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Managing Water in the West

Evaluation of Approaches to Determine Mixing and Assimilation of Reuse Effluent

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Mission Statements

The U.S. Department of the Interior protects America's natural resources and heritage, honors our cultures and tribal communities, and supplies the energy to power our future.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

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Executive Summary

This scoping proposal provided a literature review and proposed research to provide hydrodynamic modeling of effluent reuse in reservoirs. Surface waters-- especially lakes and reservoirs-- are considered to be the main source of drinking water around the globe; however, most of these waters are subjected to discharge of secondary or tertiary treated effluents.

Because different hydrodynamic models exist for different physical conditions and reservoir characteristics, the need exists to research different hydrodynamic modeling approaches. As such, this research summarized state-of-the-science hydrodynamic models useful in simulating reuse effluent in reservoirs. The research identified hydrodynamic models as either near-field or far field; near-field modeling is defined by the spread of discharge dominated by characteristics of an outflow jet into the reservoir (on the order of tens to hundred meters from the outflow jet with time scales from seconds to minutes), whereas far-field modeling is defined by longer travel times and mixing distances (occurring in time scales ranging from several hours to days within distances of the order of hundreds meters to tens kilometers from the discharge point).

The proposal seeks to provide guidelines on how best to couple near-field and far-field hydrodynamic modeling based on a reservoir's physical characteristics, and offers a step-by –step approach future research. This approach involves determining time step and grid resolution for both the near field and far field coupled models, which will ultimately simulate a plume geometry and concentration of reuse effluent in reservoirs.

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1 Introduction

The ultimate goal of supplying potable water is to provide high-quality water (Manzetti & Ghisi, 2014). Surface waters, especially lakes and reservoirs are considered to be the main source of drinking water around the globe (or in the United States). However, most of these waters are subjected to discharge of secondary or tertiary treated effluents (Hawker, Cumming, Neale, Bartkow, & Escher, 2011; Oppenheimer, Eaton, Badruzzaman, Haghani, & Jacangelo, 2011).

Although a robust wastewater treatment prior to discharge as well as efficient water treatment could insure the quality of the drinking water, monitoring of discharged effluents can also enhance the quality of delivered water to treatment plants and reduce the treatment costs (Brookes et al., 2005; Jeznach, Jones, Matthews, Tobiason, & Ahlfeld, 2016). As discharged effluent will ultimately serve as a portion of the influent for water treatment plants in cases of surface water augmentation, the discharge of even a highly treated effluent is still associated with potential health risks. Malfunction or failure of the wastewater treatment processes, release of refractory contaminants, or compounds with undiscovered health effects are some of potential hazards related to discharge of wastewater to the aquatic environments (Deblonde, Cossu-Leguille, & Hartemann, 2011; Farré, Pérez, Kantiani, & Barceló, 2008; Pal, He, Jekel, Reinhard, & Gin, 2014). In this context lake or reservoir can act as an environmental buffer which allows the discharged effluent to undergo a series of additional processes of degradation and dilution (Hawker et al., 2011; Jeznach et al., 2016). Natural chemical and biological processes such as sorption, sedimentation, biodegradation, photochemical degradation, and microbial transformation can result in further reduction of contaminant concentrations as they travel from its discharge point to the intake point (Brookes et al., 2004; Tollefsen, Nizzetto, & Huggett, 2012).

Discharged effluents may contain non-biodegradable and emerging organic contaminants (EOCs) such as nitrosodimethylamines (NDMA) (the most potent carcinogen detected in potable waters, recalcitrant to treatment even by RO) or Bisphenol A (BPA) (a carcinogen and with potential endocrine disruptive effects) that are generally recalcitrant to treatment even by advanced treatment processes (Farré et al., 2008; Hawker et al., 2011; Pal et al., 2014). For such persistent contaminants as well as compounds with undiscovered health risks, dilution and dispersion of the purified effluent into a large body of water can substantially reduce potential contaminant concentrations (Davidsen et al., 2015; Ding, Hannoun, & List, 2012). Hence, the degree of mixing of effluent with receiving waters and travel time are the two key points of a multiple barrier approach to reduce public health risks (Preston, Hannoun, & List, 2011; Torres et al., 2015).

