A NEW APPROACH TO EFFLUENT PLUME MODELLING IN THE INTERMEDIATE FIELD

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Abstract

In many densely populated coastal cities in Asia, wastewater discharges are often located in close proximity to sensitive areas such as beaches or shellfisheries. The impact and risk assessment of effluent discharges poses particular technical challenges, as pollutant concentration needs to be accurately predicted both in the near field and intermediate field.

The active mixing close to the discharge can be modelled by proven plume models, while the fate and transport beyond the mixing zone can be well-predicted by 3D circulation models. These models are usually applied separately with essentially only one-way coupling. Important phenomena such as surface buoyant spread or source-induced changes in ambient stratification cannot be addressed by such an approach.

A new method is proposed to model effluent mixing and transport in the intermediate field by dynamic coupling of a three-dimensional (3D) far field model with a Lagrangian near field plume model. The action of the plume on the surrounding flow is modelled by an equivalent diluted source flow at the predicted terminal height of rise and a distribution of sinks along the plume trajectory. In this way, a two-way dynamic link is established at grid cell level between the near and far field models. The accuracy of the method is demonstrated for a number of complex flows including the interaction of a confined rising plume with ambient stratification, and the mixing of a line plume in cross-flow. The general method can be readily implemented in existing circulation models to yield accurate predictions of the intermediate/far field.

Keywords: Plume modelling; Circulation Model; Near field; Far field; Intermediate field; Effluent discharge; Dynamic coupling; Environmental impact assessment.

1. INTRODUCTION

For environmental risk assessment it is necessary to predict the impact of effluent discharges for a wide range of discharge and ambient conditions. For many densely populated coastal cities in Asian Pacific countries, this prediction poses particular technical challenges. The effluent discharges are typically located in relatively shallow waters of 5-20 m depth, in close proximity to sensitive receivers such as beaches and fisheries. Sound management decisions on the appropriate degree of treatment must be based on impact assessment models that can cater for both the near field and intermediate/far field.

In the immediate vicinity of the discharge ("near field"), the jet trajectory and mixing are mainly governed by the source momentum flux, buoyancy flux, outfall geometry, and ambient velocity and stratification (Fig.1). The influence of the source characteristics decreases further away from the discharge point. The region where the effluent is passively transported by ambient currents and further diluted by ambient turbulent diffusion is referred to as the "far field". In the near-far field transition ("intermediate field"), the dynamics depends on both the jet momentum and buoyancy, and the ambient flow. To correctly simulate the dominant physical processes in this region, the dynamic near field effects of the discharge and the corresponding volume and mass fluxes need to be properly modelled in the far field model.

Zhang and Adams (1999) employed the 3D circulation model ECOMsi, and the near field model RSB, which only provided the plume trap height, volumetric dilution and plume width to tackle the problem. Four methods for interfacing the near and far field models were considered: 1) introduce the discharge flow and pollution load as source terms at the discharge point; 2) introduce source flow at discharge point, and release the pollution load at the trap height predicted by RSB; 3) introduce both the diluted flow and the pollution load at the predicted trap height; and 4) only introduce the pollution load at the predicted trap height. The last method is the most commonly adopted approach in practice. Due to the limitations of the near field model employed, there is not much interaction between the near and far field models.

Kim et al. (2002) coupled a jet integral model and a particle tracking model to simulate the mixing of a single buoyant jet discharge. Far field mixing and transport are simulated by particles introduced at the equilibrium rise height or the end of the computed initial mixing zone. The model results were compared with laboratory experiments for a non-stratified crossflow. The flow field or velocity distribution was not generated by 3D flow model, but interpolated from the integral jet model predictions. Although the two models are linked, there is no dynamic interaction between them.

More recently, Bleninger and Jirka (2004) proposed a methodology to couple the near-field mixing zone model CORMIX and the flow and the Delft3D circulation model. An approach similar to method 3 of Zhang and Adams (1999) is adopted, whereby the discharge volume and mass fluxes at the terminal height computed by CORMIX are incorporated into the far field model.

All of the methods described above involve either "one-way coupling" or weakly "two-way coupling"; hence the dynamic effects of the plume mixing are not reflected in the far field model. True dynamic coupling of near and far field models representing the interaction between the effluent discharge and the surrounding ambient flow has hitherto not been reported.

