Two-way-coupling near-field and far-field models for the simulation of plumes

Thom Wolf[1], W. Alexander Breugem[1], Bart Verheyen[1], Boudewijn Decrop[1]
abr@imdc.be, Antwerp, Belgium
[1]: IMDC NV

Abstract – **In this paper, two different coupling methodologies between near-field and far-field models are presented. In the first coupling methodology, the near-field model of Lee and Cheung [3] is coupled directly (online coupled) to TELEMAC-3D, in order to calculate the vertical displacement of the near-field plume, taking into account the flow velocity and density in the far field model to calculate the near-field model. In the second methodology, an offline methodology is presented, in which the results of an separate calculation with CORMIX are used to generate input in a far-field TELEMAC-3D model. Three applications are presented. In the first application, the online coupling is used to generate the spreading of a plume generated during deep-sea mining activities. In the second example, the modelling of faecal bacteria due to the release of waste water in the Adriatic sea are presented. Finally, the use of online coupling of near-field and far-field models to model the impact of dredging on the turbidity are shown.**

Keywords: plumes, TELEMAC-3D, Near-field model; Far-field model; Model coupling

I. INTRODUCTION

Plumes play an important role in environmental problems. Examples consist of sediment plumes generated by dredging works, thermal plumes or waste water releases.

The physical processes concerning plumes differ between the near field and the far field. In the near field, plumes move due to inertia and buoyancy, while strong entrainment of ambient fluids occur. In the far field on the other hand, these processes are not significant and the plume behaves as a passive plume, which moves due to advection and turbulent diffusion. Because of the different physical processes in the near-field and far-field, different numerical models are typically used for each of these, where TELEMAC-3D is often used to model the far-field dispersion of plumes.

Different near-field models exist. An often used model is CORMIX [1]. CORMIX consist of a decision support system, in combination with different modelling approaches for the simulation of the near-field plume, which are chosen based on the conditions (based on the release, the ambient flow and the ambient stratification). For each of these cases, the appropriate near-field model is based on integral models for the conservation of mass, momentum, buoyancy and scalar quantities [4,5,6]. In this way point sources as well as line sources can be simulated. CORMIX is a closed source model, which makes it difficult to couple it to directly to TELEMAC.

A different modelling approach was taken by Lee & Cheung [3]. They model the near-field plume using a Lagrangian (particle tracking) approach. The flow velocity of the plume is determined based on the conservation of mass and momentum of the plume, using a simplified expression to determine the entrainment of fluid from the ambient flow into the plume. This approach is used for example in the model VISJET.

The objective of this paper is to present the coupling between near-field models and TELEMAC-3D. Two different methodologies are discussed for the coupling:

- An online approach. In this approach the Lagrangian plume is used directly coupled with TELEMAC-3D, where the vertical flow and stratification profiles in TELEMAC-3D are used in the near-field calculations. The resulting data of the near-field model is then applied every time step in TELEMAC-3D as a Dirac source.
- An offline approach. In this approach, near-field calculations are performed beforehand for different typical conditions using CORMIX. Based on the results of these calculation, and the expected results of the simulation (put into TELEMAC-3D as a text file), a source term, is generated and applied every time step in TELEMAC-3D.

In this paper, first the coupling approaches are discussed in section II. Then, the use of the coupled models is illustrated using three different cases. In the first case, plumes generated during deep sea mining are simulated using an online coupled model. The modelling of faecal bacteria is illustrated as a second case. In this case, the offline modelling approach is used. As a third example, the online coupling approach is used to model dredging plumes due to dredging works. Finally, an outlook is given on future developments to improve the coupling methodology, and the paper is finished with comes conclusions.

II. COUPLING TELEMAC-3D TO NEAR FIELD MODELS

A. Requierements for coupling near-field and far-field models

When coupling, a near field model to a far field model, there are different considerations that need to be taken into account:

- **Coupling dynamics:** there are different coupling methods. A coupling can be offline or online and dynamic or static [2]. In an online coupling, the near-field model uses data from the far-field model and/or the far field model uses data from the near field model.