Salinity and temperature are the most important parameters in in determining the density of water and consequently density stratification in lakes and reservoirs. In general, salinity is low in lakes and reservoirs that are considered as a source of drinking water; and therefore, temperature is the determining factor in their density stratification (Okely, Imberger, & Antenucci, 2010; Preston, Hannoun, List, Rackley, & Tietjen, 2014). Thermal stratification, which is more apparent during the summer, can result in formation of three layers of water known as epilimnion, metalimnion (thermocline), and hypolimnion. Thermal stratification, especially during the summer, decreases the vertical mixing within the lakes and in the absence of wind-driven circulation can result in the lateral spread of the discharged effluent without much vertical mixing through the water column (Bocaniov, Ullmann, Rinke, Lamb, & Boehrer, 2014; B. R. Hodges, Imberger, Saggio, & Winters, 2000). In this situation, the retention time or travel time can be shortened compared to a well-mixed lake. Consequently the concentrations of the discharged contaminants at the point of intake for a drinking system could be much higher than the well-mixed situation (Ding et al., 2012; Stocker & Imberger, 2003). Surface winds and managed withdrawals for irrigation of power generation in reservoirs and lakes can result in mixing due to upwelling and internal waves. Addition of turbulent kinetic energy from wind forces can drive vertical motions that reduce thermal stratification and increase mixing (Çalişkan & Elçi, 2009; Diamessis & Nomura, 2004). The dilution and mixing behavior of the purified effluent in receiving waters is determined by lake geometry, inflow and outflow volumes, density of effluent and ambient waters, velocity and orientation of the discharge, wind forces, thermal and meteorological conditions.

2 Hydrodynamic modeling

2.1 Selection of appropriate modeling approach

The complexities and interactions among the interacting parameters often require the use of numerical approaches to obtain an accurate estimate of the mixing and transport processes (Fischer, List, Koh, Imberger, & Brooks., 1979; Kelley, Hobgood, Bedford, & Schwab, 1998; Thupaki, Phanikumar, & Whitman, 2013). Selection of an appropriate model to accurately simulate mixing and transport depends on the geometry of the water impoundment, the region of interest (e.g. near field or far field), and the type of required results from hydrodynamic model. Different processes control the shape and dilution of the plume in the near and far fields. Mixing behavior of the discharged effluent can generally be described in three different regions: near-field, intermediate field, and far-field mixing (Fischer et al., 1979; Roberts, 1999a, 1999b; Xue-Yong Zhang, 1995).

In near-field mixing, the spread of discharge is mostly dominated by characteristics of the outflow (jet) such as discharge velocity, orientation, and discharge depth. A model with small spatial and short temporal scales is required to accurately describe the near-field mixing in the vicinity of the discharge point. However, in the far-field, mixing behavior is dominated by the ambient flow conditions which function in much larger temporal and special scales, including current, ambient diffusivities and internal waves, if present (Choi & Lee, 2007; Hunt et al., 2010; Suh, 2001). Dilution in the intermediate or transition region depends on buoyant spreading motions that depend on relationships between ambient density gradients, plume buoyancy and ambient current velocity. The intermediate region is starting to be described as the region where a “handshake” takes place between the near-field and far-field mixing models (Bleninger, 2006; Choi, Lai, & Lee, 2016).

Several computer models with different modeling approaches, assumptions, and capabilities have been developed to predict the behavior of the discharged effluents.

CORMIX, VISUAL PLUMES, VISJET, and PROTEUS are the computer models most often used for simulating initial effluent discharge in the near field (Niu, 2008; Palomar, Lara, Losada, Rodrigo, & Alvarez, 2012; Palomar, Lara, & Losada, 2012). These models have a variety of input options, including buoyancy flux, outfall geometry, ambient velocity and stratification, and can be used to successfully simulate near-field mixing. Studies have shown that CORMIX, which is a U.S. EPA supported model, provides more accurate results for the near-field mixing compared to other commercial models. CORMIX also contains a built-in decision support interface which can be used for regulatory discharge analysis.

Generally, a problem with the near-field mixing models is that as the plume moves away from its source, the influence of the discharge characteristics becomes less important and instead, ambient conditions dominate the mixing processes (Bleninger, 2006; Jones, Nash, Doneker, & Jirka, 2007; MixZon Inc., 2016). In fact, steady state models or models with time and depth averaged values are not capable of simulating time-dependent variant current speeds in the far-field region. Although CORMIX provides a one-dimensional far-field model, three dimensional models with higher accuracy would be required for decision-making purposes. In addition, modeling tools such as CORMIX neglect the role of unsteady turbulence and internal waves that greatly influence mixing behavior in the far-field (Bleninger, 2006; Morelissen, Kaaij, & Bleninger, 2011; Niu, 2008).

