration of C_o. Further mixing and dilution occurs with time as the plume travels away from the zone of initial dilution, through natural turbulent diffusion that slowly

reduces the wastefield concentration from C_o to $C(x,y,z)$, asymptotically reducing towards the background concentration. Farfield dilution factor *FF* may then be defined as *FF=C_o/C(x,y,z)*. Final effluent dilution at specified farfield location is then given by $D_{farfield} = D \cdot FF$. This determination of final farfield dilution factor requires calculation of *C(x,y,z)*. The conventional approach is to solve for *C(x,y,z)* using the 3D advection-diffusion equation in the form shown below.

$$\frac{\partial C}{\partial t} + u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y} + w\frac{\partial C}{\partial z} = \frac{\partial}{\partial x}\left(\epsilon_x \frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y}\left(\epsilon_y \frac{\partial C}{\partial y}\right) + \frac{\partial}{\partial z}\left(\epsilon_z \frac{\partial C}{\partial z}\right)$$

(8)

Here, the effluent field concentration (in kg/m^3) is denoted by C and u, v, and w are ambient velocities (m/s) in x, y, and z directions, respectively. ε_x, ε_y, and ε_z are the corresponding eddy diffusivities (m^2/s) in x, y, and z directions. As in Visual Plumes, the PLUMES2.0 uses Brooks principles (Brooks, 1960) to compute the farfield spreading of the wastefield and associated dilution over time and Brooks principles are based on a simplified one-dimensional and steady-state version of the Equation 8, as shown below:

$$u\frac{\partial C}{\partial x} = \frac{\partial}{\partial y}\left(\epsilon_y \frac{\partial C}{\partial y}\right) + kC$$

(9)

where k is the transformation rate of the effluent which may be growth rate or decay rate depending on the nature of non-conservative constituent. For typical Brooks farfield applications, k value is set to zero. The primary premise for Brooks principles, is that the wastefield grows laterally with distance (Figure 5). The lateral growth is caused by turbulent mixing, represented by the lateral diffusion coefficient (ϵ_y). Brooks laws were derived by solving Equation 9 analytically via length scaled relationships for ϵ_y.

A summary of Brooks principles is shown in Table 2 showing the growth of eddy diffusivity and plume width as a function of distance. Brooks provided three case types for lateral mixing giving consideration for environmental conditions. Case 1 represents narrow river or channel where eddy diffusivity may be assumed constant. Case 2 represents estuarine conditions where eddy diffusivity may be expected to grow linearly with distance from the outfall. Case 3 represents open ocean conditions where eddy diffusivity was derived by Brooks to apply the 4/3rd power law relationship to the plume width.
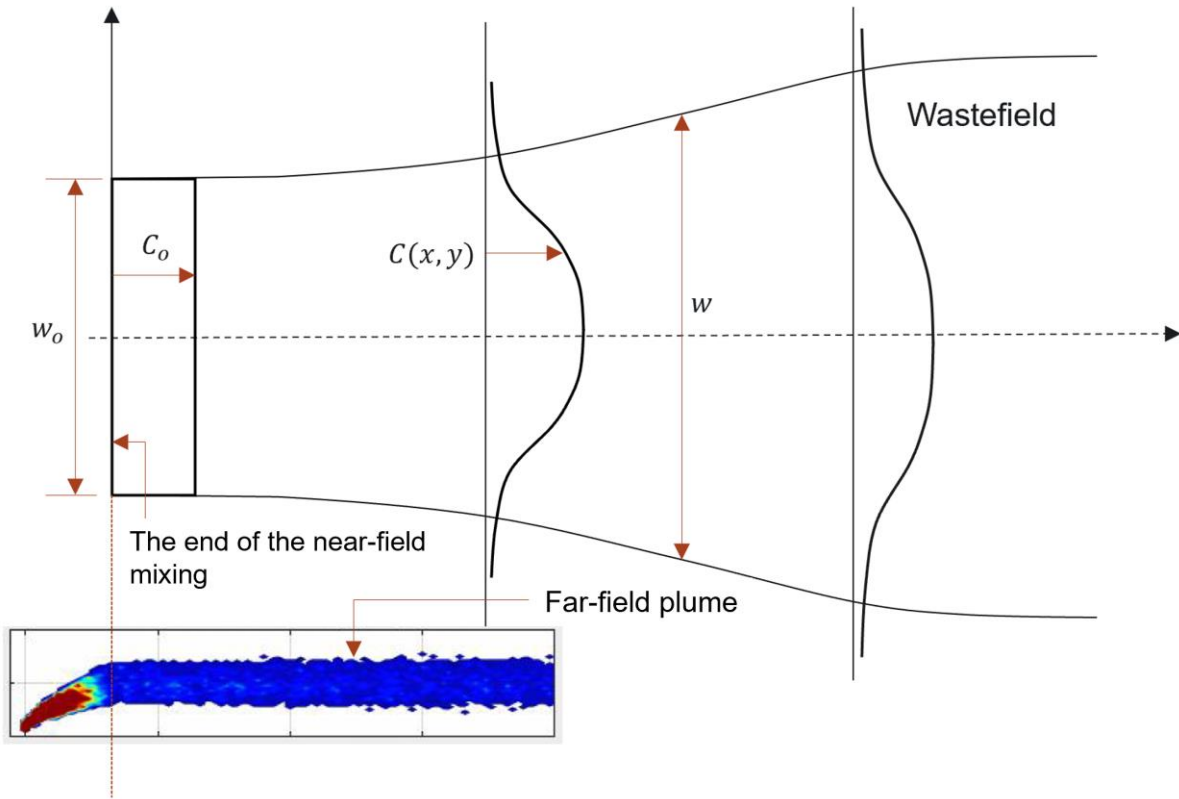
Figure 5: Schematic representation a typical farfield plume growth under steady conditions. The inset with color contours represents a vertical cross section that shows the initial dilution phase as well as the farfield transport. (Note: vertical spreading is assumed to be negligible in Brooks' farfield model calculations)

Table 1: Variation of Width of Wastefield with Distance

Case 1	Constant ϵ	$\dfrac{\epsilon}{\epsilon_o} = 1$	$\dfrac{w}{w_o} = \left(1 + 2\beta\,\dfrac{x}{w_o}\right)^{1/2}$	(10)
Case 2	Linear increase in ϵ	$\dfrac{\epsilon}{\epsilon_o} = \dfrac{w}{w_o}$	$\dfrac{w}{w_o} = \left(1 + 2\beta\,\dfrac{x}{w_o}\right)$	(11)
Case 3	4/3-Law	$\dfrac{\epsilon}{\epsilon_o} = \left(\dfrac{w}{w_o}\right)^{4/3}$	$\dfrac{w}{w_o} = \left(1 + \dfrac{2}{3}\beta\,\dfrac{x}{w_o}\right)^{3/2}$	(12)

w_o =initial width of sewage field ($w/w_o = 1$ at $x = 0$), Note, the origin or x = 0 in Brooks' calculations represents the location of the wastefield after initial dilution is complete and is different from the origin for initial dilution calculations at the outfall port. w = width at a distance x ($x = u \cdot t$) from the start of farfield calculations. ϵ is the eddy diffusivity at a distance x, and ϵ_o is the initial eddy diffusivity.

$$\beta = \frac{12\epsilon_o}{u \cdot w_0} \text{ (dimensionless)} \tag{13}$$

The farfield dimensions of the wastefield are computed using the above rules and corresponding dilutions at the center of wastefield (i.e., lowest dilutions or maximum concentration).
Table 2 provides the resulting equations used to calculate constituent concentration or farfield dilution

(C₀/C) in the wastefield for the three cases.

Table 2: The analytically-derived concentrations at the center of the wastefield (Brooks, 1960)

Case 1	$\dfrac{\epsilon}{\epsilon_o} = 1$	$C(x) = C_o e^{-kt}\operatorname{erf}\sqrt{\dfrac{3}{4\beta x/w_o}}$	(14)
Case 2	$\dfrac{\epsilon}{\epsilon_o} = \dfrac{w}{w_o}$	$C(x) = C_o e^{-kt}\operatorname{erf}\sqrt{\dfrac{3/2}{\left(1+\beta\frac{x}{w_o}\right)^2 - 1}}$	(15)
Case 3	$\dfrac{\epsilon}{\epsilon_o} = \left(\dfrac{w}{w_o}\right)^{4/3}$	$C(x) = C_o e^{-kt}\operatorname{erf}\sqrt{\dfrac{3/2}{\left(1+\frac{2}{3}\beta\frac{x}{w_o}\right)^3 - 1}}$	(16)

4   PLUMES2.0 User Instructions

4.1   Download and Installation

PLUMES2.0 software is distributed in the form of a self-extracting zip file that may be downloaded from the following locations.

US EPA's Center for Exposure Assessment Modeling via the following link.
https://www.epa.gov/hydrowq/PLUMES2

or

from the University of Washington SSMC GitHub site
https://github.com/ssmc-uw/PLUMES2.0

Download the zip file "PLUMES2.0-main.zip" from the US EPA site, or, from the GitHub site, download by clicking the Code (green) button.   `<> Code ▾`

Copy the zip file from the download folder to your designated folder (e.g., C:\Users\useraccount\Desktop\) and extract the files using Windows explorer. The operating system requirements are Windows 10 or higher. The extracted folder, also named \plumes2.0-main, contains additional subfolders (\icons, \images, and \Example_project), multiple utility files, and the PLUMES2.0 executable. The executable is labeled plumes2.0.

Launch the application by double clicking the icon. Windows defender may require your approval to run the application as it may not be recognized by Windows. [click "more information" prompt and select "run anyway" option. Having an organizational IT-Admin assisted install may be required if the user does not have administrative privileges]. We recommend the option to right click the icon and select "pin to task bar" for convenient future access.
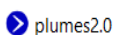
4.2   PLUMES2.0 User Interface

The PLUMES2.0 user interface was setup to mimic many features of the Visual Plumes software to allow seamless transition for the Visual Plumes community. Experienced users will recognize the diffuser, effluent, and ambient tabs for entering project-specific data. The "*Welcome*" screen or tab introduces PLUMES2.0, and additional information is also available under the "*About*" tab.

Click the "*Project*" tab or the   icon to start using PLUMES2.0.

4.2.1   Project set up

The *Project* tab screen provides step by step instructions on how to set up a new project scenario. The window under the project dashboard (Project Description) allows the user to enter project specific information and details. This could include the outfall name, project owner, project site location and serves as a project identifier. Immediately below is the *Load Existing Project* button. This allows the user to upload previously saved project configuration and data to continue prior work, or to run additional scenarios without having to re-enter the project and case-specific information.