In case only one of these couplings, we speak of one-way coupling, whereas when both area present, we speak of two-way coupling. In a dynamic coupling [2], the transfer of data from or to the near-field and far-field model occurs on time scale that is small compared to the variation of the ambient conditions.

- **Tracer mass conservation**: this is the most important requirement in the coupling. The mass of the released material must be the same in the near-field and far-field model, in other to have meaningful balances of the released material in the far field model.
- **Water mass conservation**: In many cases, also mass conservation is applied to the released water by adding the same amount of water in the far field model. The objective of doing so, is to have some effect of the release on the large scale flow structure in the far field model. Care must be taken when doing so, because the near field model considers entrainment of the ambient fluid into the jet. Therefore, sources as well as sinks of fluid might be considered in the far field model. Different methods were considered in [7]:
    - Use undiluted source in the far field model
    - Use the diluted source in the far field model.
    - Use the diluted source in the far field model in combination with sink terms to represent the entrainment.

  It was found that the third method works best.

  Note that the water mass balance in many cases has a limited influence on the results, especially when the released volume is small compared to the volume in the far field model. In those cases, the addition of water can be ignored altogether.
- **Separation of scales**: there should a clear difference between the length and time scales in the near field and in the far field. If not, coupling between these two models is not needed and either a far field or a near field model can be used stand alone.
- **Dynamic coupling**: [2]

B. *Online coupling for the Lee and Cheung model*

In order to couple TELEMAC-3D to a near field model, a new Fortran module was developed called *`moving_source.f`*, in which the equations from Lee and Cheung [3] are solved in a one-dimensional vertical profile model. The velocity and tracer concentration from TELEMAC at the location of the release are applied as input data to this near-field calculation. From this, the concentration distribution in the near-field is calculated with different methods for specific methods. In order to release the tracers, the existing Dirac source terms in TELEMAC-3D are used. When using Dirac source terms, the flowrate and concentration need to be prescribed. In the present implementation, the flow is homogeneously divided over the vertical profile, in order to limit disturbance to the flow as much as possible. Using these flow rates, the concentrations are calculated, taking into account the vertical profile calculated by the near field model, and correcting the data, in such way that the released tracer mass correspond exactly to the amount specified by the user. The fluid flux in the far field model is equal to the amount of fluid released in the near field model, i.e. the influence of the entrainment was not taken into account.

In developing the current approach, several simplifying assumptions were made. First it is assumed that the time for the tracer transport in the near-field is negligible compared to the time scales at which the plume and flow adopts in the far field, and to the time scale at which the releases vary in time. Hence the delay between the release of tracer in the near field model and the time the tracer enters the far field model is not taken into account. Second, it is assumed that the horizontal distance travelled in the near-field model is small compared to the dimensions of the far-field plume. Hence the release of tracers and waste water is applied at the location of the release, rather than at the calculated distance downstream of the release. Third, it is assumed that the horizontal size of the plume (at the moment it enters into the far field model) is small compared to the mesh resolution. Hence the release is applied at one node in the mesh.

C. *Offline coupling of Cormix*

Because the CORMIX software is not open source, a fully coupled approach is not possible. Instead an offline approach was developed. In this approach, CORMIX simulations are performed first for a set of flow and stratification conditions that occur in the model domain. For each of these conditions, the elevation, height and width of the resulting plume are determined. These conditions are then given to TELEMAC-3D in the form of an Ascii input file, together with the released amount of tracer. In the offline coupling, the water release is not taken into account. Therefore, the total amount of tracer released during a time step is added to the existing tracer in TELEMAC-3D using a shape function, that is based on the gaussian profile of the plume that is assumed in CORMIX:

$$\Delta C = F\Delta T \frac{\exp\left(\frac{-\vec{x} - \overrightarrow{x_0}}{\vec{\sigma}}\right)^2}{\int \exp\left(\frac{-\vec{x} - \overrightarrow{x_0}}{\vec{\sigma}}\right)^2 d\vec{x}}$$

Here, F is the tracer flux, ΔT the time step, $\vec{x}$ the (3d) coordinates of the mesh, $\overrightarrow{x_0}$ the coordinate of the location of the release and, $\vec{\sigma}$ the width and height of the plume coming from CORMIX.