In the far field, three dimensional models such as DELFT3D, POM, MIKE21/3, ECOM-si, and EFDC with a capability of simulating time-dependent motions are able to provide more accurate estimates (Bleninger & Jirka., 2004; Bleninger, 2006; Niu, 2008). Spatial and temporal scales of mixing processes in near-field and far-field processes are very different. Near-field mixing is focused on the processes taking place at distances on the order of tens to hundred meters from the outflow jet with time scales from seconds to minutes. However, far-field mixing is dominated by the processes occurring in time scales ranging from several hours to days within distances of the order of hundreds meters to tens kilometers from the discharge point. Therefore, far-field models with coarse grid sizes are not able to resolve near- field motions, and as a result cannot predict the contaminant concentration in the near field (Bleninger, 2006; Morelissen, van der Kaaij & Bleninger, 2013; Niu, 2008; Xue-Yong Zhang, 1995).

Recent studies suggest adopting coupling approaches by considering two different near-field and far- field mixing models. In the coupled system, interactions of both models with each other should be taken into account. In the other words, results of the near-field should be used as the inputs to the far-field model, and feedback from the far-field model should also be used to adjust the near-field model (two-way coupling method). When coupling the models, it is important to ascertain that buoyant spreading motions in the transition have been taken into account (Morelissen et al., 2013; Morelissen, Vlijm, Hwang, Doneker, & Ramachandran, 2015; Paper, Autran, Bmt, Edward, & Bmt, 2016).

2.2 Previous coupling studies

Zhang and Adams (1999) coupled NRFIELD (one of the modules in VISUAL PLUMES, formerly known as RSB) as the near-field model to ECOM-si as the far-field model to study the mixing processes related to the Boston wastewater outfall. Since the

NRFIELD model cannot predict plume trajectories or centerline flux development, the interactions between the two models could not be fully taken into account (X.-Y. Zhang & Adams, 1999).

Roberts (1999) coupled NRFIELD to FRFIELD using a particle tracking method to model an outfall in Hawaii. No circulation between near-field and far-field was considered, but in a one-way coupling approach, velocity measurements from the near-field were introduced to the particle tracking algorithm (Roberts, 1999a, 1999b).

Bleninger (2006) proposed a sophisticated method for coupling CORMIX and Delft3D that successfully took intermediate mixing into account. However, in the proposed one-way method, consideration of the feedback from the ambient flow in the near-field model was not sufficient \(Bleninger, 2006).

In a comprehensive two-way coupling method, Choi and Lee (2007) connected JETLAG (one of the VISJET modules) with EFDC as the far-field model. Using a distributed entrainment sink approach (DESA) the diluted plume information from the intermediate-field was transferred to the cells of the far- field region, and feedback from the ambient flow of the far-field was also introduced to the intermediate zone. However, buoyant spreading motions were not fully considered in the system (Choi & Lee, 2007). Niu (2008, 2011) used PROMISE as the near-field model and MIKE 3 as far-field model. To improve the interactions between the two models, Niu adopted a two-way approach for coupling. In comparison with CORMIX, the PROMISE model also represented satisfactory results (Niu, Lee, Husain, Veitch, & Bose, 2011; Niu, 2008).

Morelissen , van der Kaaij and Bleninger further improved the Bleninger's (2006) approach in the use of CORMIX and Delft3D mixing models. Using the DESA method proposed by Choi and Lee (2007), Bleninger's one-way method was improved to two-way method (Morelissen, Kaaij, & Bleninger, 2011; Morelissen, Kaaij, Vossen, & Vossen, 2011; Morelissen et al., 2013).

Zhao et al. (2013) coupled VISJET as the near-field model with a far-field model based on an explicit second-order finite difference method to simulate Grand Banks of Newfoundland, Canada. A dynamic coupling system based on method of (Choi & Lee, 2007) with consideration of the interaction between the discharged was employed in their model. The field validations were in good agreement with modeled processes both the near-field and far-field (Zhao, Chen, & Lee, 2013).