For a new project, click the *New Project* button. It opens a Windows explorer style menu. Navigate to the directory where you would like to conduct model runs, right click in the selected directory to create a new project folder. Double click to enter the new project folder, provide a project file name and hit the save button. The project data and configuration that will be entered in subsequent steps will be saved automatically under the project file name once the model run is executed. The saved project information may be reloaded if the user wishes to close the program and return to it later, thereby avoiding the need to re-enter the input data. Once the New Project is created, the tabs - *Diffuser*, *Effluent*, and *Ambient* for entering project specific data become available along with the *Model*

Run tab to run the dilution calculations (see below).
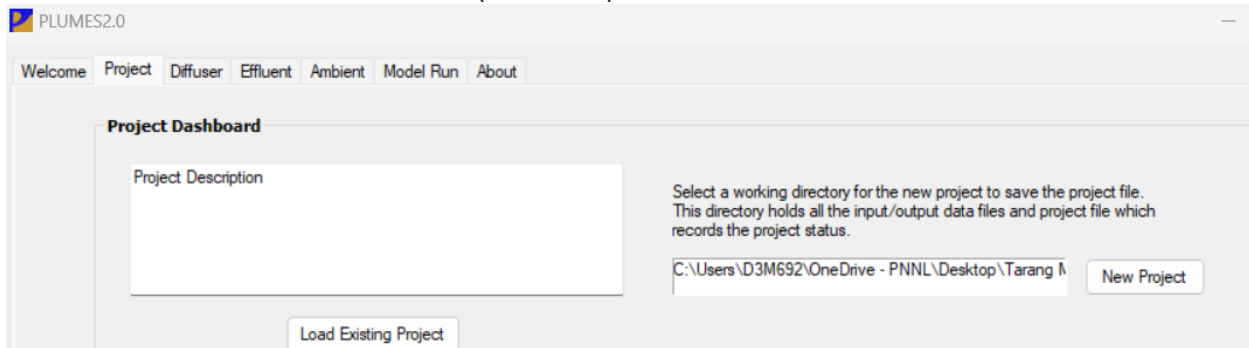
Also provided on the *Project* page is an added feature or option *Independent Farfield Calculation* to allow stand-alone simulation of farfield transport of a wastefield using Brook's farfield transport algorithm. This allows the user to estimate farfield plume transport independent of the nearfield dilution process (see Section 3.2.7).
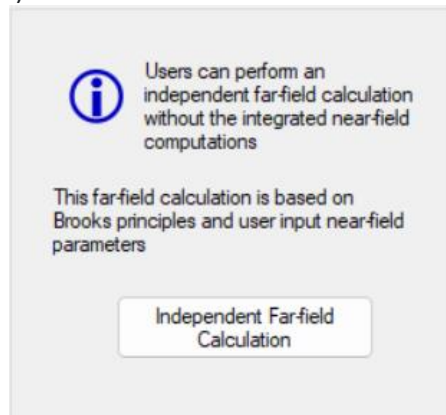
4.2.2   Diffuser characteristics

Wastewater effluent is typically discharged to the surface waters through an outfall pipe. To increase jet-induced mixing and initial dilution, the outfall design often includes a diffuser section, located at the end of the outfall pipe. Rather than discharge directly through a pipe with a large diameter and low velocities, the effluent is released under pressure through multiple ports with small diameters, and therefore at higher (jet) velocities. This section of the outfall pipe with multiple ports arranged in a row is called the diffuser section. The strong mixing provided by the diffuser also helps trap the wastefield lower in the water column at the end of the buoyancy-induced mixing phase.

Outfall designs vary from the simplest configuration of an open-ended outfall pipe (single port) to complex multiport diffusers with ports at the end of risers arranged uniformly or in a fan or with alternating angles to maximize efficiency in settings with reversing tidal currents. The UM3 code is designed for single-port or multiport diffusers with uniformly arranged ports. Diffuser configuration consists of the following parameters.

1. Port diameter   : Diameter (assuming circular opening) or equivalent diameter, m
2. Port elevation   : Distance from the seabed to port center, m
3. Vertical angle   : Angle of port/discharge vector to horizontal plane,
                                      +tive counter-clockwise from x-axis
4. Horizontal angle   : Angle of port/discharge vector to vertical plane,
                                      +tive counter-clockwise from x-axis
5. Number of ports   : 1 = single port outfall, n = multiport diffuser with n ports

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6. Port spacing : Distance between ports, m (or average spacing for irregular diffusers)
7. Port depth : Distance from water surface to the port centerline
8. X and Y coordinates : Diffuser location or the starting point for the plume calculations

Figure 6 provides a schematic representation of a submerged outfall and diffuser configuration defining the parameters for setting up a project run.

Click the *Diffuser* tab to see a simplified version of Figure 6 and a table where numeric values for the diffuser parameters may be entered. The user also has an option to load a previously saved diffuser configuration. Click the *Load* button to load "Diffuser_example.csv" file. This file is in the Example_project folder. Figure 7 shows that the example diffuser has 18 ports spaced 6.1 m apart. Each port is on a riser pipe with a port diameter of 0.076 m. Each port is angled up at 45° to the horizontal plane. The horizontal angle of the discharge vector is at a 30° angle to the x-axis which is also the direction of the ambient current. The diffuser location (X, Y) coordinate is specified using the centerline of the middle port or the mid-point of the diffuser section (the user may select any arbitrary location for the origin, and orientation of x-axis). Selecting an x-axis along the shoreline or along the current direction simplifies data entry. The port elevation is 0.31 m and port depth at the diffuser is 11 m. Check the case button to select this diffuser. The table may be populated with multiple diffuser designs but only the checked diffuser configuration is used in calculations. All inputs are saved to the project file automatically upon model run. But the user may wish to save the selected diffuser configuration for later re-use. Additional notes on diffuser configuration:

- Port depth plus port elevation equals water depth at the diffuser location. However, water depth away from the diffuser may be greater and may be entered via the *Ambient* tab. The ambient tab allows entry of water profiles at a representative ambient location which may be different from the diffuser site and deeper.
- The data entry by default for all parameters is in SI (metric) units, but the user may use the drop-down arrows on the unit cell in the respective column to switch to Imperial units (foot, pound, second). Note that all model results are provided in the SI units only.
- The *Model Run* tab (described later in Section 3.2.5) has two additional characteristics related to the outfall/diffuser for user entry: diffuser contraction coefficient and distance to nearest shoreline.
- The port elevation may be set to zero. However, initial dilution will be terminated as the plume will immediately touch the bottom. The user will need to shut off "stop the plume at bottom hit" criterion on the *Model Run* tab.
- The model cannot be applied for surface discharges. Port depth cannot be zero. Similarly, port elevation cannot equal port depth.
- All ports must face the same direction.
- There is no limit on the number of ports, but it is assumed that the diffuser design provides sufficient exit velocity (densimetric Froude number, $Fr = U/((gD(s-1)^{1/2}) > 1$, to prevent salinity intrusion. Here, U and $D,$ are port velocity and port diameter, respectively, and 's' is the ratio of ambient and effluent densities.

Note that the entered information is not saved until the model run is executed. The diffuser configuration may be saved using the *"Save"* button. Similarly, previously saved diffuser configuration may be loaded using the *"Load"* button.
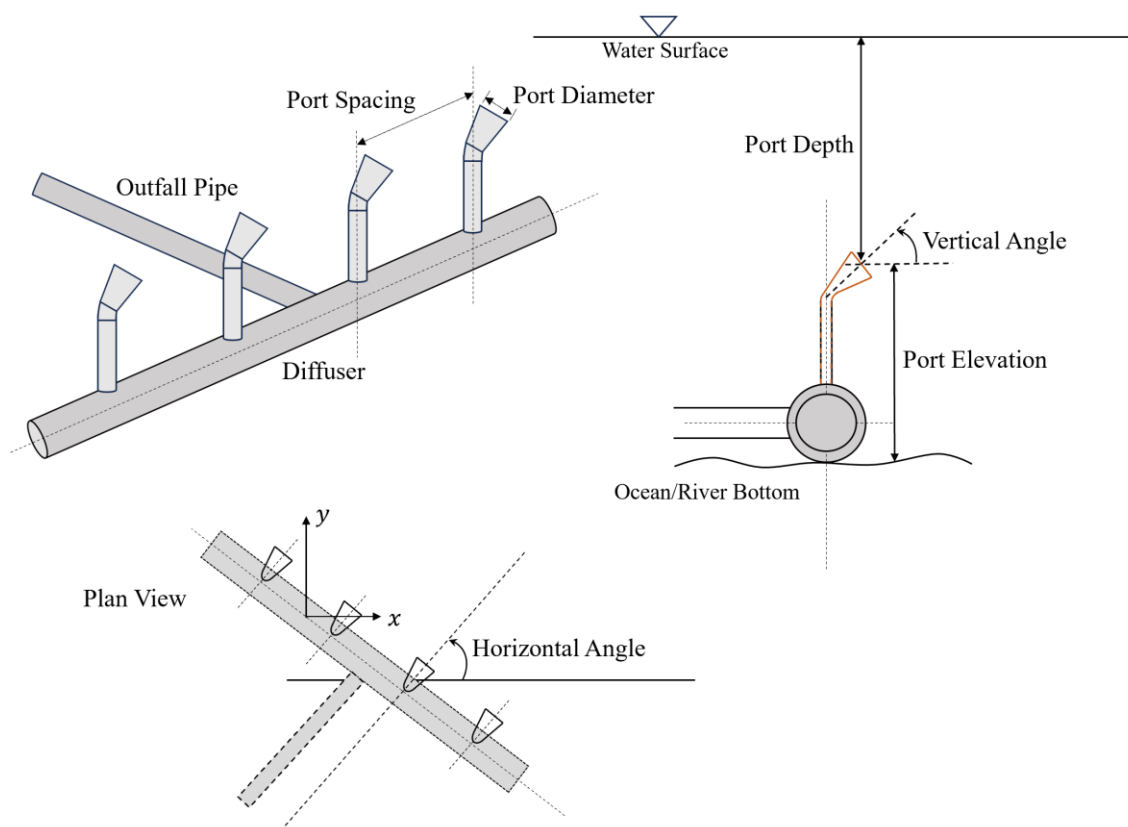
Figure 6: Schematic representation of outfall pipe and definition of diffuser parameters.
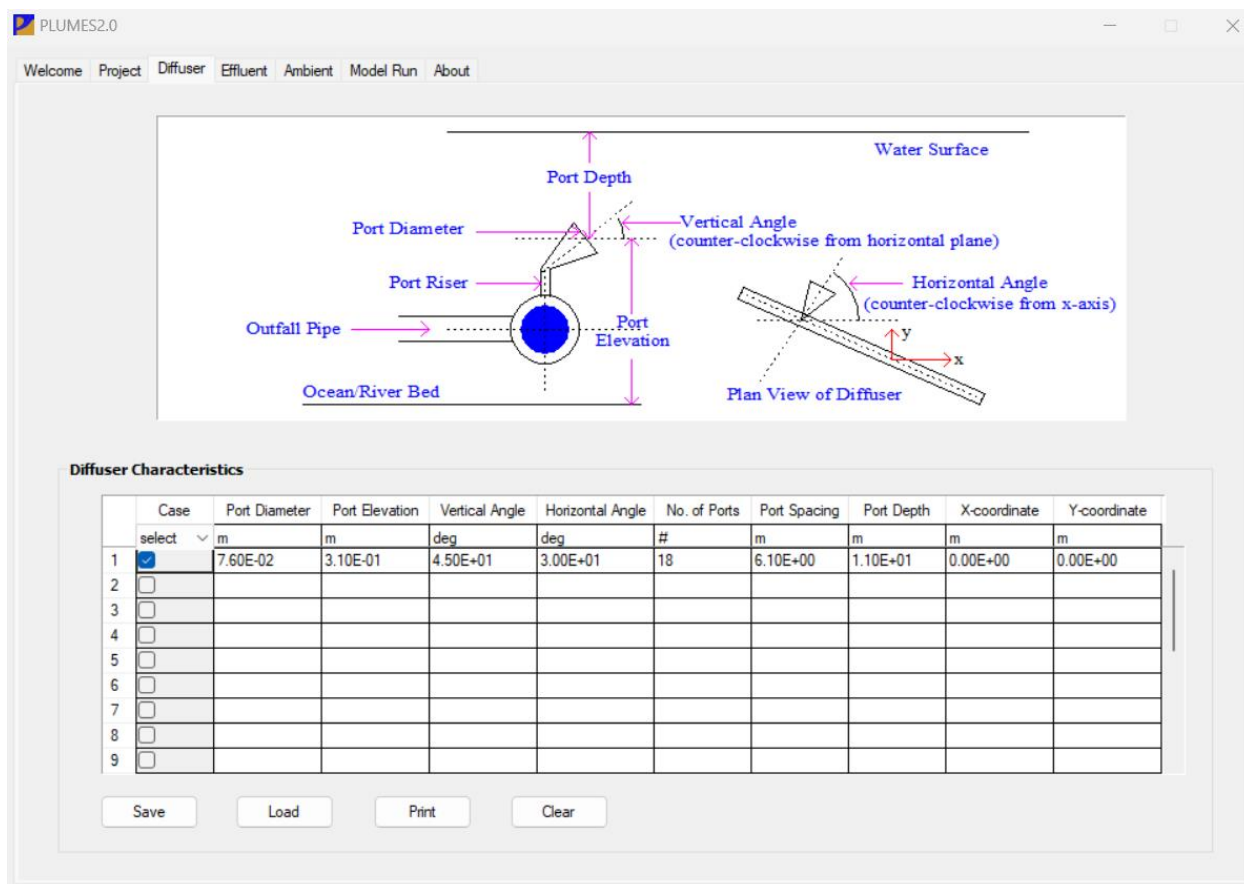
Figure 7: Diffuser tab populated with example diffuser configuration. The dimensions may be entered in units of meters or feet.