In this approach, the same limiting assumptions are applied as in the online approach (section II.B), with one exception. The third assumption, that the dimensions of the plume are small compared to the mesh size in the far field model, is lifted here.

III. APPLICATIONS

A. *Deep sea mining*

During deep sea mining, nodules are collected from the sea bed and pumped towards the surface. The water sediment mixture that is pumped can form plumes when released in midwater. The online coupling between TELEMAC-3D and the Lee- and Cheung [3, section II.B] model was used to study these plumes (see section). The TELEMAC-model was setup for an area in the deep ocean (with a depth of 4-5 km), using a combination of 66 z and sigma layers. Here, the z layers are used in the top 1500 m of the water column, in order to limit artificial mixing of the temperature and salinity, whereas the sigma coordinates are used below. The KPP turbulence from the General Ocean Turbulence Model (GOTM) was used to parametrize the turbulence [9]. The model was driven by meteorological data, in combination with data from OSU/TPXO for the tide [10] and HYCOM [11] for the large-scale flow [more details can be found in 8].

In order to couple the near field and far field, the near field model was run every time step of the far field model. From the result of the near-field model, the release height in the far field model was determined, as the vertical location, where the vertical velocity in the near field had decreased to a sufficiently low value. At this location, the near field material was released into the far field model. A gaussian distribution for the concentration profile was used, for which the thickness depends on the cross section of the plume calculation in the Lagrangian plume model. In the far field model, the sediment was modelled as a tracer with a constant settling velocity.

A typical result of the calculation is shown in Figure 1. A comparison between experimental data and a similar near field model [8] shows that these near field models work well to simulate the near field behaviour of this kind of plumes. Unfortunately, no measurements are available to validate the far field approach.

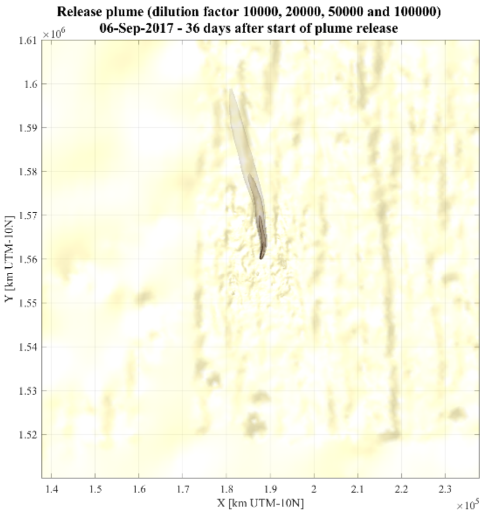

Figure 1. Example (top view of the plume of a midwater release)

B. *Faecal bacteria modelling*

Bathing water in coastal areas is unfortunately not always meeting the water quality required standards for faecal bacteria. To guarantee a good quality of bathing water, or to asses potential risks causing poorer quality, (local) governments have measurements being carried out to base assessments on. However, these often lack the temporal and spatial extent to make a sound assessment of the water quality of a coastal area. Numerical water quality models can provide these insights by simulating both the dispersion and fate of introduced faecal bacteria.

An example of this, is a recently developed numerical model train which has been used to study of the dispersion of sewage effluent (faecal bacteria) along the Istrian coast. Here, a large-scale TELEMAC-3D model of the Istrian coast was constructed to study the dispersion and fate (decay) of faecal bacteria released through an opening at the end of a number of sewage outfall pipes at the sea bed. The initial dispersion and mixing processes of the waste water discharge from the outfall pipes cannot be captured well using the coastal model. Therefore, a near-field CORMIX model is applied to analyse the near field behaviour of the waste water discharge and results are used to provide boundary conditions for the far-field model. For each outfall. A CORMIX model was set up consisting of a diffusor or single pipe outlet. As input, it furthermore uses the local water depth, ambient flow velocity from the far-field model and a schematized density profile. The latter is in this area different for summer (stratified) and winter (mixed) conditions (Figure 2) and hence investigated as distinct scenarios.