Morelissen et al. (2015) used CORMIX and DELFT3D for the modeling of large-scale cooling water outfalls. They further developed the distributed entrainment sinks approach which was proposed by (Choi & Lee, 2007) . The improved coupled model was validated against field measurements. The field measurement agreed well with the model and indicated that this coupled approach resulted in more precise and safer predictions l (Morelissen et al., 2015). Table 1 summarizes models and coupling methods used in a number of previous coupling studies.

Table 1. Previous coupling studies in hydrodynamic modeling

Author(s)	Near field	Far field	Coupling method
Zhang and Adams (1999)	RSB (VISUAL PLUMES)	ECOM-si	One-way
Roberts (1999)	NRFIELD (VP)	FRFIELD (VP)	One-way
Choi and Lee (2005)	VISJET	EFDC	Two-way
Bleninger (2006)	CORMIX	DELFT3D	One-way
Niu (2008, 2011)	PROMISE	Mike3	Two-way
Morelissen, Kaaij, Bleninger (2011a, 2011b, 2013)	CORMIX	DELFT3D	Two-way
Zhao et al. (2013)	VISJET	Finite difference	Two-way
Morelissen et al. (2015)	CORMIX	DELFT3D	Two-way

2.3 Review of available near-field models

CORMIX , VISUAL PLUMES , and VISJET are the most prominent available models for discharge analysis and simulation in the near-field region. The features, capabilities and limitations of each model are briefly described below:

2.3.1 CORMIX

CORMIX is an Eulerian modeling tool, supported by U.S. EPA which can used for discharge simulation in near-field and intermediate-field regions. A flow classification system based on hydrodynamic criteria and empirical knowledge from field experiments enables the model user to distinguish different flow classes with distinct hydrodynamic properties. Some additional features of the model are:

Batch running mode and time-series data, sensitivity analysis, GIS linkage, considering upstream intrusion, buoyant spreading, wind induced entrainment, passive diffusion in the far field region, capability of design optimization and regulatory discharge zone analysis:

The major limitations of CORMIX are as follows:

1) It is a steady-state model, and as a result, the user is unable to consider the spatial and temporal variations of ambient currents.
2) Due to adopted simplifications in the far-field region, the model does not fully consider the dilution in lateral direction, and therefore, the predictions in the far-field region may not always be accurate (Bleninger, 2006; MixZon Inc., 2016; Morelissen et al., 2015; Niu, 2008; Palomar, Lara, Losada, et al., 2012; Palomar, Lara, & Losada, 2012).

2.3.2 VISUAL PLUMES

VISUAL PLUMES is an Eulerian computer model, supported by U.S. EPA that can be used for simulation of single and merging submerged plumes. It is able to simulate the mixing process in arbitrarily-stratified ambient flow and buoyant surface discharges. Some additional capabilities of this model are: sensitivity analysis, conservative tidal background-pollutant build-up, and multi-stressor pathogen decay model that predicts coliform bacteria mortality based on temperature, salinity, solar insolation, and water column light absorption.

The most prominent limitations of this model are:

1) It is not able to simulate spatial variation of field velocities

2) The model does not have a module for intermediate mixing.

3) The far-field model is very rough and does not consider upstream intrusions or vertical mixing (Frick et al., 2003; Niu, 2008; Palomar, Lara, Losada, et al., 2012; Palomar, Lara, & Losada, 2012).

2.3.3 VISJET

VISJET can be used to simulate a single or group of buoyant jets in uniform or stratified ambient flows. Instead of solving the Eulerian equations of fluid dynamics and mass transport, this Lagrangian model works based on tracking the evolution of average properties of the plume element at different steps by conservation of momentum, heat.

Limitations:

1) The model is restricted to near-field simulation and cannot predict the mixing situation in intermediate or far-field region (Choi & Lee, 2007; Niu, 2008; Palomar, Lara, Losada, et al., 2012; Palomar, Lara, & Losada, 2012; “VISJET” 2016).

