CHAPTER 170

A New Approach to 3D Flow and Transport-Modeling

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Abstract

In recent years two-dimensional numerical models have been applied successfully not only to large scale tidal computations, but also to small scale detailed flow computations (Bosselaar et al., 1987, Leendertse et al., 1989). However the application of three-dimensional models for fine-grid computations is very limited due to the very high requirements for computer times, caused by the explicit numerical algorithms which are being used. This problem is now alleviated by use of an alternating direction implicit computation method for three-dimensional flow- and transport-modeling. With this method, presented in this paper, the effective computation time is about an order of magnitude smaller then with previous models with similar accuracy.

Introduction

Two- and three-dimensional numerical models are used more and more for fine grid computations. At the 20th I.C.C.E., Taiwan, 1986, small scale applications were presented of fine grid two-dimensional models for the Delta-project in the Dutch Eastern Scheldt estuary. In this case, flow patterns near the construction sites of the storm surge barrier and compartmentation dams at different stages have been computed (Bosselaar et al., 1986, Klatter et al., 1986).

The gridsizes in these models varied from 400 m. down to

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10 m. In Figure 1 an example is given of a flow pattern in a two-dimensional model for the northern channel Hammen in the Eastern Scheldt estuary.

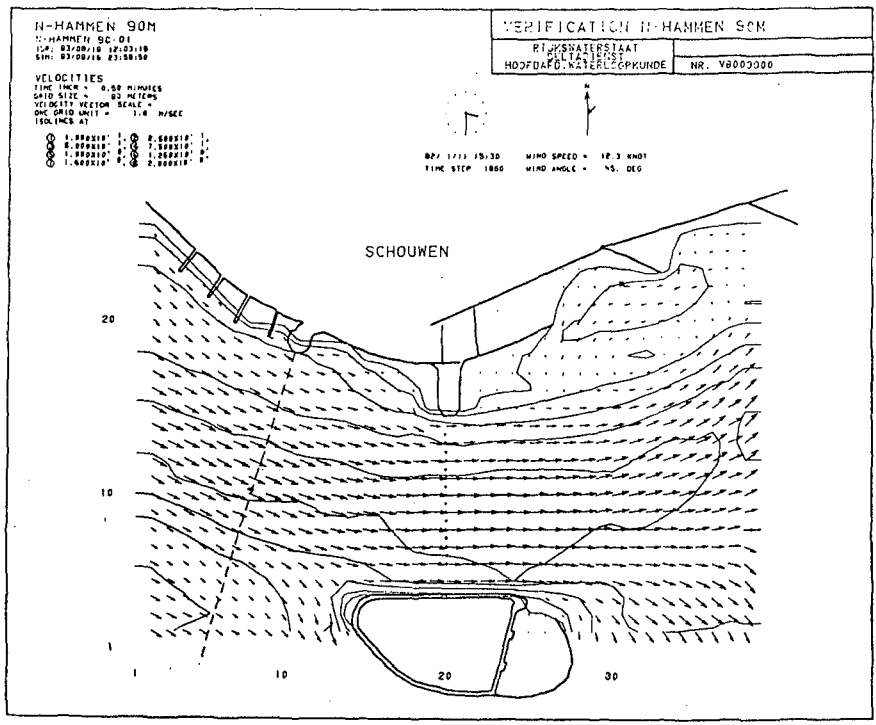

Figure 1.: Flow-pattern in the two-dimensional model of the Hammen

The results were used for example for stability-analysis of the bed protection by mattresses and the computation of sand losses. Therefor, velocities and shear stresses in the bottom layer were needed. The possibility of using three-dimensional models was investigated and 3D-computations were made with the available explicit 3D-code, developed by Leendertse and Liu (1973, 1987) (see Figure 2).
These 3D-computations appeared to be feasible but the computer-time needed was very large. This can be understood from table 1.

The gridsize in the 2D-model was 45 m., but for the comparison a gridsize of 90 m for the 2D- and 3D-models has been used. The 2D-modelling system WAQUA (Stelling, 1983) is using an implicit ADI-type of scheme, so a