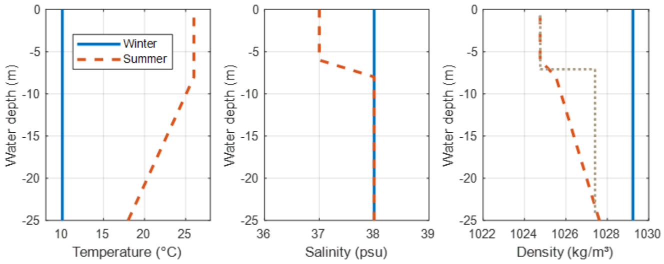

Figure 2. Variation in sea water conditions over the vertical for winter and summer. Left: variation in temperature, middle: variation in salinity, right: variation in water density (blue: well mixed winter conditions, red: stratified summer conditions that are represented by the grey dashed line in CORMIX).

The calculated result of CORMIX indicates the dimensions (vertical position in the water column and width) of the waste water plume at the edge of the near field mixing area. At this point, the dispersion of the waste water plume is dominated by the local flow conditions, which are calculated using the far-field coastal model. Because the density of the waste water effluent (having zero salinity) is lower than the sea water, a positively buoyant jet is generated, which has the tendency to move towards the water surface. Depending on the water depth and the exit velocity from the pipe, the waste water plume will be fully mixed or spread towards the higher parts of the water column. Examples of the plume dimensions calculated using CORMIX are shown in Figure 3 and Figure 4 for respectively a winter case (well mixed sea water conditions) and a summer case (stratified sea water conditions). The comparison of the cross section shows that the waste water plume during summer is trapped beneath the thermocline in summer.

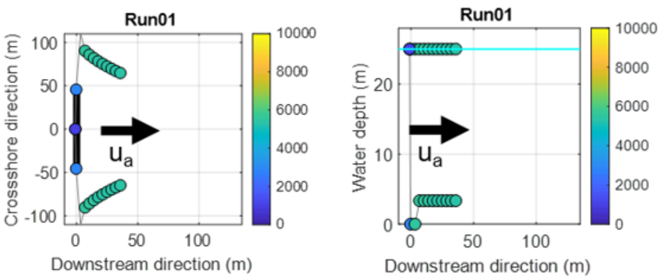

Figure 3. Illustration of CORMIX results for the winter case with indication of the direction of ambient flow (U_a). Left: top view of the waste water plume (black is the diffusor), right: cross section through the waste water plume indicating that the plume spreads from 3 meters above the bed towards the water surface.

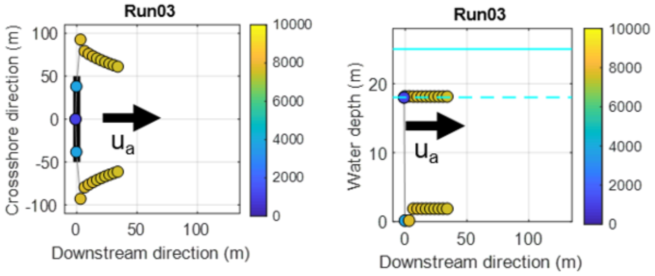

Figure 4. Illustration of the CORMIX results for the summer stratified case with indication of the direction of ambient flow (U_a). Left: top view on the waste water plume (black is the diffusor), right: cross section through the waste water plume spreading from one meter above the bed towards the location of the pycnocline.

The shape of the waste water plume at the edge of the near field mixing area is given by CORMIX as the parameters (width and height) of a top-hat profile to TELEMAC, and applied using the method described in section II.C.