2. THE METHOD OF DYNAMIC COUPLING

To provide a truly “two-way coupling” between the near field and far field models, it is proposed to represent the effluent discharge by introducing (i) the predicted diluted flow and pollution loading at the predicted terminal level of plume rise; and (ii) a series of entrainment sinks along the predicted plume trajectory. These sources and sinks are determined from an embedded near field model and incorporated into the far field model.

The key difference between the new approach and the commonly employed “source only” methods is the modelling of near field plume mixing by the equivalent source and sink terms at “grid cell” level in the far field model. In so doing, the interaction of the plume entrainment and the ambient flow and density are modelled in a way similar to the “filling box” mechanism described by Turner (1973). The diluted flow and mass sources fill up the spreading layer at the trapping level, while the entrainment sinks draw the ambient fluids back into the plume. Hence, the effect of unsteady evolution of the ambient flow on the plume trajectory and dilution, as well as the changes in plume mixing on the ambient flow are fully accounted for.

To represent the effluent discharge, the corresponding volumetric and mass source/sinks are introduced in the governing equations for the 3D far field model. We have the continuity equation as:

$$\frac{\partial U}{\partial x}+\frac{\partial V}{\partial y}+\frac{\partial W}{\partial z}=Q_s \tag{1}$$

and the mass transport equation (for both salinity and tracer) as

$$\frac{\partial(HC)}{\partial t}+\overline{\mathrm{V}}\cdot\nabla(HC)=\frac{\partial}{\partial x}\left[Hq_x\right]+\frac{\partial}{\partial y}\left[Hq_y\right]+\frac{\partial}{\partial z}\left[E_v H\frac{\partial C}{\partial z}\right]+Q_C \tag{2}$$

The effect of the ambient flow (vertical profile of ambient velocity and density) on the plume trajectory is predicted by the near field model and will be reflected in the positions of the sources and sinks. In view of the typically large difference in length scales between the near and far field models, it is not necessary to consider the plume momentum separately in the far field model. Only volumetric and mass sources/sinks are needed, that is term Q_s and Q_C in Equation 1 and 2.

In the present study, the 3D flow model is based on the Environmental Fluid Dynamics Code (EFDC) which is a public domain modelling system for solving the surface water flow and transport problems (Hamrick 1992). EFDC is a finite difference model that solves the shallow water equations using the Mellor and Yamada scheme for turbulent closure. The model uses a staggered grid for discretisation and a sigma grid co-ordinate in vertical direction. The modal splitting technique is used to solve the discretised equations. The near field model employed is JETLAG (Lee and Cheung 1990, Lee and Chu 2003). JETLAG is a well-proven robust Lagrangian jet model that predicts the mixing of an arbitrarily-inclined round buoyant jet in a stratified crossflow, with a three-dimensional trajectory. It tracks the evolution of the average properties of a plume element by conservation of horizontal and vertical momentum, conservation of mass accounting for shear and vortex entrainment, and conservation of mass/heat.

With the jet trajectory and the entrainment flows computed by JETLAG, the near field effects upon the far field flow regime can be represented as follows (Fig. 2). A series of sinks corresponding to the computed turbulent entrainment of each predicted plume element can be obtained from the discharge point up to the trapped level. Similarly, a source term representing the diluted flow and the discharged pollution loading (tracer mass flux) can be introduced at the same level. Solution of the continuity, momentum and scalar transport equations then yields the updated flow and scalar fields. Limited by the model grid size, the details of the near field-induced circulation pattern may not be resolved, but the bulk water and mass movement induced by the effluent discharge as well as the influence of background concentrations or recirculation can be fully modelled in a dynamic manner.

With the computed flow and mass distributions in the far field model, the near field model can then be driven by the updated ambient conditions (including both the ambient current, scalar concentrations and density) to generate the new source and sink terms for the next time step. Hence, the effects of changing ambient conditions upon the plume behaviour can be accounted for in the near field simulation. As any changes in one model will immediately be passed to the other model, a two-way dynamic coupling is ensured.

