Predictive modelling of hydrodynamics and marine water quality: three applications along the South African coastline

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Abstract

The predictive capability of hydrodynamic and water quality models is illustrated by three applications of the Delft3D modelling suite from WL|Delft Hydraulics along the South African coastline. The first application involves dredging-induced turbidity in Saldanha Bay on the west coast. Modelling of the hydrodynamics and the dispersion and deposition of the turbidity plumes was performed to assess the impact of the plumes on the sensitive ecology in the bay. The second application investigates the feasibility of using seawater for industrial cooling at Saldanha Bay. Since this study involves a thermal discharge into a highly stratified environment, the Del A3 D model was applied in three-dimensional baroclinic mode including air-sea heat fluxes. The model outputs of absolute temperature, increase in temperature due to the thermal discharge and dilution enabled the ecological impacts to be assessed and the optimum discharge location to be identified. The final application is the design of a marine outfall discharging a buoyant effluent near Durban on the east coast. Since the initial dilution process exhibited significant temporal and spatial variability, a dynamic coupling of near- and far-field hydrodynamic models was developed to accurately simulate the impact of the outfall. The results indicated that, under stratified conditions, a local optimum in the required pipeline length with respect to the impact of the effluent at the shore exists - the so-called "pipeline paradox".

1 Introduction

As in other countries, the coastal zone in South Africa is coming under increasing pressure due to rapid growth in domestic and industrial development along the
coastline. This is placing conflicting requirements on the water quality in these areas, requiring an increased understanding of the underlying processes and a predictive capability to optimise solutions to these problems. Hydrodynamic and water quality models are well suited to this task and in this paper we discuss three applications of the Delft3D modelling suite from WLIDelft Hydraulics along the South African coastline.

The first application involves modelling dredging-induced turbidity plumes in Saldanha Bay on the west coast of South Africa. The second is a study to determine the feasibility of a thermal discharge into Saldanha Bay, while the third involves the design of a marine outfall on the east coast. In this paper we highlight some of the interesting or unique aspects in each of these studies.

2 Description of the models

The Delft3D modelling suite from WLIDelft Hydraulics in the Netherlands was used in the three applications described in this paper. The two modules applied in these applications were the Delft3D-FLOW hydrodynamic model and the Delft3D-WAQ water quality model.

2.1 Delft3D-FLOW hydrodynamic model

The Delft3D-FLOW model (WLIDelft Hydraulics [1]) solves the unsteady shallow water equations in three dimensions. The system of equations consists of the horizontal momentum equations, the continuity equation and the transport equations. The model includes formulations which take into account the following processes: tidal forcing, wind shear stress, air-sea heat fluxes, the effect of the earth’s rotation (Coriolis force), free surface gradients (barotropic effects), horizontal gradients in pressure due to changes in water density (baroclinic effects), water with variable density due to temperature or salinity differences (equation of state), bed shear stress at the seabed, drying and flooding on tidal flats, discharge and withdrawal of mass (discharges and intakes), transport of heat, salt and other conservative constituents (advection-diffusion equation) and turbulence induced mass and momentum fluxes (k-ε turbulence closure model). An irregularly-spaced orthogonal curvilinear grid is used in the horizontal direction and a σ-coordinate grid is used in the vertical. The time integration method is the Alternating Direct Implicit type.

2.2 Delft3D-WAQ water quality model

The Delft3D-WAQ model (WLIDelft Hydraulics [2]) solves the advection-diffusion equation in three dimensions. Over one hundred substances may be modelled, including sediment particles, heavy metals, phytoplankton, macro algae, nutrients, organic waste, oxygen and bacteria. Processes that may be modelled include settling-deposition-resuspension of particles, adsorption-desorption of trace metals to these particles, primary production, mineralization, oxygen demand and bacterial
die-off. These processes are implemented as additional source or sink terms in the advection-diffusion equation. The model obtains the hydrodynamic database through an offline coupling to Delft3D-FLOW.