In this study, a model mesh was constructed with 97,000 nodes and a mesh resolution ranging between 50 m in the area of interest to 4 km near the offshore model boundary. The model domain is divided into 15 double sigma vertical layers. Because a good turbulence model is essential in order to correctly model the vertical stratification and mixing in the Adriatic Sea, GOTM was coupled to TELEMAC-3D [9] using a k-epsilon model with a second-order algebraic closure model for the stratification fluxes. To capture the fate of faecal bacteria, a decay rate was used in TELEMAC.

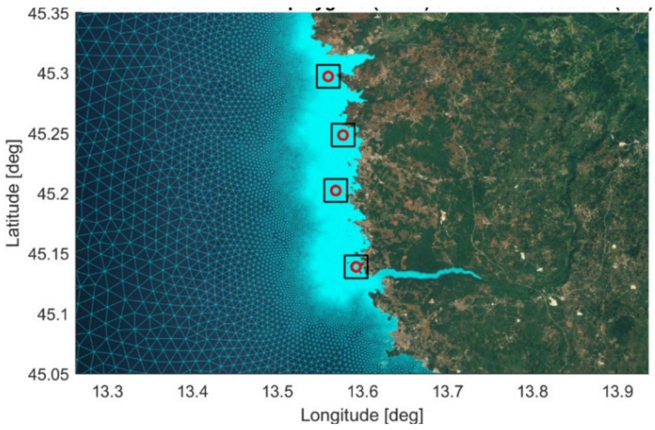

Figure 5. Model grid (zoom) of the Istrian coast TELEMAC model. Red dots indicate the approximate locations of sewage outfall pipe ends.

Time averaged ECOLI concentrations for a ten day simulation period are shown for the summer and winter case in Figure 6 and Figure 7, respectively. Both cases show that there is a main north south transport orientation of the concentration patterns of the faecal bacteria around the outfalls.

Similar to the near field model, it is found that during stratified conditions (which often occur in summer), the waste water discharge is trapped deeper in the water column and cannot reach the surface easily, even though it consists of fresh water with a density smaller than the sea water. Therefore, the highest faecal bacteria concentrations are found near the middle of the water column, where the density gradient is strongest (Figure 6), whereas significantly less ECOLI bacteria are found near the surface. Conversely, for the mixed winter case (Figure 7), results show that the highest concentrations are found at the water surface. This is due to the fresh water effluent being strongly positive buoyant, by which faecal bacteria quickly disperse to the water surface after which the bacteria further disperse with the local currents.