3. TEST CASES

To examine the performance of the proposed method in modelling the near field effects of the buoyant discharge in the intermediate and far field, a wide range of complex flows have been studied. Representative verification tests are reported herein.

As the reference for assessing the performance of the proposed approach (Method 1), three alternative "source only" methods for coupling the near and far fields have also been considered:

a) Undiluted source introduced at discharge point (Method 2): it is the most commonly used approach in engineering practice when only the far field model is used. The volumetric and mass source terms are introduced at the discharge point in the continuity and mass transport equations (Fig. 3a).

b) Diluted source and mass source terms introduced at the terminal level determined by the embedded near field model (Method 3) in the far field equations (Fig. 3b). This method is approach 3 described in Zhang and Adams (1999). It is similar to Method 1 but without the entrainment sinks. The near field model is driven by the updated ambient conditions from the far field model, while the location and strength of the source terms in the far field model are updated by the near field model.

c) Undiluted source included at the location determined by the embedded near field model (Method 4): It is similar to Method 3 except that the undiluted source is applied to ensure exact water mass conservation.

Test case 1 – Vertical round buoyant jet in stagnant linearly density-stratified ambient fluid: Wong (1986) carried out a series of laboratory experiments to study the behaviour of a round buoyant jet in stratified fluid. The (negatively) buoyant jet was created by discharging fluid downwards from a circular orifice into a linearly stratified receiving water in a 61 cm x 457 cm x 91 cm deep tank. The jet fluid was heavier than the ambient fluid at the point of discharge and passive tracer was added for the purpose of measuring the dilution. The changes in the ambient salinity profiles before and after the experiment was studied in one of the experiments.

A model with horizontal grid size 21.8 cm by 20.3 cm and 20 uniform vertical layers is employed. The model is cold started and run for a duration of 15 minutes, similar to the length of experiment. A time step not greater than 0.25 second (with maximum Courant No. $u\Delta t/\Delta x$ around 0.03) is needed for a stable solution. From Fig. 4, it can be seen that the predicted change in vertical salinity profile due to the jet discharge is in excellent agreement with the experimental data. On the other hand, the alternative near-far field coupling methods (Method 2, 3 and 4) fail to reproduce the observed change in ambient stratification. In particular, the thickness of the spreading layer is under-predicted. For Method 3, the extra water introduced cause excessive reduction in the ambient salt concentration. With the embedded near field model, Method 4 predicts the trapping level better than Method 2. From the computed tracer distribution, the minimum dilution achieved can also be calculated from the maximum concentration predicted and they are shown in Table 1. Again Method 1 gives a much better estimation on the dilution, Method 2 and 4 significantly under-predicts the dilution and Method 3 over-estimates the dilution.

Table 1. Summary of predicted jet characteristics for round jet in stratified fluid

	Measured	JETLAG	Method 1	Method 2	Method 3	Method 4
Minimum dilution at trapping level	25.5	23.4	20.9	4.7	73.1	3.7

The method has also been used to simulate an inclined plane (slot) buoyant jet in linearly stratified fluid (Lee and Cheung 1986). The experiments were carried out with a slot jet discharge in a laboratory tank of effective length of 6 m, 0.152 m wide by 0.76 m deep. Besides the maximum height of rise and tracer concentration distribution in the spreading layer, the change in the ambient stratification caused by the discharge of the plane negatively buoyant jet was also measured. The predicted change in ambient density profile for a plane plume (Fig. 5) is also in excellent agreement with data, while the other methods distinctly fail in different aspects.

Test case 2 – Line plume in perpendicular crossflow: Roberts (1979) performed experiments in a rectangular basin with a slot diffuser to represent a line plume of finite length in steady current. The basin is 6.1 m wide by 11.0 m long. Experiments were carried out for a wide range of current speed u and discharge buoyancy flux b per unit length. The experiments show that the mixing is governed by a Froude number, $F = u^3/b$, representing the ratio of buoyancy-induced to ambient velocity. Small values of F indicate a flow dominated by the buoyancy, resulting in the formation of a buoyant surface wedge with an initial width greater than the diffuser length. On the other hand, high values of F represent a flow dominated by the ambient current. For this case, a model with horizontal grid size of 43.5 cm by 30.5cm and 20 uniform vertical layers is employed and the line plume is represented by several equivalent round plumes. As shown in Fig. 6, the observed waste-field pattern is well predicted. With $F < 1$, the mixed effluent has a plume-like pattern. A surface buoyant layer is formed with gravitational spreading sideways and upstream intrusion. The lower surface concentrations for $F > 1$ indicates the bottom attachment of the effluent field. The computed vertical sectional tracer concentration distributions (not shown) are also in good agreement with observations.