3 Dredging-related turbidity in Saldanha Bay

3.1 Background

Saldanha Bay is located on the west coast of South Africa approximately 100 km north of Cape Town. It is an important tourist and industrial resource, supporting activities such as mariculture, fishing, cargo handling and large industries such as the steel industry, all of which place conflicting requirements on the water quality in the bay.

A proposed upgrading of the oil terminal presently operated in Saldanha Bay will require dredging up to 2.5 million m³ of material from the existing entrance channel. Although dredged material is to be disposed in a confined disposal area it is anticipated that "leakage" associated with the dredging operation will place a quantity of fine sediment into suspension. Transported by the ambient flow regime, the suspended material can potentially move throughout the bay in the form of turbid plumes and so impair water quality and the surrounding habitat, in particular the adjacent mariculture areas and the ecologically-sensitive Langebaan Lagoon (an international Ramsar site). In order to assess these impacts, computer modelling of the hydrodynamics and the dispersion and deposition of the turbid plumes was performed.

3.2 Hydrodynamic modelling

The Delft3D-FLOW hydrodynamic model was used to simulate the three-dimensional flow regime in the semi-enclosed Saldanha Bay system. The processes included in the model were tidal forcing, wind forcing, Coriolis effects, baroclinic flows due to thermal stratification and the drying and flooding of tidal flats in the lagoon. An orthogonal curvilinear grid with cell sizes ranging from 200 m in the areas of interest to 1 000 m near the model boundary was used in the horizontal direction, with eight σ-coordinate layers used in the vertical.

The model was calibrated based on current and water temperature data measured at four locations in the bay for a 12 day period. Measured wind, water level and thermistor string data were used at the model boundaries. The following coefficients were found to give the best correlation to the measured data: Chezy coefficient for bottom friction = 65 m⁰⁵/s, horizontal eddy viscosity = 1 m²/s, horizontal eddy diffusivity = 0.5 m²/s, wind coefficient = 6.3x10⁻⁴ + 6.6x10⁻⁵xU₁₀ (based on Smith and Blanke [3]) where U₁₀ is the wind speed 10 m above the water surface. Figure 1 indicates a good comparison between the measured data and model currents. The water temperature is modelled less accurately since in this case the air-sea interaction module was not used and the thermal stratification is driven
by the imposed open boundary conditions only. A significantly improved calibration was possible when running the model in three-dimensional baroclinic mode compared to three-dimensional barotropic or two-dimensional modes. Figure 2 depicts the simulated three-dimensional current structure. Predicted current magnitudes are generally below 0.5 m/s, except in the constriction at the entrance to Langebaan Lagoon where currents may exceed 1.0 m/s at spring tide.

3.3 Turbid plume modelling

The Delft3D-WAQ water quality model was used to simulate the advection, dispersion, settling and deposition of the turbid plumes arising from the dredging operations. The model solves the advection-diffusion equation in three dimensions including settling of particles and deposition or erosion based on specified critical shear stresses. The bed shear stress is computed as the sum of the stress due to currents and waves. A wave refraction-diffraction model was used to simulate the wave heights throughout the model domain under the dominant wave conditions.

The turbidity loading rate due to “leakage” of fine sediment at the dredger was based on the measured characteristics of the sediment, the type of dredger and the proposed dredging plan. A best estimate loading of 9 kg/s for the silt/clay material (< 63 microns) and an extreme loading of 70 kg/s due to a failure of the pipeline
from the dredger were determined (refer to Luger [4]). The silt/clay material was subdivided by mass into three fractions each with a characteristic settling velocity and critical shear stress for deposition. Settling velocities of 0.05 mm/s, 0.5 mm/s and 2.0 mm/s (based on measurements) and corresponding critical deposition shear stresses of 0.1 Pa, 0.2 Pa and 0.3 Pa were used in the simulations.