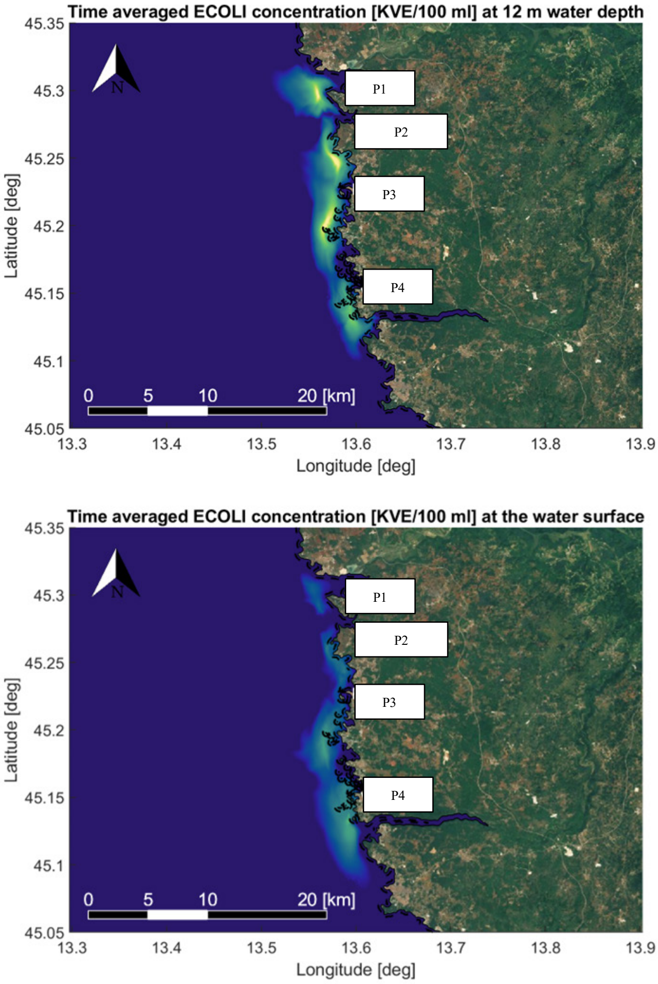

Figure 6. Summer scenario results of time averaged ECOLI concentrations at a level of 12 m water depth (top figure) and at the water surface (bottom figure).

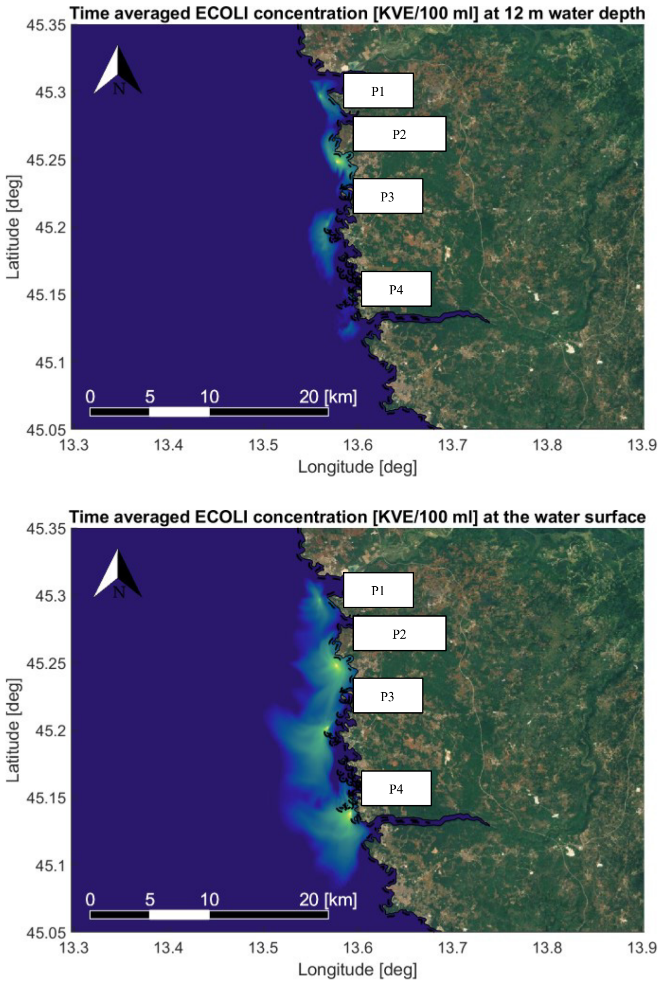

Figure 7. Winter scenario results of time averaged ECOLI concentrations at a level of 12 m water depth (top figure) and at the water surface (bottom figure).

With this kind of water quality modelling, model results can be used to identify beaches with a likelihood of being exposed to high concentrations of faecal bacteria or for instance to investigate the effectiveness of potential measures such as filtering systems of waste water treatment plants.

C. *Dredging plume simulations*

Dredging works are often executed, for example to maintain a sufficient draft for shipping traffic. Different equipment is used to dredge. An often used vessel is the trailing suction hopper dredger (TSHD). These vessels dredge sediment, and store it in a barge. In order to store as much sediment as possible, an overflow is used to release water and fine sediment from the barge while the coarser sediment settles in the barge. This generates plumes of sediment, whose behaviour is important to know for to environmental reasons.