4.2.3 Effluent characteristics

Effluent characteristics consisting of flow rate, temperature, and salinity play an important role in determining the behavior of the effluent plume and initial dilution at the culmination of nearfield mixing. The wastewater effluent flow rate may vary during the year based on water use whether it is industrial or municipal effluent. Similarly, effluent temperature may vary depending on the season, particularly for treatment plants with settling ponds that are exposed to varying air temperatures. Effluent salinity for municipal and industrial outfalls is typically zero. For existing outfalls, the effluent characteristics are typically set or selected based on analysis of available monitoring data. Higher flow rates cause stronger jet mixing, but also deliver a large volume/mass and correspondingly have less dilution during subsequent phases. Conversely, lower flow rates provide lower jet mixing, but with a smaller volume/mass to mix, resulting in more dilution in turbulent mixing with ambient currents. In most situations, a combination of high effluent flow during low ambient currents results in the lowest dilutions. Regulatory guidance varies from state to state on how to select effluent characteristics. Most guidance documents suggest setting a combination of effluent flow rate, temperature, and salinity that would result in lowest dilutions, representative of critical conditions.

Click the *Effluent* Tab to enter input data related to effluent characteristics. The user also has an option to load previously saved effluent characteristics. Click the '*Load'* button to load the "Effluent_example.csv" file. Figure 8 shows loaded effluent characteristic values. Here the user also has the option to enter pollutant concentrations for two constituents of concern for mixing zone compliance

evaluation. The example effluent is a freshwater discharge at 8 million gallons per day (MGD) and has a temperature of 26.3°C. Only one pollutant is entered with a concentration of 100 mg/L. PLUMES2.0 will simulate all pollutants as conservative pollutants, meaning the pollutant concentration is only altered upon discharge by dilution in the ambient receiving water, unless a decay rate is entered on the *Ambient* tab (described in the next Section).

Also shown under the *Effluent* Tab is a table to enter data related to Mixing Zone dimensions. Figure 8 also shows a schematic representation of acute and chronic mixing zone for a single port outfall. Mixing zone requirements vary by state and are established in state water quality standards regulations. For the example case in the PLUMES2.0 package, the selected mixing zones are chronic mixing zone = 102 m, and acute mixing zone = 10.2 m. Mixing zone dimensions may also be loaded from a prior saved file. Click the *Load* button to see to see the "Mixing_Zone_Example.csv" file.

Click the "case" buttons for the effluent characteristics and mixing zone characteristics to select the case of interest before moving to the *Ambient* tab.

Figure 8: Effluent tab populated with example effluent characteristics. The flow rate units may be million gallons per day (MGD), cubic meters per second (cms), or cubic feet per second (cfs). Temperature units may be °C or °F. Concentration of pollutant may be in units of mg/L or kg/kg of effluent.

4.2.4   Ambient characteristics

Ambient characteristics are the receiving water properties near the outfall discharge. Specifically, PLUMES2.0 requires entry of properties that affect the mixing and dilution of the effluent plume. They include ambient currents and stratification defined by temperature and salinity profiles. Strong ambient currents lead to faster dilution through entrainment mixing. However, in some situations, results may be counterintuitive. Stronger currents could also mean that the plume and the effluent are transported rapidly to the mixing zone boundary before the dilution process is completed, with lower initial dilution values (D) than expected. Similarly, strong stratification may result in trapping of the plume lower in the water column, terminating the buoyancy-induced mixing. Lack of stratification may result in rapidly surfacing plume, in which case initial dilution may be limited by water depth. To account for such possibilities, regulatory agencies will run multiple scenarios under the range of expected ambient conditions to address the possibility that, for stratified waterbodies, the worst-case conditions could occur at either maximum or minimum stratification and during both low and high current speeds.

Figure 9 provides a schematic representation of a water column cross-section with salinity, temperature, and velocity profiles near a submerged outfall defining the ambient input data needed for setting up a project run. The figure shows U (x-component of velocity), T (temperature, °C), and S (salinity) plotted as a function of depth (measured positive from the water surface).

The *Ambient* tab (see Figure 10) includes columns to enter velocity magnitude and direction, temperature, and salinity data as water column profiles. Note that nearfield velocity column represents velocity profile at the diffuser site. Farfield velocity profile represents currents to be used by the model for farfield transport and dilution calculations which may be different from currents at the diffuser location. Often nearfield and farfield current profile are the same, but it is not uncommon see applications where tidally averaged current velocities are entered for farfield transport when the calculations are to be conducted over large distances and over multiple tidal cycles. As explained in the introduction, the final concentration of the pollutant after dilution is affected by the background concentration of the pollutant. The background concentration may be a natural condition or impacted by pollution from upstream sources. These values may be entered under the *Backg.Con* column. If the pollutant is conservative then there is no decay, but if the pollutant concentrations diminish with time, then a decay rate may be entered in the column under *Pollu.Decay.* For example, if the pollutant is fecal bacteria, then a die-off rate of ≈ 1/day may be entered as a preliminary default value based on median value from several studies (US EPA, 1985).

The last three columns on this page are data needed for conducting farfield dilution calculations using the Brooks' method. They include the farfield velocity profiles – magnitude and direction (these may be the same as nearfield), and α (*alpha*) that is used to compute initial eddy diffusivity ϵ_o in the Brooks farfield transport and dilution equations. Initial diffusivity is a function of initial plume width w_o and is defined by the equation below.

$$\varepsilon_o = \alpha(w_o)^{4/3} \tag{17}$$

where, α may vary from 0.0001 $m^{2/3}s^{-1}$ to 0.0005 $m^{2/3}s^{-1}$. A standard value of α = 0.00038 $m^{2/3}s^{-1}$ is the recommended default, suitable for most cases (Brooks, 1960).
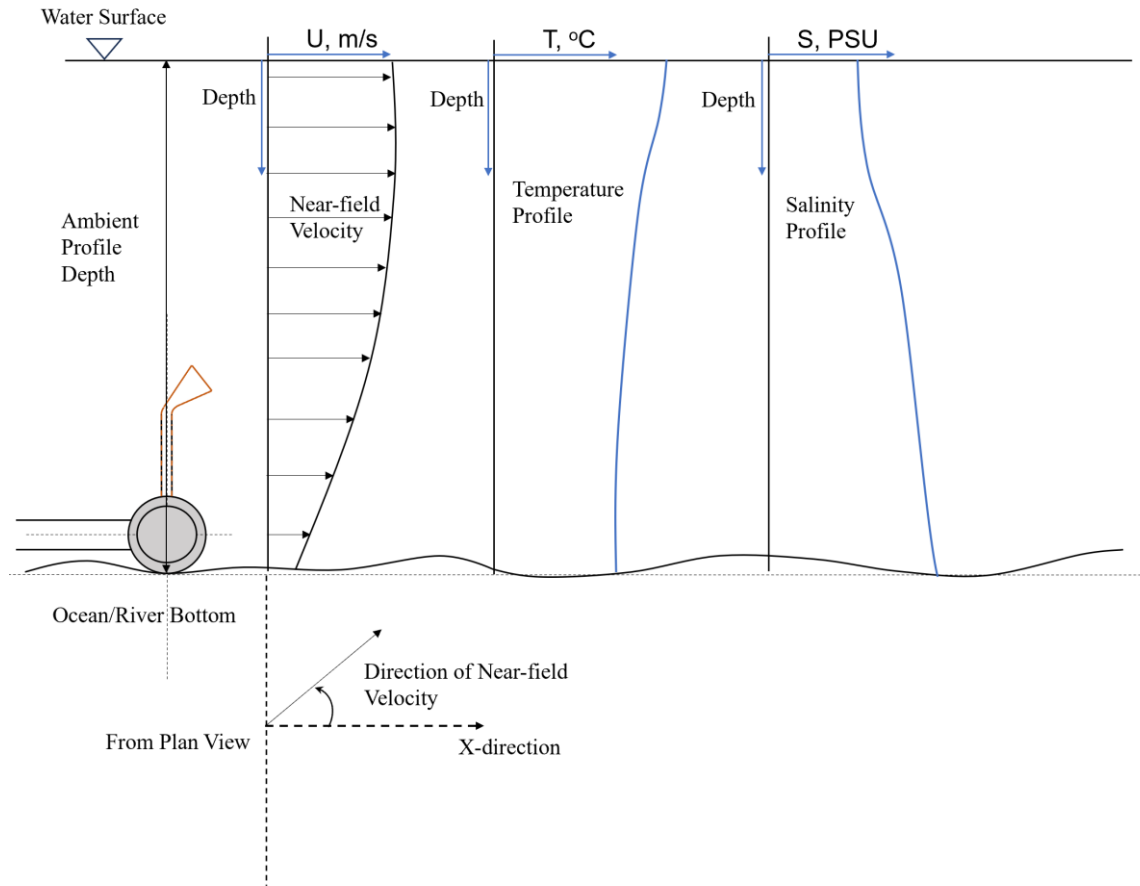
Figure 9: Schematic representation of ambient cross section near an outfall diffuser.

Click the *Ambient* Tab to enter input data related to ambient characteristics. The user also has an option to load a previously saved ambient characteristics. Click the *Load* button to see "Ambient_example.csv" file. Figure 10 shows loaded effluent characteristic values. In this example, the velocity profile shows currents varying in magnitude from 0.09 m/s at the surface to 0.05 m/s near the bottom. The current direction is 0°, so the current is flowing parallel to the shoreline (x-direction). The temperature profile shows warm temperatures of 14°C at the surface with a thermocline at 4 m depth, below which the temperatures are uniform at 8°C. Ambient salinity is 32 psu, uniformly distributed with depth. The farfield velocity field is populated with constant values of 0.05 m/s also flowing in the x-direction, the eddy diffusivity is set at the default α of 0.0003 $m^{2/3}$. Farfield calculations using Brooks' method assume constant ambient conditions, and the model determines those conditions based on the depth of the plume when the initial dilution ends (surface or plume trapping depth).

The user can visualize the *Ambient Profile* data by clicking the desired plot. Entered values may be saved as *.csv files for future use.