The following outputs were obtained from the model simulations: contour plots of maximum turbidity, time series of turbidity levels and exposure times at the ecologically-sensitive sites in the bay as well as contour plots of the deposition thickness throughout the bay. Figure 3 shows the predicted turbidity plume due to the extreme loading case of 70 kg/s. The turbidity at the ecologically sensitive sites was predicted to be below 25 mg/l, which is within the range of the natural background turbidity. Wave-generated bottom shear stresses were found to have a significant influence on the results by inhibiting deposition of the finer mud fractions in the exposed areas of the bay, resulting in a pervasive spreading of these particles into the lagoon and also out to sea. The maximum deposition thickness in the lagoon was, however, predicted to be less than 2 mm over the dredging duration of 4 months.

3.4 Conclusions

When running the hydrodynamic model in three-dimensional baroclinic mode, a good correlation between observed and modelled currents was achieved. The wave-generated bottom shear stresses were found to have a significant influence on the turbid plume behaviour by inhibiting deposition of the finer mud fractions in the exposed areas of the bay.
Figure 3: Predicted turbidity plume 3 hours after a simulated failure of the dredge line has been repaired.

4 Thermal discharge into Saldanha Bay

4.1 Background

This study investigated the feasibility of using seawater for industrial cooling as an alternative to ground water or river water. The thermal effluent would be discharged into Saldanha Bay at a temperature 27 °C above intake temperature at a flow rate of 5 m³/s. The potential impacts of this effluent include: increased temperatures and the associated impact on the ecology, biocidal action of possible residual chlorine in the effluent and modification of the food supplies to mussels due to displacement of natural waters by the effluent stream (which will contain negligible particulate organic matter). The objectives of the study were thus to predict the extent of these impacts and determine a discharge position which minimises these impacts.

4.2 Set-up of the hydrodynamic model

Except for a few months during winter, the Saldanha Bay system displays strong thermal stratification with temperature differences up to 8 °C measured across the thermocline. This stratification is maintained by atmospheric heat fluxes into the surface waters and the inflow of cold bottom waters from upwelling on the adjacent open shelf. The water temperature in the system also displays a high temporal variability due to wind-induced vertical mixing and the advection of cold water from the shelf and warm water from the lagoon. This temperature structure has a significant influence on the hydrodynamics in the system and thus on the advection-dispersion of the thermal plume. In addition, the impact of the thermal plume on the ecology will depend on the relative temperature change compared to ambient variability. It was thus important to simulate the ambient stratification realistically.
The simulations were performed using the three-dimensional baroclinic Delft3D-FLOW model and the following processes were included: tidal forcing, wind forcing, Coriolis effects, drying and flooding of tidal flats, as well as air-sea heat fluxes due to insolation, back radiation and turbulent heat fluxes across the air-sea interface. The scenarios modelled included representative spring, summer, autumn and winter conditions as well as periods of exceptionally calm conditions which were anticipated to constitute a worst case scenario. Each scenario comprised a 28 day period of simulated bay hydrodynamics forced by measured winds, predicted tidal levels at the mouth of the bay and seasonal atmospheric inputs of insolation, relative humidity, air temperature and thermal stratification at the mouth of the bay. Five different discharge locations were investigated including both surface and bottom discharges.

4.3 Results

To determine the increase in temperature due to the thermal discharge, the simulated temperatures with and without the discharge were compared at each time step in each computational segment. These temperature increases were presented as exceedance contours at the 50%, 80% 95% and 99% levels for each of the discharge options. Figure 4 shows the 99% exceedance contours near the seabed for the five different discharge locations. Also of importance in determining thermal impacts are the occurrence of high short-term increases in temperature as well as the time of exposure to various water temperatures. Time series of the temperatures at a number of ecologically sensitive monitoring sites were therefore produced.