4. CONCLUDING REMARKS

Effluent mixing in the near to intermediate/far field has been successfully modelled by a new method of coupling plume models with 3D circulation models. By representing the discharge by a system of equivalent source and sinks, the effect of near field plume mixing is properly represented in the far field model. A true dynamic linkage between the near and far field models is achieved along with full water and tracer mass conservation. Tests for a wide range of complex flow scenarios have confirmed the accuracy of the predictions. The general and robust method can be readily implemented in existing circulation models to yield accurate predictions of the intermediate/far field for many environmental transport problems.

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REFERENCES

Bleninger, T. and Jirka, G.H. (2004). “Near- and far-field model coupling methodology for wastewater discharges”, Environmental Hydraulics and Sustainable Water management (Eds. J.H.W. Lee and K.M. Lam), Balkema, London, pp. 447-453.

Hamrick, J.M. (1992). A Three-dimensional Environmental Fluid Dynamics Computer Code: Theoretical and Computational Aspects, The College of William and Mary, Virginia Institute of Marine Science, Special Report 317, 63 pages.

Kim, Y.D., Seo, I.W., Kang, S.W. and Oh, B.C. (2002). “Jet integral - particle tracking hybrid model for single buoyant jets”, Journal of Hydraulic Engineering, ASCE, Vol. 128, pp. 753-760.

Lee, J.H.W. and Cheung, V. (1986). “Inclined plane buoyant jet in stratified fluid”, Journal of Hydraulic Engineering, ASCE, Vol. 112, No. 7, pp. 580-589.

Lee, J.H.W. and Cheung, V. (1990). "Generalized Lagrangian model for buoyant jets in current", Journal of Environmental Engineering, ASCE, Vol. 116, No. 6, pp. 1085-1105.

Lee, J.H.W. and Chu, V. (2003). Turbulent Jets and Plumes – A Lagrangian Approach, Kluwer Academic Publishers, 390 pages.

Roberts, P.J.W. (1979). "Line plume and ocean outfall dispersion", Journal of Hydraulic Engineering, ASCE, Vol. 105, No. 4, pp. 313-331.

Turner, J.S. (1973). Buoyancy Effects in Fluids, Cambridge University Press, 367 pages.

Wong, D.R. (1986). Buoyant Jet Entrainment in Stratified Fluids, Report No. UMCE 85-9, The University of Michigan, 408 pages.

Zhang, X.Y. and Adams, E.E. (1999). "Prediction of near field plume characteristics using far field circulation model", Journal of Hydraulic Engineering, ASCE, Vol. 125, No. 3, pp. 233-241.