PLUMES2.0

Welcome   Project   Diffuser   Effluent   Ambient   Model Run   About

Ambient Data

	Depth	Near Velocity	Near Vel. Dir.	Salinity	Temp.	Backg. Con.	Pollu. Decay	Far-field Velocity	Far-field Vel. Dir.	Alpha
	m	m/s	deg	psu	C	mg/L	day^-1	m/s	deg	m^(2/3)/s
1	0.00E+00	9.00E-02	0.00E+00	3.20E+01	1.40E+01	0.00E+00	0.00E+00	5.00E-02	0.00E+00	3.00E-04
2	2.00E+00	8.50E-02	0.00E+00	3.20E+01	1.20E+01	0.00E+00	0.00E+00	5.00E-02	0.00E+00	3.00E-04
3	4.00E+00	7.00E-02	0.00E+00	3.20E+01	8.00E+00	0.00E+00	0.00E+00	5.00E-02	0.00E+00	3.00E-04
4	6.00E+00	6.50E-02	0.00E+00	3.20E+01	8.00E+00	0.00E+00	0.00E+00	5.00E-02	0.00E+00	3.00E-04
5	8.00E+00	6.00E-02	0.00E+00	3.20E+01	8.00E+00	0.00E+00	0.00E+00	5.00E-02	0.00E+00	3.00E-04

Save   Load   Print   Clear

Note: Eddy Diffusivity Eo = (alpha)*(width)^(4/3), Standard value of alpha is 0.00038 m^(2/3)/s which is suitable for many user cases.

Ambient Profiles

Currents
— U-velocity (x-direction)
— V-velocity (y-direction)
— Velocity Magnitude
Stratification

Velocity Along Depth

Figure 10: Ambient tab populated with example receiving water characteristics. Depth and velocity data may be entered in units of m and m/s or ft and ft/s.

4.2.5   Model Run

Once the diffuser, effluent, and ambient data entry are completed, the final model run settings may be selected and a dilution run initiated. Click the *Model Run* tab to enter the nearfield and farfield settings. For convenience, many of the menu items are pre-selected or pre-filled with default values.

Under the Nearfield Setting tab, the following three entries are pre-filled with default values (same values as Visual Plumes defaults for UM3; see insert below or Figure 11).

- Aspiration coefficient: The aspiration coefficient specifies the rate at which ambient fluid is entrained into the plume. The default value of 0.1 is an average value that has been commonly used. A different value causes increases or decreases in plume spreading and affects other characteristics, like plume rise.

- Diffuser contraction coefficient: Users may specify a contraction coefficient (reduction in area of the jet relative to the port area) based on the type of discharge ports on the diffuser. The discharge coefficient of sharp-edged ports (cylindrical hole in the diffuser pipe wall) is about 0.61. For

Nearfield Settings

Aspiration Coefficient	1.00E-01
Diffuser Contraction Coefficient	1.00E+00
Light Absorption Coefficient	1.60E-01

bell-shaped ports (flaring inward into the direction of flow), a value of 1.0 is usually used. The default value is 1.0.

- Light absorption coefficient (not used in current version of PLUMES2.0): This coefficient is provided as an option for future development. It is for specifying the light absorption coefficient for the Mancini bacteria model. This is the coefficient k_e found in Mancini, 1978, that describes water clarity. The default value is 0.16.
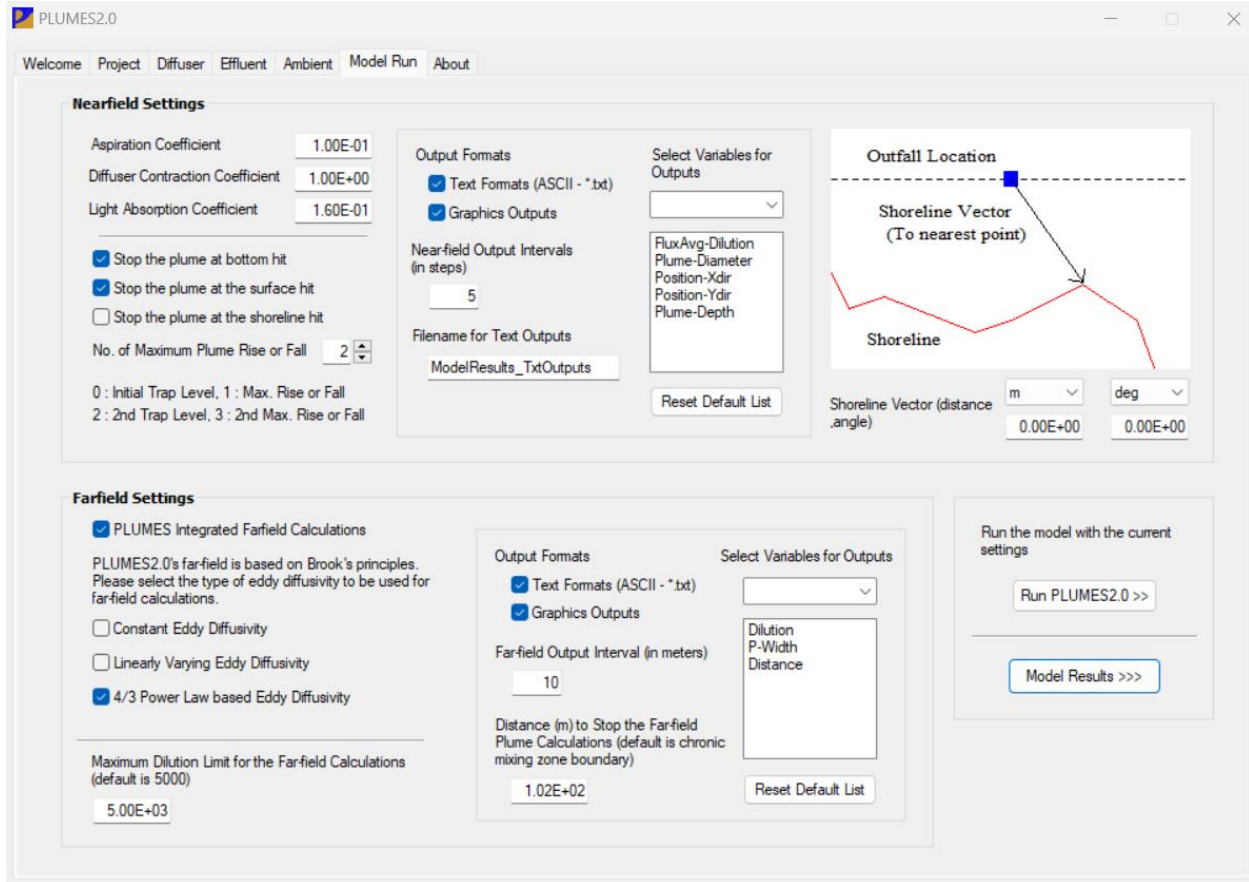
Figure 11: Model Run tab populated with example/default settings.

Here the user should also select the options that define termination of the initial dilution stage of calculations, based on impingement with boundaries including the bottom, free surface, shoreline, and/or trapping depth, by checking the suitable box(es). As shown in Figure 11, the boxes "Stop the plume at bottom hit" and the "Stop the plume at the surface hit" are checked as default. If these values are used, the initial dilution calculations will be terminated automatically if the plume surfaces or encounters the bottom. If the shoreline hit box is selected, then the model asks for the vector corresponding to the shortest distance to the shoreline from the diffuser. For atypical settings such as diffusers on a slope with downward facing ports, bottom impingement can occur immediately. The user must ensure that ambient water depth in such settings is significantly greater than the port depth.

Selection of "No of Maximum Plume Rise or Fall" (0, 1, 2, or 3) provides additional options to

instruct the program when to terminate initial dilution and begin far-field calculations. In some situations, the plume may stabilize in the middle of the water column, or the user may wish to allow the calculations to continue beyond surface interaction (boil). When "0" is selected, initial dilution is terminated during the initial plume rise when the neutral buoyancy depth (initial trapping depth) is reached. When "1" is selected, the plume momentum is allowed to carry it beyond the initial trapping depth to its maximum rise in the water column. When the default value of "2" is selected, gravity allows the plume to settle back to a new neutral buoyancy depth (2nd trapping depth). When "3" is selected, the downward momentum allows the plume to sink deeper beyond the 2nd trapping depth to its maximum fall. For discharges with negative vertical angle of the discharge, the rise and fall sequence is reversed. As described in in Frick et al. (2003), under ideal conditions a plume will oscillate about a varying trapping level at the so-called Brunt-Väisala frequency as a wave form.

A schematic is shown on the top right panel of the tab with cells for entering distance and direction to the shoreline. The convention for the angle is +tive counter-clockwise from the x-axis. Under "Output Formats", the user may enter the selections for type of model output (ascii text or graphical). The "Select Variables for Outputs", with a dropdown menu, allows the user to add more variables to be included in addition those indicated in the default list. Model results are written to output files at a user-defined number of intervals (steps). This allows the user to add or reduce the output resolution. For the nearfield, the setting is based on internal model steps and the highest resolution is setting the interval = 1 (model step). The default value in the model is set at 5.

Under the farfield settings section, the user may select linked computation of nearfield and farfield dilution by checking the box next to PLUMES Integrated farfield calculations (already checked as default). By doing so, the model transitions automatically from the nearfield phase to the farfield phase, using the projected area calculations to determine the initial wastefield width, and initiates the Brooks method for farfield dilution calculations. Depending on the nature of the ambient waterbody, the user may select (a) Constant Eddy Diffusivity (for rivers and narrow channels), (b) Linearly Varying Eddy Diffusivity (for estuarine condition), or (c) Eddy Diffusivity Variation based on Brooks 4/3rd law (for open ocean conditions, checked as default) (Table 2).

This tab also provides an option to limit Maximum Dilution (a high value such as 5000:1, default) or distance values (such as chronic mixing zone length or user-defined distance beyond the study area of interest) to terminate the farfield calculations. As in the nearfield menu, the user may select variables to be printed in addition to those listed as default and select text or graphical output formats (or both).

For the farfield model, the output interval is in meters and the default is set at 10 m. A larger number for the interval (steps for the nearfield and meters for farfield) results in lower spatial resolution but a shorter printout. The user may also enter the file name for the model results output file to be saved in the project directory.

Once the model inputs are completed, click the *Model Run* button to initiate the model run. If the inputs are complete and the model runs without errors, a message "Model run was completed successfully!" is displayed.

4.2.6   Model Results

The results are saved in the filename provided in the box under "Filename for Text Outputs" on the *Model Run* page. In this example the filename provided was "ModelResults_TxtOutputs". After the model runs, click OK to close the dialogue box indicating message "Model run was completed successfully!". At the lower right corner of the *Model Run* tab, a new *Model Results* tab becomes available following the completion of model run. Click the *Model Results* to see Graphic Outputs. Slide the Graphic Outputs window and move it to a side to see the Text Output window hidden behind.

The text output organization was deliberately designed to be identical to the output file that

users are familiar with from the Visual Plumes interface (see Figure 12). The Ambient Table and Diffuser Table summarize user-provided inputs for the scenario. Simulation Results are provided immediately below. The results are written in rows at the indicated model steps. The default output columns include (1) Flux-averaged Dilution, (2) Plume Diameter, (3) and (4) x- and y- coordinates of the plume centerline, (5) Plume depth relative to water surface. Optional user-specified output parameters included in the example in Figure 12 were (6) Plume salinity, and (7) Pollutant concentration. Note that the results are only presented in metric system of units.

In this example, the buoyant plume rises in the water column and is also carried away in the x-direction by the ambient currents. The plume dilution increases with each step as the plume rises all the way to the water surface. In this example, the upward momentum of the plume carries it past the trapping depth to the surface and the calculations are terminated when the plume outer boundary touches the water surface (see Figure 13(a)). A shown in the text output in Figure 12, this occurs when the plume upward momentum has carried it beyond the initial trapping depth of 3.0 m to a (plume centerline) depth of 2.5 m below the surface when the outer boundary of the plume touches the water surface. The volumetric dilution of the plume at this stage is 169.8:1.

If the user had unchecked the "Stop the plume at the surface hit", the upward momentum would have carried the plume to the boil-over stage to a maximum centerline elevation, a depth of 1.9 m. This distance is less than the plume diameter (≈7.8 m in this case) indicating the formation of a plume boil, and with a higher initial dilution of 185:1. With the "No. of Maximum Plume Rise of Fall" switch set at the default value of 2, the plume calculations continue. The plume reverses direction and falls back to the second trapping depth of 3.4 m. The plume at this stage is further away from the diffuser and at a higher initial dilution of 217:1. Note that caution is advised when using the model beyond the boundary interaction point (surface hit), because the model over-simplifies the complex mixing in a plume boil.