2.4 Far-field models

There are over 30 professional modeling tools which are capable of simulating unsteady environmental hydrodynamics. Among them are MIKE 3 (from DHI - Danish Hydraulics Institute), POM (Princeton Ocean Model - Princeton University), ECOM-si (modified version of POM used at Hydroqual), Delft3D (from Delft Hydraulics), ELCOM (from University of Western Australia), Telemac 3D (from EDF, Electricité de France, and Wallingford), and SisBAHIA (University of Rio de Janeiro, COPPE, 2000), which are the most cited models applied in area of hydraulic modeling of lakes and reservoirs. MIKE3, DELFT3D, and ELCOM are the two best-known models with wide environmental and hydrodynamic applications that have been used in coupled models in recent years. They are more user-friendly and contain modules that simplify the coupling process (Bleninger & Jirka, 2010; Bleninger, 2006; Choi & Lee, 2007; Niu, 2008). The features, capabilities and limitations of MIKE3, DELFT3D, and ELCOM are briefly described below:

2.4.1 MIKE3

MIKE3 is a hydrodynamic package developed by the Danish Hydraulics Institute (DHI). MIKE3 contains several modules which can be applied to simulate hydraulic behavior in reservoirs, lakes, and estuaries. It is able to generate flexible mesh grids to improve the precision and computational efficiency of predictions. MIKE3 is a general package that is able to simulate time-dependent currents, bathymetry, density variation, as well as external meteorological forces.

Limitation:

1) The model is restricted to far-field simulation and cannot predict the jet trajectory and mixing situation in near-field region (Bleninger, 2006; DHI, 2016; Niu et al., 2011; Niu, 2008).

2.4.2 DELFT3D

DELFT3D is a software package developed by the Delft Hydraulics Institute in the Netherlands, and has wide range of applications in modeling of lakes, reservoirs, river, coastal and estuarine areas. Different hydrodynamic conditions such as unsteady currents, variation of water elevations, density, salinity and vertical diffusivity and viscosity can be defined for the model. The software package contains several interacting modules that enable it to simulate various hydrodynamic and environmental phenomena including fluid motions, morphological developments, sediment transport, far-field and mid-field water quality, and ecological processes.

Limitation:

1) The DELFT3D model is restricted to far-field simulation and cannot predict the jet trajectory and mixing situation in the vicinity of the discharge point (Bleninger, & Jirka, 2010; Bleninger, 2006; Morelissen et al., 2015; Niu, 2008).

2.4.3 ELCOM

The estuary, lake and coastal ocean model (ELCOM) is a three-dimensional hydrodynamic model developed by the University of Western Australia. ELCOM's numerical methods have been described by Hodges (2000). It can be used for simulation of transport, mixing, and salinity distribution in stratified water bodies. ELCOM has been used to model internal waves in a stratified lake (Hodges, Imberger, Saggio, and Winters, 2000). ELCOM can be coupled with the CAEDYM (Computational Aquatic Ecosystem Dynamics Model) to simulate the biogeochemical processes influencing water quality. The ELCOM-CAEDYM model has been used in previous reservoir modelling studies, including Padre Dam/San Vicente Reservoir (Ding, Hannoun and List, 2012) and Lake Mead (List, Hannoun and Preston, 2011; Preston, Hannoun, List, Rackley, and Tietjen, 2014a, 2014b).

Limitations:

1) The ELCOM model is restricted to far-field simulation, and grid sizes considered in previous studies have been coarser than those of studies with other far-

field models such as DELFT3D or MIKE3.

2) Based on literature reviewed to date (Bleninger, 2006; B. Hodges, 2000; Marti, Mills, & Imberger, 2011; Niu, 2008), there aren't any studies that couple ELCOM with a near-field model. As a result, while general procedures of exchanging information between near-field and far-field models will likely apply, additional work would be needed to establish specific approach to couple ELCOM with a near-field model such as CORMIX.

2.5 Proposed coupled near-field and far-field models:

After an extensive literature review, and considering capabilities and limitations of available tools, a combination of CORMIX (for near-field modeling) and DELFT3D (for far-field modeling) is recommended to be used for this project. Justifications for selecting these models are summarized as follows:

2.5.1 CORMIX

CORMIX is a standard modeling tool which has been applied for a wide range of regulatory problems since 1988. It is a user-friendly modeling tool, capable of design optimization and performing sensitivity and regulatory discharge analyses (Jirka, Doneker, & Hinton, 1996; MixZon Inc., 2016).

Since the use of different models may lead to inconsistent results, for situations where determination of a minimum regulatory near-field dilution is important, use of CORMIX as a U.S. EPA approved modeling tool, would be very beneficial.