Figure 4: Predicted increase in water temperature near the seabed for five possible locations for a thermal discharge.
The stratification present in the bay was found to play a significant role in both the near- and far-field behaviour of the thermal plume. Strong stratification in the vicinity of the discharge together with strong flows tended to trap the thermal plume in the subsurface layers for bottom discharges and restrict the plume to the surface layers in the case of surface discharges. In the far-field, temperature reductions occurred by heat loss to the atmosphere and mixing of the thermal plume with the cold bottom waters of the bay, the latter being the most effective process. The surface discharges therefore lead to larger impacts than the bottom discharges.

4.4 Conclusions

In this study, involving a thermal discharge into a highly stratified environment, a three-dimensional baroclinic model including air-sea heat fluxes was required to take all the relevant processes into account. The model outputs of absolute temperature, increase in temperature and dilution enabled the ecological impacts to be assessed and an optimum discharge location to be identified.

5 Design of a marine outfall near Durban

5.1 Background

Durban is located on the east coast of South Africa. The coastline in this region is relatively straight with an average seabed slope of 1:140. A study has been performed to design a marine outfall discharging buoyant wood pulp effluent. The objective was to determine the outfall length and diffuser configuration which minimised the visibility of the effluent at the adjacent beaches.

5.2 Modelling approach

In far-field hydrodynamic models based on the three-dimensional shallow water equations and the hydrostatic assumption, the immediate effect of buoyancy on vertical acceleration is in general not considered and density differences are taken into account only in the horizontal pressure gradients and in the vertical exchange coefficients. The grid size is also large (typically 50 to 100 m) compared to the spatial scales involved in the initial dilution processes (diffuser port diameters in the range 0.1 to 0.5 m). These models are thus generally not capable of accurately modelling the initial dilution process, which may lead to inaccuracies in the far-field predictions. For this reason, a coupling of near- and a far-field models was developed for this study.

The far-field model (Delft3D-FLOW) was run in three-dimensional baroclinic mode and included the following process: wind forcing, Coriolis effects, baroclinic flows due to thermal stratification and remote forcing due to the Agulhas current. The latter forcing was included as a velocity boundary condition using time series of measured currents. The far-field model was used to predict time-series of current and density profiles at the diffuser position. These data are used to compute the
near-field rise height and initial dilution for each diffuser port at each time step using a diffuser hydraulics model coupled to the UOUTPLM near-field model developed by the US EPA [5]. These results are used to compute into which elements in the three-dimensional far-field grid the effluent should be released.

5.3 Results

An example of the input and output from the near-field model is shown in Figure 5. Note how the effluent surfaces when the stratification is reduced by mixing and the associated increase in initial dilution due to the increased length of buoyant rise. The far-field model results were analysed to determine the three-dimensional zone impacted by the effluent for various percentages of time (Figure 6). The model simulations were performed for outfall lengths between 3 and 9 km. Comparing the predicted impact of the effluent at the shore, a local optimum of approximately 5.5 km is found (Figure 7). This unanticipated result is caused by the increasing strength and persistence of the thermal stratification with distance offshore, which tends to trap the plume within 15 m of the seabed and reduces the initial dilution for the longer pipelines to an extent which cannot be compensated for by the increased secondary dilution associated with the longer travel time to shore.

5.4 Conclusions

The initial dilution process exhibited significant temporal and spatial variability which required a dynamic coupling of near- and far-field hydrodynamic models to accurately simulate the impact of a marine outfall. The results indicated a local

Figure 5: Time series of the input and output from the near-field model
optimum in the required pipeline length with respect to the impact of the effluent at the shore existed - the so-called "pipeline paradox".

6 Conclusions

Hydrodynamic and water quality models are able to provide a predictive capability which can assist in optimising solutions to water quality problems. While these models are capable of adequately addressing the "what-if" questions with regard to the physical and bio-geochemical impacts of pollutants, further research is required in addressing the "so-what" questions regarding the corresponding ecosystem responses.

References

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