Back to the Figure 12 example, having checked PLUMES Integrated Farfield Calculations and Brooks 4/3rd Power Law for Eddy Diffusivity, the computations transition automatically to the farfield phase. The farfield calculations begin with two key, internally calculated wastefield characteristics: (1) starting dilution of the wastefield after initial dilution, 169:8, and (2) the width of the wastefield in the direction of the current (note that this will represent the width of merged plumes from a multiport diffuser). This internally computed value is based on final multiple merged plumes at the termination of initial dilution dimensions, affected by current direction and diffuser configuration (109 m in this example).

Results shown in Figure 12 indicate that, at a distance 100 m, just before the specified 102 m mixing zone boundary, flux averaged dilution of the plume is 176.7:1 and the wastefield is 143.1 m wide. To see the result at the exact 102 m distance, the user must set the farfield output interval to 1 m instead of the 5 m interval used in the example. .

In the Graphic Outputs window (see insert), the user can choose to explore numerous visualization options that are available. Two examples are provided below.

Figure 13 shows plots of the plume trajectory in x-y or Depth-X plane. Figure 13(a) corresponds to the case when the plume calculations were terminated at surface impact (consistent with the example project). Figure 13(b) corresponds to the case described above when plume calculations were allowed to go past the surface impact and shows the plume boiling over.

As shown in the insert to the right or in Figure 13, there are many plotting options available to the user for examining various plume properties such as Plume (flux averaged) Dilution, Plume Diameter, Plume (centerline dilution), Temperature, Salinity, and Density. Double-click each option to see the desired plot.

```
************************************************************************************
--------------------------------------------------------------------------------
Ambient Table:
   Depth   Amb-cur   Amb-dir   Amb-sal   Amb-tem   Amb-pol     Decay   Far-spd   Far-dir   Disprsn
       m       m/s       deg       psu         C     kg/kg       s-1       m/s       deg   m0.67/s2
   0.000     0.090     0.000    32.000    14.000     0.000     0.000     0.050     0.000   0.00030
   2.000     0.085     0.000    32.000    12.000     0.000     0.000     0.050     0.000   0.00030
   4.000     0.070     0.000    32.000     8.000     0.000     0.000     0.050     0.000   0.00030
   6.000     0.065     0.000    32.000     8.000     0.000     0.000     0.050     0.000   0.00030
   8.000     0.060     0.000    32.000     8.000     0.000     0.000     0.050     0.000   0.00030
  10.000     0.055     0.000    32.000     8.000     0.000     0.000     0.050     0.000   0.00030
  12.000     0.050     0.000    32.000     8.000     0.000     0.000     0.050     0.000   0.00030
--------------------------------------------------------------------------------
Diffuser Table:
   P-dia    P-elev   V-angle   H-angle     Ports   Spacing   AcuteMZ   ChrncMZ   P-depth   Ttl-flo   Eff-sal      Temp   Polutnt
     (m)       (m)     (deg)     (deg)        ()       (m)       (m)       (m)       (m)    (m3/s)     (psu)       (C)   (kg/kg)
    0.08      0.31     45.00     30.00     18.00      6.10     10.20    102.00     11.00      0.35      0.00      2.63    100.00
Simulation Results:
           Avg-Dil     P-dia    x-posn    y-posn     Depth
   Step         ()       (m)       (m)       (m)       (m)
      5      1.101     0.083     0.011     0.007   -10.987
     10      1.213     0.091     0.024     0.014   -10.972
     15      1.337     0.101     0.038     0.022   -10.956
     20      1.474     0.111     0.054     0.031   -10.938
     25      1.624     0.122     0.071     0.040   -10.919
     30      1.791     0.135     0.089     0.051   -10.898
     35      1.975     0.149     0.110     0.063   -10.874
     40      2.178     0.164     0.133     0.076   -10.848
     45      2.402     0.181     0.158     0.090   -10.820
     50      2.650     0.199     0.185     0.105   -10.789
     55      2.923     0.220     0.216     0.122   -10.754
     60      3.225     0.242     0.249     0.141   -10.717
     65      3.558     0.266     0.286     0.161   -10.676
     70      3.926     0.293     0.326     0.183   -10.631
     75      4.332     0.323     0.370     0.207   -10.582
     80      4.780     0.355     0.419     0.233   -10.528
     85      5.275     0.391     0.472     0.261   -10.469
     90      5.822     0.430     0.530     0.292   -10.405
     95      6.425     0.472     0.594     0.325   -10.335
    100      7.092     0.518     0.663     0.360   -10.259
    105      7.827     0.569     0.738     0.399   -10.176
    110      8.640     0.624     0.820     0.440   -10.085
    115      9.536     0.683     0.910     0.484    -9.987
    120     10.527     0.747     1.007     0.531    -9.879
    125     11.620     0.817     1.111     0.581    -9.763
    130     12.827     0.892     1.225     0.633    -9.636
    135     14.159     0.972     1.346     0.689    -9.499
    140     15.631     1.059     1.476     0.747    -9.351
    145     17.255     1.151     1.614     0.806    -9.192
    150     19.049     1.250     1.758     0.867    -9.024
    155     21.029     1.355     1.910     0.929    -8.844
    160     23.215     1.467     2.069     0.992    -8.654
    165     25.629     1.586     2.235     1.055    -8.453
    170     28.294     1.713     2.407     1.118    -8.241
    175     31.236     1.847     2.586     1.181    -8.017
    180     34.485     1.988     2.771     1.244    -7.782
    185     38.072     2.139     2.963     1.306    -7.536
    190     42.032     2.298     3.162     1.367    -7.278
    195     46.404     2.466     3.369     1.427    -7.008
    200     51.232     2.644     3.583     1.486    -6.726
    205     56.562     2.832     3.805     1.544    -6.432
    210     62.446     3.031     4.035     1.600    -6.126
    215     68.943     3.241     4.275     1.655    -5.807
    220     76.117     3.463     4.525     1.708    -5.475
    225     84.036     3.698     4.785     1.760    -5.132
    230     92.781     3.947     5.057     1.811    -4.775
    235    102.435     4.209     5.341     1.860    -4.406
    240    113.094     4.486     5.639     1.907    -4.024
    245    124.863     4.784     5.949     1.952    -3.632
    250    137.648     5.144     6.256     1.994    -3.263
-------------------------- Plume traps ---------------------------
    255    147.499     5.462     6.466     2.020    -3.029
---------------------- merging happened --------------------------
    260    155.017     5.722     6.621     2.038    -2.869
    265    161.123     5.987     6.763     2.055    -2.732
    270    165.961     6.243     6.894     2.069    -2.614
-------------------------- Plume surfaces ------------------------
    275    169.754     6.481     7.017     2.082    -2.512
---------------------- Starting Farfield Calculations -------------
Farfield dispersion based on wastefield width of :      109.59 (m)
4/3 Power Law based Eddy Diffusivity is used:
  Dilution     width  Distance
        ()       (m)       (m)
   169.754   109.610     7.320
   169.754   110.556    10.000
   169.754   114.075    20.000
   169.756   117.598    30.000
   169.795   121.149    40.000
   169.999   124.732    50.000
   170.519   128.345    60.000
   171.445   131.988    70.000
   172.796   135.662    80.000
   174.549   139.365    90.000
   176.666   143.099   100.000
.....................  Reached Chronic Mixing Zone .....................
   177.706   144.760   104.421
```

Figure 12: Example of ascii text format output from PLUMES2.0. Initial dilution was terminated when the plume boundary encountered the water surface, when the plume centerline was at a depth of 2.5 m below the water surface at an initial dilution of 169.8:1. The farfield calculations began at this point with a merged wastefield width of 109 m. The farfield calculations were terminated at the Chronic Mixing Zone boundary (102 m). The dilution of the plume at this distance was approximately 177:1 with interpolation.
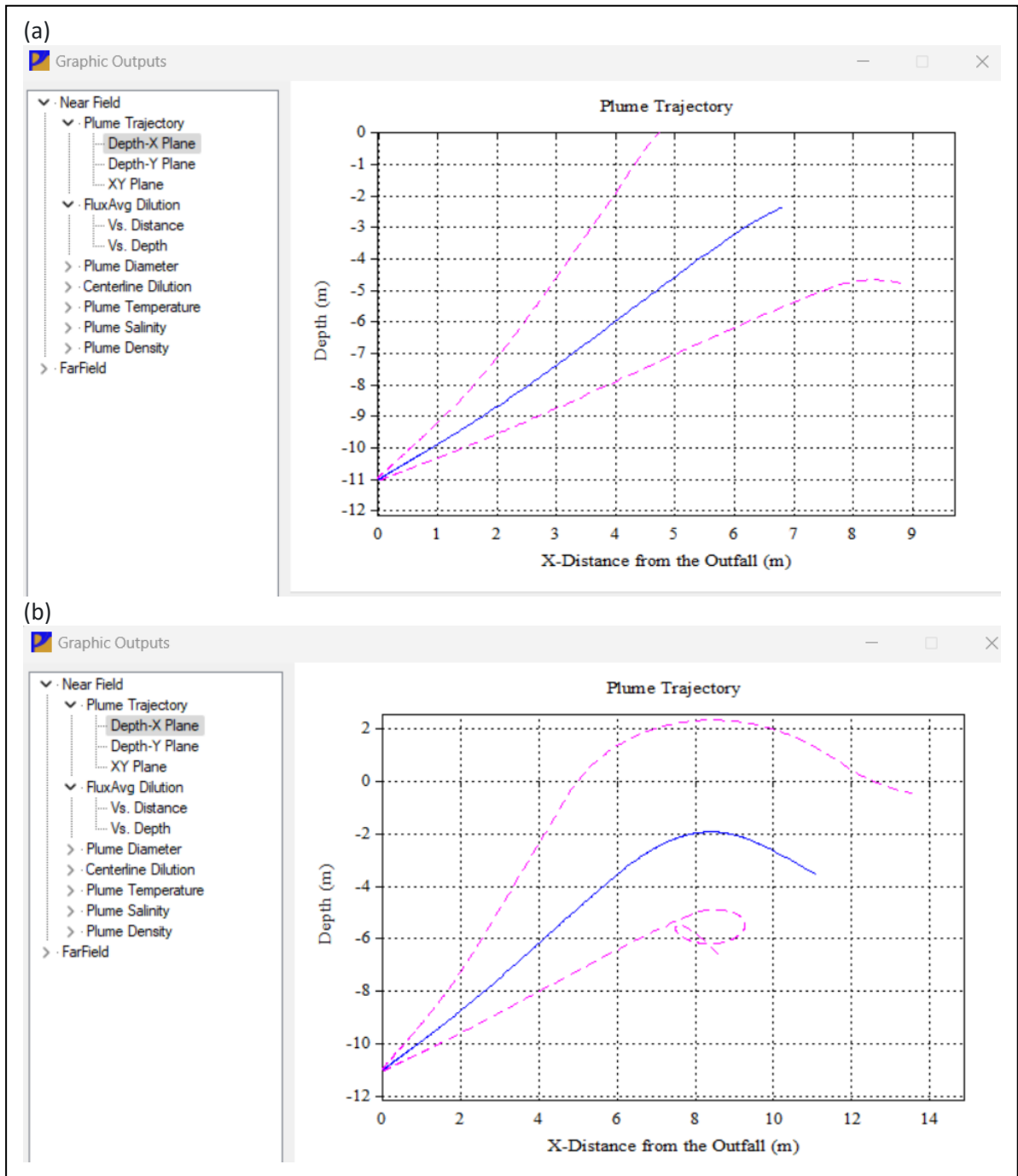
Figure 13: Example of plume trajectory in Depth-x plane until the termination of initial dilution phase. (a) initial dilution is terminated at surface hit; (b) initial dilution is allowed to continue past surface hit to completion of the boil.