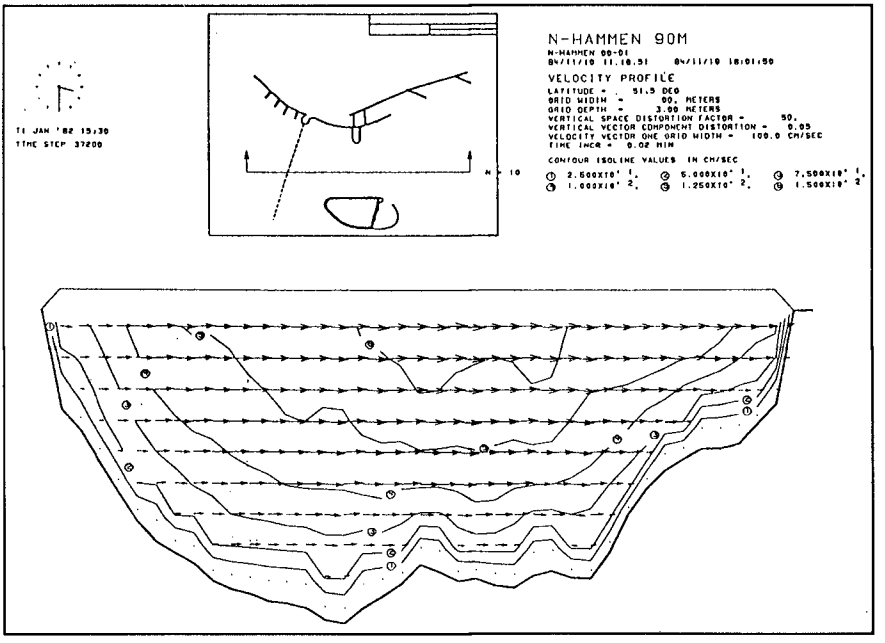

Figure 2.: Flow-pattern in a cross-section of the three-dimensional model of the Hammen

model characteristics	2-dimensional model	3-dimensional model
gridsize (m)	90	90
timestep (s)	60	1.5
method	implicit ADI	explicit
number of layers	1	10

Table 1: characteristics of the 2D- and 3D-model Hammen

stability requirement is absent and timesteps of 0.5 to 1 minute are possible. The explicit 3D-scheme however, needs a timestep of 1.5 second for stability reasons. The 3D-model has 10 layers and a lot of CPU-time is needed for a computation.

It should be emphasized that for accurate flow-computations the approximation of the advection-terms in the momentum equations is very important. An inaccurate time- and space discretisation will introduce numerical (eddy-) viscosity or will make the scheme first order accurate (Stelling, 1983) and details in computed

velocity distributions will be lost. Only fourth order dissipation is introduced by the approximations in the schemes for the advection terms.

For successful investigations and detailed 3-dimensional flow-computations with numerical models an implicit 3D-scheme is required and the computation method used has to meet the following requirements:
- The computation method must be stable,
- The algorithm must have an accuracy of at least second order,
- Numerical (eddy-) viscosity must be absent,
- The computation method must allow for large timesteps and must be efficient.

Computation method

The requirements above are met by the two-dimensional system WAQUA and also by the extension in the 3D-algorithm, which will be explained briefly in the next sections. For more details about the equations, the finite difference approximations and the solution technique the reader is referred to (Leendertse, 1989).

In this three-dimensional system also an alternating direction implicit computation method is used. The variables in the three-dimensional field are solved by successive solution of sets of equations that are described in vertical planes. With the use of special advection term approximations, the three-dimensional problem is broken down in a sequence of two-dimensional problems, which in turn can be reduced to the solution of sets of one-dimensional problems.

The most important aspects of this three-dimensional solution technique are:
- The use of horizontal momentum and continuity equations for the different layers in the model,
- The use of an ADI-type of scheme on a horizontal and vertical staggered grid,
- The use of asymmetrical higher order advection term approximations developed for the cross-advection terms in a two-dimensional model by Stelling (1983),
- The hydrostatic pressure assumption,
- A second order accuracy of the solution method with fourth order dissipation,
- An unconditional stability of the computation,
- A limitation of the timestep by requirements for accuracy only.

For the one layer case, this 3D-method reduces to the original two-dimensional scheme, except for some minor details.

Flow-computation

The solution of the finite difference equations for each stage in the ADI-method are solved iteratively. In general, iterations are required only for the expressions for the advection term coefficients and for the upstream gradients in the advection terms in case the local flow direction is different from the dominant flow direction.

In the first half-time-step (stage 1) of the multistep operation, the horizontal V-velocities in the vertical planes in Y-direction are computed first. The coordinate system used is X and Y for the horizontal and Z for the vertical direction with velocities U, V and W respectively.