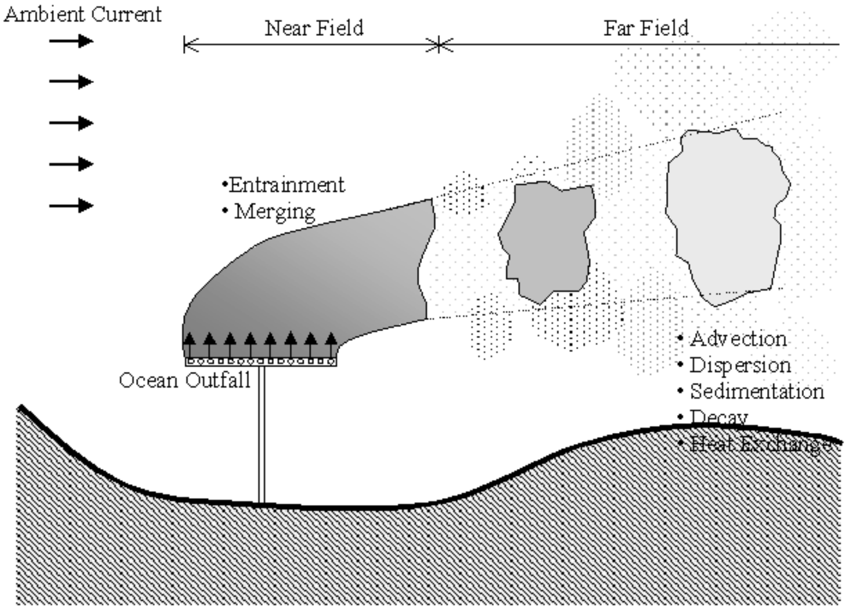


Fig. 1 Mixing and transport of coastal outfall discharge.

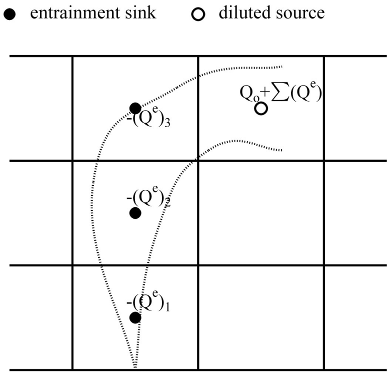
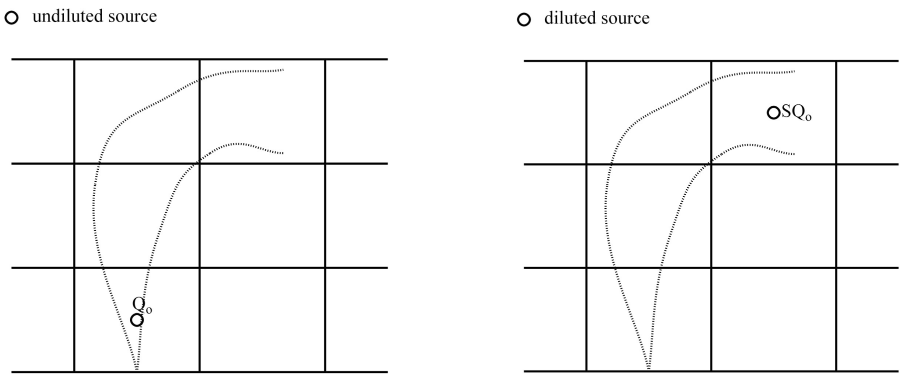
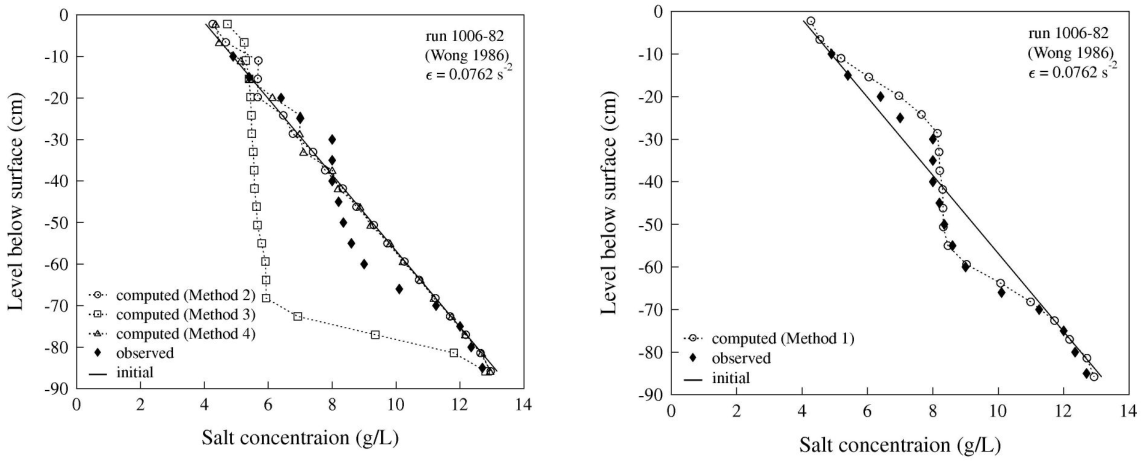


Fig.2 Representation of plume mixing by diluted source flow and entrainment sinks along the jet trajectory (method 1).