4.2.7 Independent Farfield Calculation

There are many instances where effluent transport and mixing in the surface waters occurs without the benefit of nearfield mixing provided by an outfall diffuser. A wastefield may form because of discharges from multiple sources, irregularly distributed in a localized area. The wastefield may then be carried away by ambient currents being diluted by farfield mixing processes. Conventional use of a

dilution model such as PLUMES2.0 is not feasible in such instances. However, transport and dilution of the wastefield may be estimated through independent application of Brooks' laws.

To facilitate use of the model for such situations, we have included the Independent Farfield Calculation option. This can be accessed from the *Project* page. The only inputs required are (a) *Initial wastefield dilution* (existing dilution ratio at the start of farfield transport), (b) *Initial wastefield width*, (c) *Initial wastefield location* (distance from the outfall), (d) *Mixing zone location* (distance from the outfall), and (e) *Ambient current velocity*. If *Initial wastefield dilution* is known, then the Brooks' calculations provide the combined Farfield dilution as a function of distance travelled. If the initial dilution is unknown, the users may enter 1 (a conservative approach assuming no dilution of the effluent in the wastefield at the start of farfield calculations). The Brooks' calculations then provide a relative farfield dilution factor.
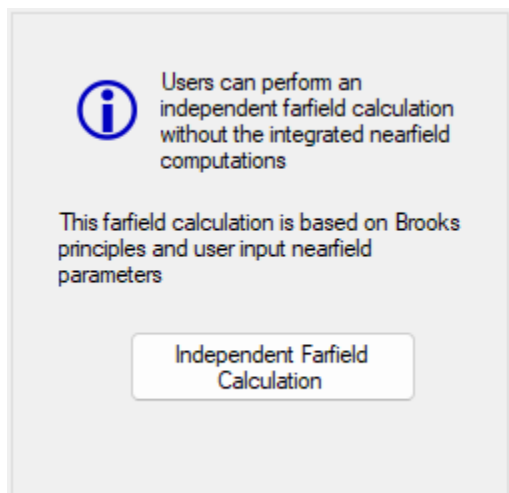
Click the Independent Farfield Calculation button. This opens a new dialogue box. It is not possible to save the settings of the Independent farfield calculations, so the user must input values each time.

In this example, *Initial wastefield dilution* was set at 100:1. *Initial wastefield width* was set at 50 m. The *Initial wastefield location* was set to 0.001 m. (note this value can be as small as 0.001m but not zero). The mixing zone boundary was set at 200 m from the outfall. The unidirectional ambient current speed (same as Farfield velocity) was set at 0.05 m/s. The value of α that is used to estimate initial Eddy Diffusivity of the wastefield is set at 0.0003 as a default. Results for this example are shown in Figure 14 below.

The user has the option to select the variation of Eddy Diffusivity based on the environment. Typically, Constant Eddy diffusivity is selected for rivers and bounded channels, Linearly Varying Eddy diffusivity is recommended for estuarine settings, and Brooks' 4/3rd power law variation is recommended for open ocean conditions. The user has the option to specify the Initial Concentration of the Pollutant in the wastefield, and a decay rate if applicable. Click the Run Farfield Calculations button to initiate the Independent Farfield Simulation. The text output results open in a new window and must be saved by clicking the File and Save as options.

```
┌─────────────────────────────────────────────────────────────────┐
│  ⚡ Text Outputs for Independent Farfield Calculation              │
├─────────────────────────────────────────────────────────────────┤
│  File   Edit   Search                                             │
├─────────────────────────────────────────────────────────────────┤
│  🖨 🔍 | 🗋 🔖 🗙                                                    │
├─────────────────────────────────────────────────────────────────┤
│ Farfield dispersion based on wastefield width of :     50.00 (m) │
│ 4/3 Power Law based Eddy Diffusivity is used:                    │
│ ---------------------------------------------------------------- │
│ The alpha value used for dispersion calculation:      0.0003     │
│ The ambient current in the farfield (m/s):    0.0500             │
│ ************************************************************************ │
│ Simulation Results:                                              │
│ ---------------------------------------------------------------- │
│     Conc   Dilution     width   Distance        Time             │
│   (kg/m^3)     ()         (m)       (m)        (hrs.)            │
│     0.000   100.000     52.137     8.001        0.044            │
│     0.000   100.004     54.303    16.001        0.089            │
│     0.000   100.100     56.499    24.001        0.133            │
│     0.000   100.495     58.724    32.001        0.178            │
│     0.000   101.326     60.977    40.001        0.222            │
│     0.000   102.609     63.258    48.001        0.267            │
│     0.000   104.294     65.567    56.001        0.311            │
│     0.000   106.319     67.903    64.001        0.356            │
│     0.000   108.625     70.266    72.001        0.400            │
│     0.000   111.163     72.657    80.001        0.444            │
│     0.000   113.894     75.073    88.001        0.489            │
│     0.000   116.786     77.516    96.001        0.533            │
│     0.000   119.816     79.985   104.000        0.578            │
│     0.000   122.965     82.480   112.000        0.622            │
│     0.000   126.216     85.000   120.000        0.667            │
│     0.000   129.559     87.545   128.000        0.711            │
│     0.000   132.984     90.115   136.000        0.756            │
│     0.000   136.483     92.709   144.000        0.800            │
│     0.000   140.049     95.329   152.000        0.844            │
│     0.000   143.678     97.972   160.000        0.889            │
│     0.000   147.365    100.639   168.000        0.933            │
│     0.000   151.106    103.330   176.000        0.978            │
│     0.000   154.899    106.045   184.000        1.022            │
│     0.000   158.740    108.783   192.000        1.067            │
│     0.000   162.627    111.544   200.000        1.111            │
│     0.000   166.559    114.328   208.000        1.156            │
│     0.000   170.534    117.135   216.000        1.200            │
│     0.000   174.550    119.965   224.000        1.244            │
└─────────────────────────────────────────────────────────────────┘
```

Figure 14: Example of Farfield plume trajectory in -x direction. Initial wastefield width was set to 50 m and ambient current carrying the wastefield or plume away from the source was 0.05 m/s.

In its present state of development, the user does not have control over the output interval in the independent farfield calculator. The calculator divides the user-defined distance to the mixing zone boundary into 25 steps, and 3 additional steps beyond the mixing zone boundary are included in the output. In the example above, the distance to the mixing zone boundary (200 m) is divided by the fixed number of output steps (25) and the model outputs the dilution in 8 m intervals. Three additional steps past the mixing zone boundary result in the final model output at 224 m.

5   Summary and Discussion

The Visual Plumes (UM3) model has been a workhorse for public domain mixing zone modeling for many years. The original Visual Plumes was a Windows-based computer application that superseded the DOS based PLUMES mixing zone modeling system. However, its availability and usability waned in recent years due to compatibility issues with the latest versions of mandatory Windows upgrades. As a result, many users were inconvenienced. SSMC scientists had developed a Fortran version of UM3 as part of the Salish Sea Model. The objective of this work was to take advantage of the preliminary development efforts by the SSMC scientists and develop, test, and release a new version of PLUMES (PLUMES2.0) along with a User's Manual. This goal has been accomplished with potential for future improvements such as addition of carbonate chemistry modules for pH and total alkalinity (TA) and simplified dissolved oxygen kinetics. Since then, the model development team has become aware of another (web based) public domain version of Visual Plumes UM3 offered by the San Francisco Estuary Institute and the Aquatic Science Center (SFEI 2024). The user community is therefore now well supported by two independent sources of public domain software based on the Visual Plumes suite of tools.

The simplicity and ease of use allows PLUMES2.0 application to many complex problems. For example, simulation of dissolved oxygen (DO) or pH can be supported by PLUMES2.0 estimates of nearfield dilution to estimate concentrations prior to further biogeochemical or carbonate chemistry analyses. However, caution must be exercised as many settings will likely fall outside of the ideal combinations of diffuser geometries and receiving water conditions that were assumed in the development of the model formulations and numerical solutions. For example, the model assumes steady state and laterally uniform receiving water conditions with a cross flow. In stagnant environments or in tidally reversing currents, re-entrainment can occur. The actual dilutions of the effluent may be different from those provided by the model due to unsteady conditions and cumulative effects on ambient concentrations. Limitations of the model relating to boundary interaction was discussed previously. While the model provides options for the plume calculations to be terminated upon boundary impingement, experienced users may use the model beyond this limit with proper selections of eddy diffusivity and other parameters. Validation of model predictions using dye-dilution field studies is recommended while using PLUMES2.0 in complex and non-ideal settings. Similarly, although the model is designed to accommodate only regular geometry (e.g., linear diffuser with all ports in the same direction), experienced users can simulate irregular settings by breaking up the complex discharges into simpler geometries and using the principle of superposition. It is also important to note that the model was designed for simulating buoyant discharges. Discharge of brine or sediment loaded fluids heavier than ambient through PLUMES2.0 is possible by adjusting the density through T and S, but the model will terminate soon after the initial jet phase as the plume with water heavier than ambient begins to reverse before the initial dilution process is completed. Also, as discussed in Section 2.3.1, the model provides an estimate of centerline dilution, which is the minimum dilution for circular plumes with the understanding that dilution can vary significantly from near the port to the termination of initial dilution.

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Appendices

Appendix A: Quality Assurance

A.1. Quality Assurance Project Plan

The information generated in this report was performed under CEMM Quality Assurance Project Plan (QAPP) "Quality Assurance Project Plan for - Development of Visual Plumes Model Update (PLUMES 2.0)" J-ACESD-0033631-QP-1-1, approval date: June 27, 2023.

A.2. Quality Assurance Audit

An audit, J-IO-Audit-1537, was conducted on this project and findings were identified. Corrective actions were implemented and completed prior to the closing of the audit. The audit was closed prior to this STICS clearance.

The findings from the audit were as follows.

Finding 01: Deviation documented, approved, and closed: The information required from the contractor was received in a different format as described in the QAPP. The deviation of format was determined to be acceptable by the EPA Project Lead.

Finding 02: Deviation documented, approved, and closed: The comment-line documentation was determined insufficient during the audit of J-IO-Audit-1537 from the contractor and whether it has been corrected to the satisfaction of the technical lead of the project. Contractor corrected and the code was reviewed to be satisfactory by the EPA Project Lead.

Finding 03: Documented and closed. GUI testing and verification needed to state what was done for testing, whether it was documented at the time of testing, and attach any supporting information identifying the testing was done. This includes internal Technical Reviews or summary of test results (All Pass or Satisfactory or not), and whether the type/amount of testing that has been done is satisfactory to still meet the Data Quality Objectives identified in the QAPP and pose any limitations on the quality of the system.

Finding 04: Deviation documented, approved, and closed Records were missing from the contractor on for code versioning, and the difference in tools used. Documentation includes potential impacts this may or may not pose once code is transferred to the EPA. No further corrective action can be performed for not having proper versioning. EPA will perform proper versioning once the application is transferred to the EPA moving forward.

The corrective actions for each deviation that resulted in a finding for the audit J-IO-Audit-1537, were deemed acceptable at addressing the root cause of the finding. Objective evidence supplied demonstrated corrective actions were put in place; therefore, this audit was closed prior to clearance of this product.

A.3. Data Quality Summary

This effort included comparing model results from testing (see Appendix B : PLUMES2.0 Model Validation and Testing) to previously reported Visual Plumes model runs and resulting output.