According to its website (MixZon Inc., 2016), CORMIX is a widely-used package that provides documented analysis to over 6,000 environmental professionals around the world. Hydrodynamic studies also confirm that CORMIX provides more accurate results compared to other modeling tools, especially for the intermediate mixing region (Bleninger, 2006; Morelissen et al., 2013; Niu, 2008).

Bleninger (2006) in comparing different near field models, stated that they should also be seen in the context. VISJET and CORMIX are commercial models with order of magnitudes difference in pricing VISJET prices for a commercial/academic license are 300 / 150 US $, whereas comparable CORMIX prices are 5,200 / 1,500 US $). However, the CORMIX system includes a high-level of quality assurance, professional support and detailed documentation (Jirka et al., 1996), help system and bug fixing. VISJET, although it is more academically oriented, is at the beginning in that regard.

2.5.2 DELFT3D

In general, selection of a far-field model is less critical than selection of the near-field model. All major far-field models such as DELFT3D, MIKE3, and POM/ECOM can be employed to simulate mixing processes. However, DELFT3D has more capabilities focused on assessment of discharged effluents in water bodies. User friendliness and the capability of efficiently coupling with CORMIX are the other benefits of using DELFT3D. It should be mentioned that, in several recent modeling studies, a combination of CORMIX and DELFT3D has been adopted as an efficient system for predicting discharge mixing and transport. As a result, a large number of verified coupling instructions and validation methods are available for the CORMIX/DELFT3D system than for other software combinations (Bleninger & Jirka, 2010; Tobias Bleninger, 2006; Morelissen, Kaaij, & Bleninger, 2011; Morelissen, Kaaij, Vossen, et al., 2011; Morelissen et al., 2013, 2015).

2.6 Dynamic aspects of coupling

Based on the degree of interaction between near-field and far-field models, coupling methods can be classified in two major categories:

2.6.0.1 One-way/offline (passive) coupling

In this approach it is assumed that the source-driven flow does not affect the flow properties of the far- field region. Therefore, only the properties of ambient flow and diluted concentrations at the end of the near-field need to be transferred between the models, and the dynamics of the ambient conditions are not fully considered in the near-field model. It should be mentioned, if source induced motions can change the ambient flow properties, the passive coupling method should not be used (Morelissen et al., 2013, 2015; Niu, 2008).

2.6.0.2 Two-way/online (active) coupling

In this method, the results of both near-field and far-field are transferred to each other. As a result, near field-induced motions will be considered in the far field model, and in the same way, variations of ambient flow in the far field will be fed back to the near-field model (Morelissen et al., 2013, 2015; Niu, 2008).

2.6.1 Coupling time step

Since the aim is to couple a steady model (near-field) to a time dependent model (far-field), a time scale for the coupled system needs to be defined. The time step should be small enough to reflect the ambient variations in the far-field region. It should be mentioned that the plume’s travel time from the discharge point to the coupling location is also a determining factor (Bleninger, 2006; Niu, 2008).

2.6.2 Coupling location

An appropriate coupling location mostly depends on, coupling time step, properties of discharged flow, and the predictions of the near-field model. Generally, if the buoyant spreading motions are considerable, the coupling location can be defied at the end of intermediate region. For the case that buoyant spreading motions are not significant, the end of near-field region would be an appropriate coupling location. In order to transfer the results between the near-field and far-field models, a minimumfar-field grid resolution also needs to be defined (Tobias Bleninger, 2006; Morelissen et al., 2013; Niu, 2008).

2.6.3 Steps for two-way coupling method

Details of a two-way coupling algorithm can be found in (Choi & Lee, 2007; Morelissen, Kaaij, Vossen, et al., 2011; Morelissen et al., 2015). A summary of their approach is as follows:

1) In the first step, based on a reasonable time step and grid resolution (Courant number < 0.5) the boundary and initial conditions should be defined for the far-field model (DELFT3D).

2) In the next step, the results of far-field model (DELFT3D for example), should be introduced to the near-field model (CORMIX) to determine the required minimum grid size and coupling time step. The obtained grid resolution and time step should be then *re-defined* for the far-field model, and predictions (refined results) of the far-field model should be introduced to the near-field model.

3) By running the near-field model, plume geometry and concentration will be obtained. This information is then used as the source information for the far-field model to predict the mixing in the far-field region. After that, the far field model can progress to the next time step. If the elapsed time is less than the coupling time step, the model should continue running until time attains the next coupling time step.

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