For the simulation of dredging plumes, the online model of Lee and Cheung [3] is used, which uses the local flow velocity in a profile in TELEMAC-3D to calculate the sediment concentration profile. The results of the Lee and Cheung model were then used in the parametric model develop by [12], that was based on CFD simulations of the dredging plume around a TSHD (Figure 2). In the far-field model, a standard advection diffusion approach is used to simulate the transport of suspended sediment.

In the coupling code, a functionality was made, such that the location of the dredging vessel can change each time step, based on prescribed positions in a text file, in order to simulate the motion of the dredging vessel. Additionally, the release of sediment at the dredge head was simulated using a simple parametric profile, and the resuspension of sediment by the propeller of the dredging vessels was simulated using an additional parametrisation based on a parametrised model of the propellor jet, in combination with the Partheniades equation to calculate the resuspension of sediment from the bed from the jet velocity.

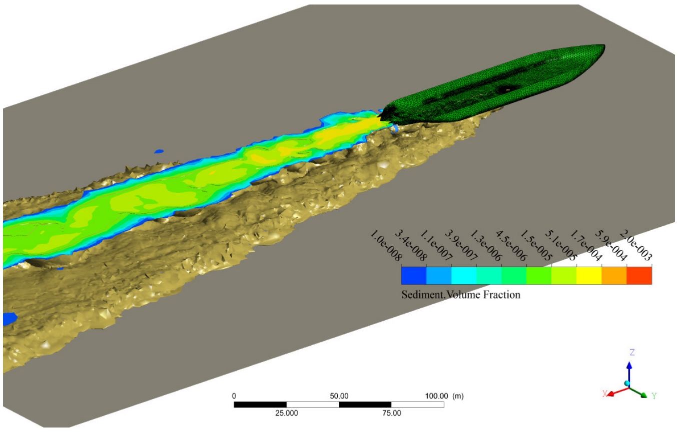

Figure 8. Example result of the CFD calculations of the dredging plume of TSHD from [11]

The characteristic result of an application is shown in Figure 9. In this figure different dredging plumes are visible, calculated using the coupled TELEMAC-3D near field model.

Figure 9. Instantaneous snapshot sediment concentrations due to dredging activities simulated using the coupled near-field far-field model.

IV. OUTLOOK

The current methodologies work well in practise, despite some limiting approximations. The online-approach is the preferred method for future tracer dispersion modelling. However, the offline approach uses a slightly more advanced approach for applying the near-field data in the far field model (using a plume that is not restricted to a single node). Therefore, the idea is to merge these two approaches, in order to have the advantages of each of these two approaches.

There are multiple limitations in the online model. First, the calculation of the plume in a 1DV vertical profile model, instead of in the full model, which leads to the neglect of horizontal displacements of the near-field plume. Further, no time lag is applied between material entering the near-field model and leaving the near-field model, which is not fully realistic (particularly for large near-field plumes and low vertical velocities). In order to overcome these two assumptions, the idea is to use the particle tracking module (*streamline.f*) in TELEMAC to calculate the Lagrangian model of Lee and Cheung [3]. For this, the flow field needs be modified such that the particle tracking module uses the velocity of the near-field jet, which depends on its buoyancy and momentum as well as on the entrainment of the ambient fluid. A methodology to use particle velocities that differ from the ambient fluid velocity has previously been applied in the simulation of macro-plastic objects in TELEMAC-3D [13], and seems applicable here as well.

V. SUMMARY AND CONCLUSIONS

In this paper, two different approaches were presented for coupling near-field models to TELEMAC-3D for the simulations of plumes:

- An online approach, based on the Lagrangian model of Lee and Cheung [3]. Successful applications of this model for simulation of dredging plumes as well as plumes due to return flow of deep sea mining activities were shown.
- An offline approach, in which results from separate CORMIX calculations were applied into TELEMAC-3D. A successful application is shown for the calculation of plumes of faecal bacteria in the Adriatic Sea, where it is shown that the seasonal differences in the spreading of the bacteria are well captured by the model.

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