# Appendix B: PLUMES2.0 Model Validation and Testing

Verification and testing were conducted for the three main stages of the PLUMES2.0 development process. The objective was to ensure that the Fortran based PLUMES2.0 reproduced the Visual Plumes (VP) UM3 model outputs for both nearfield and farfield calculations. The first stage of testing and verification was conducted after the completion of nearfield development. A comprehensive set of scenario cases were simulated with PLUMES2.0 covering a wide range of ambient currents, stratifications (temperature and salinity), discharge flowrates, and several diffuser configurations (i.e., single port/multiport/different port orientation angles/staggered/non-staggered). The results were then compared with the corresponding outputs produced by UM3. In the second stage of testing, similar comprehensive scenarios were examined for the farfield plume parameters computed with Brooks principles implemented in PLUMES2.0. The model results were compared against the Brooks farfield parameters produced by Visual Plumes. Third stage testing and verification was conducted to ensure the proper operation of the GUI.
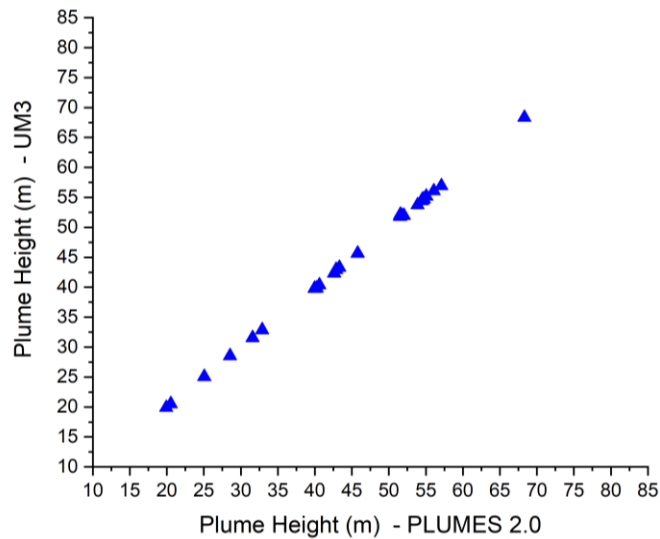
B.1 Nearfield Dilution

The model testing and validation were conducted for three major plume parameters: (1) Plume diameter; (2) Plume height; and (3) Plume dilution at termination of nearfield mixing. Figures A.1, A.2, and A.3 compare PLUMES2.0 model performance against UM3 results. As shown in the figures, the PLUMES2.0 produces almost identical results to those from UM3 for all the cases. Although we expect the results to be identical, the differences are caused by differences in precision levels in language specific intrinsic mathematical functions. Table A.1 shows the model skill metric (Average absolute relative error percentage) for each plume parameter which is less than 0.5%. This demonstrates that the PLUMES2.0 can robustly reproduce the UM3 model performance for the nearfield plume parameters together with the fate of the plume (trapping, surfacing, merging, and bottom contact).
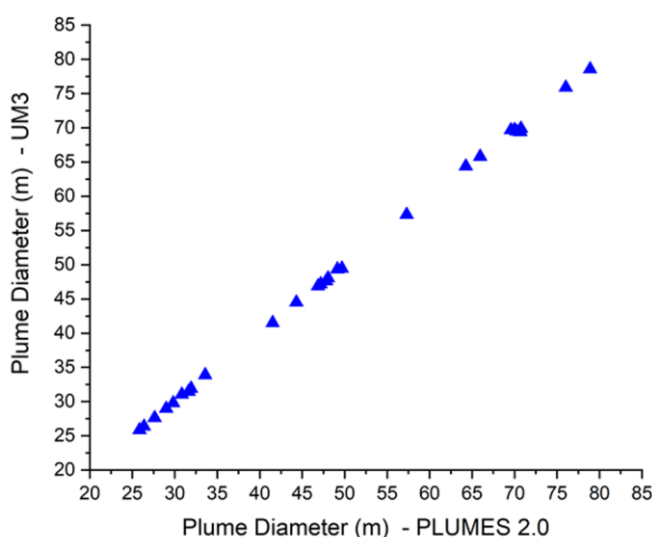
Figure B.1: The Comparisons of PLUME 2.0 results and UM3 model results; Plume diameter.
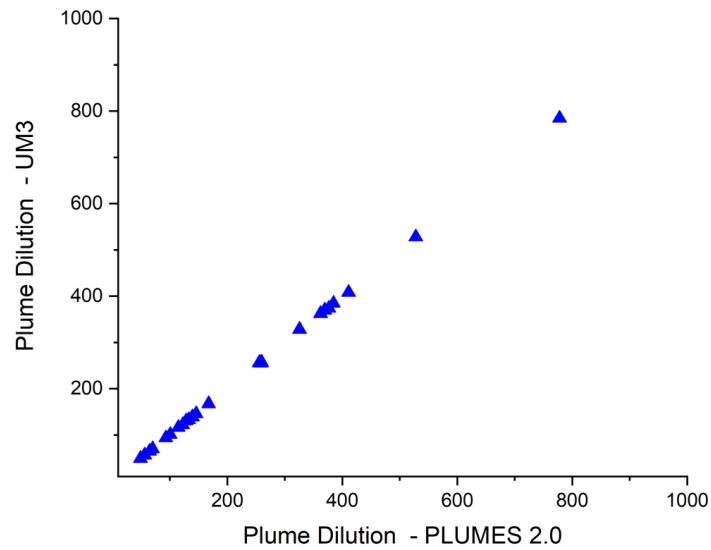
Figure B.2: The Comparisons of PLUME 2.0 results and UM3 model results; Plume Dilution.

Figure B.3: Comparison of PLUMES2.0 results and UM3 model results; Plume height at the conclusion of initial dilution.

Table B.1: PLUMES2.0 Model Skill Relative to Visual Plumes for Nearfield Plume Parameters

Model Skill Assessment – Averaged absolute error percentages		
Plume diameter (%)	Plume height (%)	Plume dilution (%)
0.37	0.26	0.41

R^2 statistics for plume dilution was calculated as $R^2 = 0.9999$. Similarly, for plume diameter, $R^2 = 0.9996$. Both meet the acceptance criteria of $R^2 = 1.0$.

Table B.2: Comparison of PLUMES2.0 output and VP (UM3) Output for Nearfield Plume Dilution
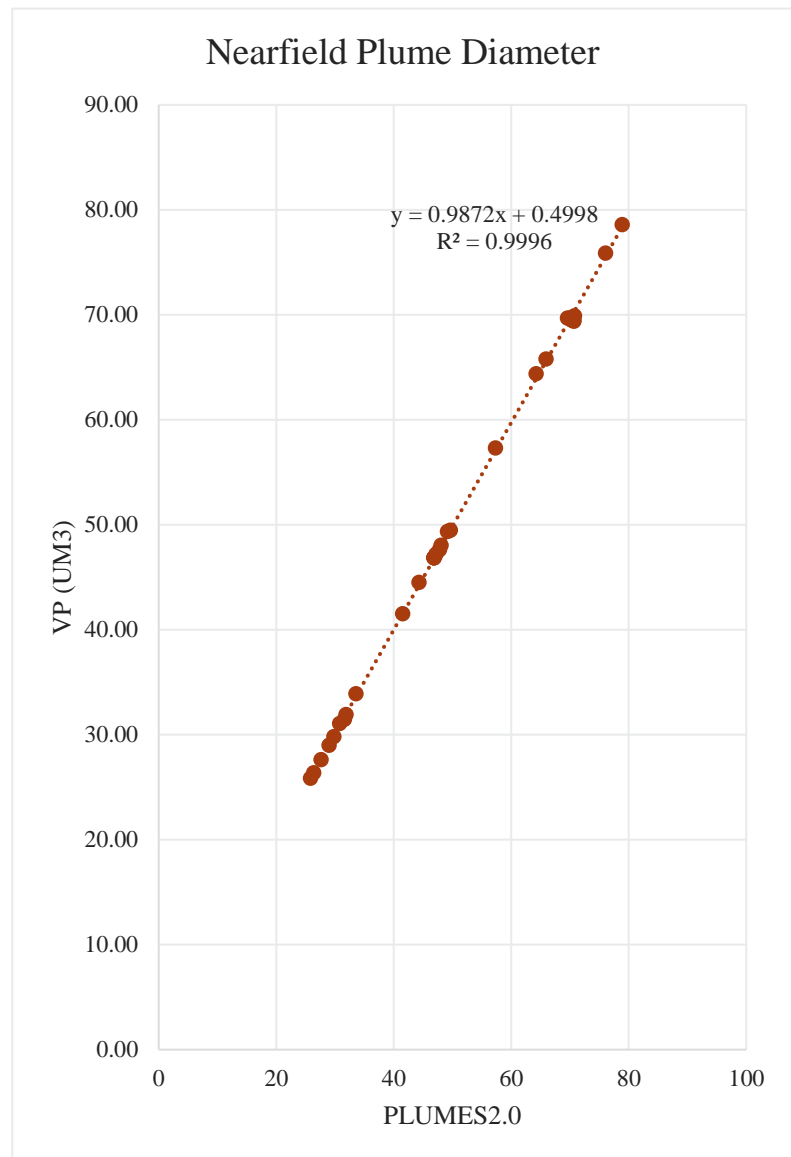
Nearfield Plume Dilution	
PLUMES2.0	VP (UM3)
132.714803	133.00
362.409223	362.40
122.412558	122.00
114.73999	116.10
128.264756	130.20
527.947369	527.90
325.749201	328.20
376.840461	373.90
369.656583	369.70
384.58932	384.60
410.996562	408.10
362.409203	362.40
362.409206	362.40
362.409211	362.40
167.45121	167.50
145.845113	145.80
778.153221	784.50
255.734072	256.20
259.15555	255.60
259.356519	256.00
259.649461	257.40
256.902562	256.20
257.164794	255.30
93.0727418	93.69
139.245838	138.80
100.646919	101.10
64.7438084	64.74
56.3660052	56.37
70.0746303	70.07
70.073837	70.07
49.0750747	49.08
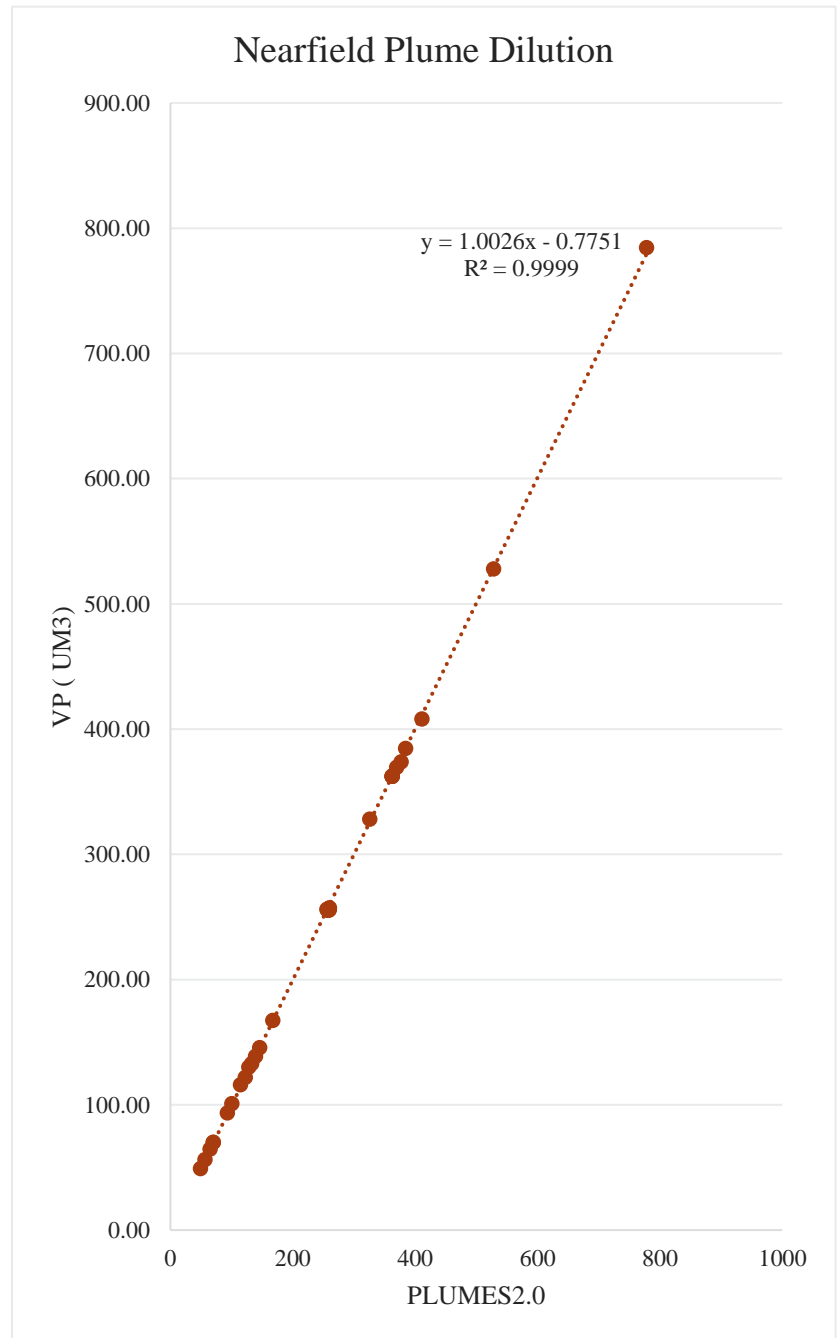
Figure B.4: Nearfield Plume Dilution Comparison of PLUMES2.0 results and UM3 model