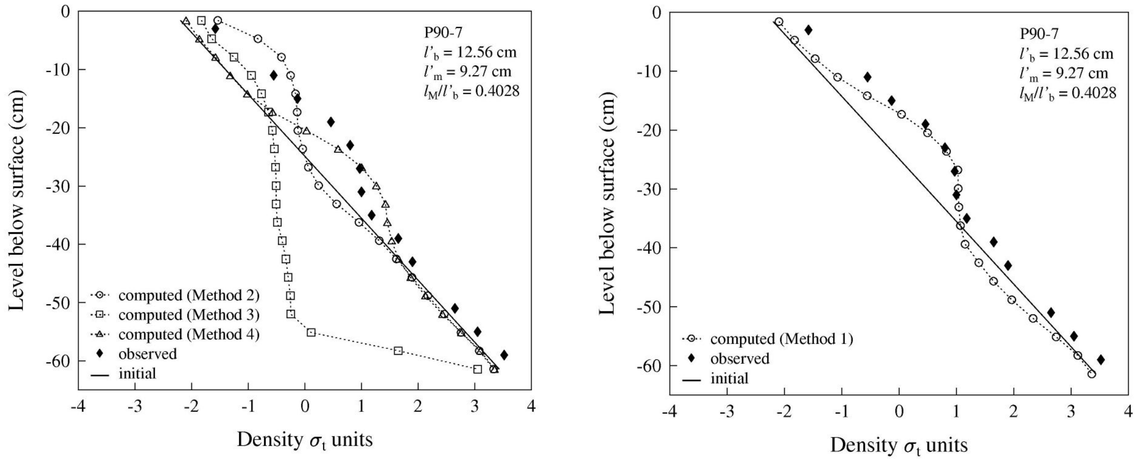
a) Method 2 b) Method 3

Fig. 3 Near field jet mixing represented by “Sources” (S = average dilution)



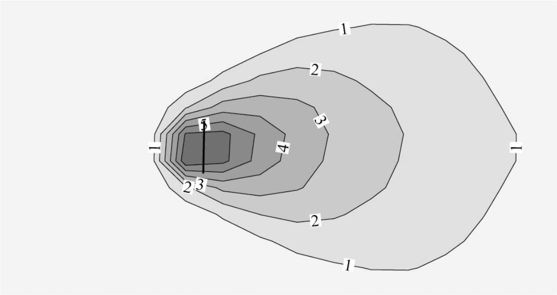
a) Method 1 b) Method 2, 3 & 4

Fig. 4 Ambient salt concentration profiles before and after a round jet discharge into a linearly stratified fluid (Wong 1986)

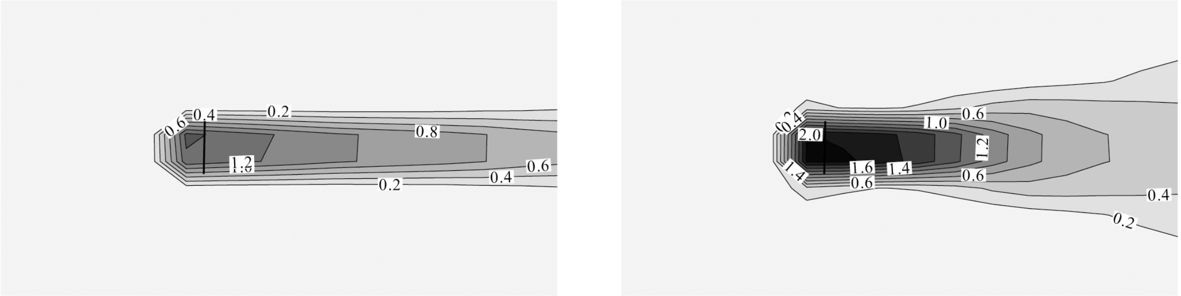


a) Method 1 b) Method 2, 3 & 4

Fig. 5 Ambient density profiles before and after a slot discharge into a linearly stratified fluid



a) F ~ 0.1



b) F ~ 1.0

c) F ~ 10.0

Fig. 6 Computed surface tracer concentration field for a finite line plume in a perpendicular crossflow (concentration contour in $0.01C_o$)