Table B.3. Comparison of PLUMES2.0 output and VP (UM3) Output for Nearfield Plume Diameter

Nearfield Plume Diameter	
PLUMES2.0	VP (UM3)
65.9576239	65.79
46.8691099	46.87
31.6317789	31.48
30.8299141	31.06
33.5800443	33.90
57.3057271	57.31
44.3267589	44.51
47.8163873	47.61
47.1856959	47.19
48.0446643	48.04
49.6646848	49.47
46.8681112	46.87
46.8682562	46.87
46.8684768	46.87
31.9081993	31.91
29.811709	29.81
49.147933	49.36
69.5674545	69.68
70.6634704	69.40
70.6760233	69.47
70.7648909	69.90
69.976245	69.70
70.2115447	69.50
64.2614455	64.39
78.8906576	78.59
76.0334049	75.89
41.5216712	41.52
27.6311397	27.63
26.3766259	26.38
25.8573627	25.86
29.0015315	29.00

Nearfield Plume Diameter

$y = 0.9872x + 0.4998$
$R^2 = 0.9996$

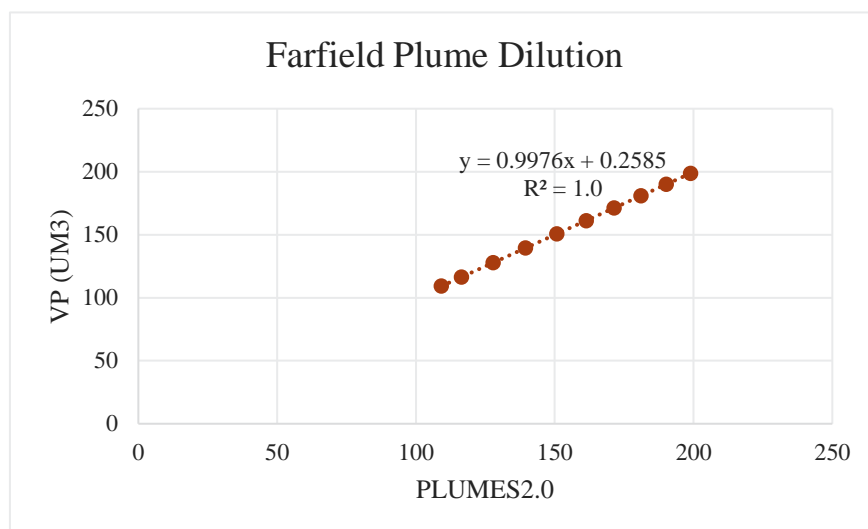**Figure B.5:** Nearfield Plume Diameter Comparison of PLUMES2.0 results and UM3 model

B.2 Farfield Dilution

Since the Brooks farfield model is comprised of a set of explicit analytical equations, no specific numerical modeling technique is required to calculate the associated farfield parameters. PLUMES2.0's farfield results were compared against the Visual Plumes model results for various farfield ambient conditions as part of quality assurance and quality control validation. The model comparisons shown in Figure A.4 is for 12 cases of different ambient conditions with both constant eddy diffusivity and 4/3 power law-based eddy diffusivity (option 1 and 3). The relative error percentages for dilution of plume width predictions of PLUMES2.0 in comparison with Visual Plumes for 12 farfield cases are listed in Table A.2. For each test, R^2 = 1.0000, which meets the evaluation criteria of R^2 = 1.0.

**Table B.4.** Comparison of PLUMES2.0 Output and VP (UM3) Output for Farfield Plume Dilution

Farfield Plume Dilution	
PLUMES2.0	VP (UM3)
109.182	109.2
116.41	116.4
127.797	127.7
139.479	139.4
150.703	150.6
161.35	161.2
171.445	171.3
181.04	180.9
190.191	190
198.947	198.7

Farfield Plume Dilution

$y = 0.9976x + 0.2585$
$R^2 = 1.0$

Figure B.6: Nearfield Plume Diameter Comparison of PLUMES2.0 results and UM3 model

Table B.5. Comparison of PLUMES2.0 output and VP (UM3) Output for Farfield Plume Width

Farfield Plume Width	
PLUMES2.0	VP (UM3)
65.217	65.19
77.715	77.66
88.464	88.39
98.042	97.95
106.764	106.7
114.825	114.7
122.356	122.2
129.45	129.3
136.175	136
142.583	142.4
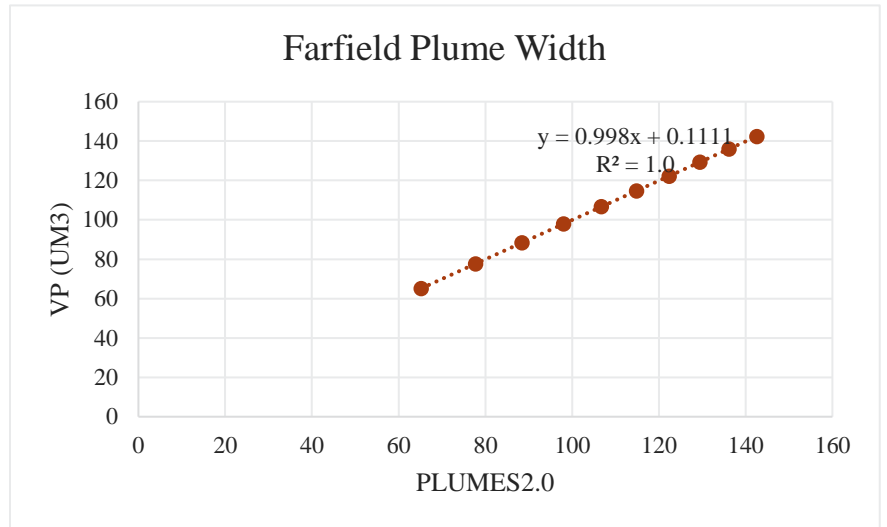
Figure B.7: Farfield Plume Width Comparison of PLUMES2.0 results and UM3 model.
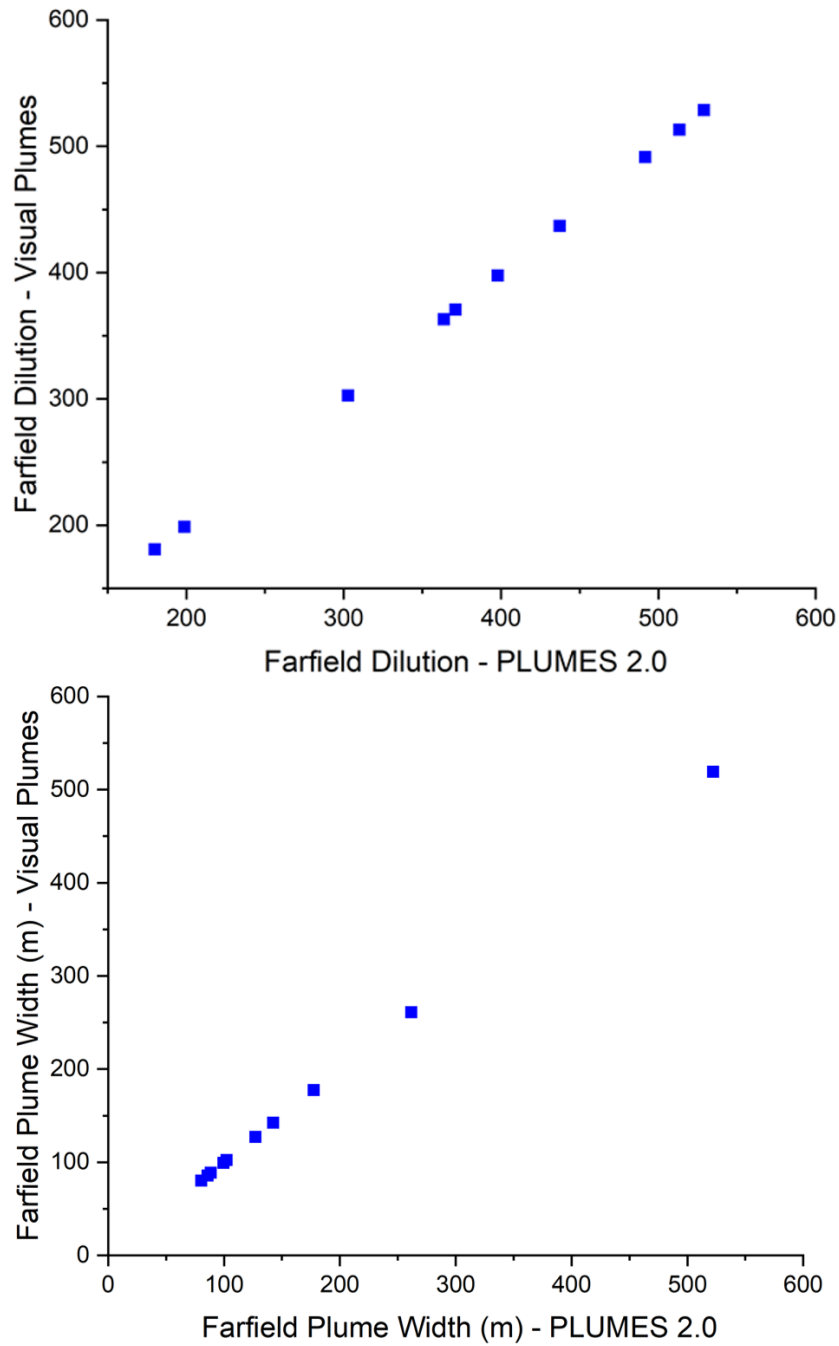
Figure B.8: Comparison of PLUMES2.0 Farfield prediction with Visual Plume results – Farfield Dilution and Plume Width.

Table B.6: PLUMES2.0 Model Skill Relative to Visual Plumes for Farfield Plume Parameters
for the 12 test cases

Dilution Ratio Relative Error (%)	Plume Width Relative Error (%)
0.12	0.13
0.25	0.26
0.06	0.09
0.13	0.15
0.06	0.07
0.09	0.10
0.54	0.07
0.07	0.62
0.03	0.06
0.06	0.08
0.12	0.13
0.25	0.26

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