For each column the momentum equations for the V-velocities are implicitly coupled in the vertical by the approximation of WV_{zz}, resulting in a three-diagonal system of equations for V which can be solved very economic way.
In the vertical plane the implicit horizontal coupling in Y-direction, due to the upwind-differencing for the gradients V_y in the advectionterm VV_y, can be solved with 2 iterations in opposite Y-directions using just computed values of V during the ongoing iterations.
Also the implicit horizontal coupling in X-direction due to the upwind-differencing for the gradients V_x in the advection term UV_x can be solved with 2 iterations over the planes in opposite X-directions using just computed values of V in the planes during the ongoing iterations.

The solution of the horizontal velocities U, the vertical velocities W and the waterlevels in the other equations in stage 1 is more complicated. The velocities U are coupled in the vertical by the approximation of WU_{zz} in the U-momentum equations and in the horizontal by the approximation of the continuity equation. This coupling is solved as follows: substitution of the discretized U-momentum equations in the continuity equation and summation over the vertical results in a three-diagonal system of equations for the waterlevels to be solved. With the new waterlevels U and W can be solved respectively with the U-momentum and the continuity equations. Iterations are needed for the non-linearities in the continuity equation.

The second half-time-step (stage 2) follows the same pattern described above for the first stage, but now first the U-velocities are computed implicitly with the U-momentum equations, followed by the implicit computation of V and the waterlevels with help of the V-

momentum and continuity equations.

The combination of both upwind- and central differencing alternatively in the 2-step scheme results in a second order accurate approximation in time and space of the horizontal advection terms with fourth order dissipation. If the advection is expressed upstream, and the coefficients of the nonlinear terms are constant during the timestep, the above presented computation method can be proven to be unconditionally stable.

Transport-computation

Not only the fluid flow is important in three-dimensional modeling. Dissolved substances, salinity distributions and sediment distributions need also to be computed simultaneously with the water motions. For accurate computations of transport and concentrations of dissolved matter in fine-grid models of for example estuaries, an accurate flow-computation is essential.

Experiments have shown (Ridderinkhof, 1990) that for small gridsizes advection is dominant for the dispersion of constituents. With a accurate transport-scheme also stratified flow or transport of sediments can be computed.

For this, a new numerical transport-scheme has been developed, is based on the principles explained above in the scheme for flow computation and is using the same asymmetrical approximations for the advection. The computation method is conservative, second order accurate and shows very limited spatial oscillations near steep fronts, due to the higher order of approximations.

Results

An example of both flow- and transport computation is the dispersion due to wind of a pollutant flowing into lake Ijssel from the river Ijssel in the Netherlands.
The different flow-directions in top- and bottom-layer caused by wind, results in quite different results in concentrations, compared to the results obtained with a two-dimensional model.

The first application of this new approach has been a management type of model of a closed-off estuary, lake Ijssel. A wind driven circulation was generated by a south-easterly wind of about 11.3 m/s. An inflow into

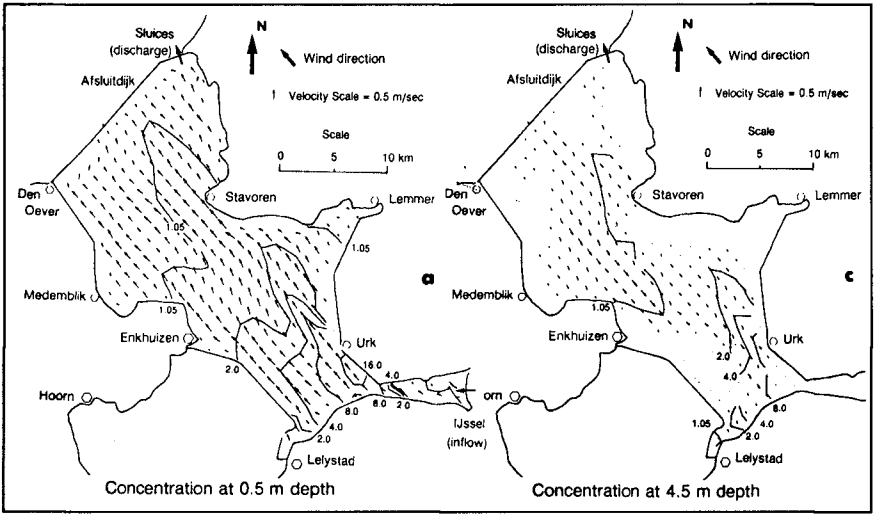

Figure 3.: Computed concentrations and velocities 72 hours after start of computation at 0.5 m depth (a) and 4.5 m depth (c)

the lake from the river Ijssel of 500 m3/s was assumed with a concentration of 50 gr/m^3 for a limited period to simulate a spill. The outflow at discharge sluices in the north was also set to 500 m3/s.

The lake was represented by a grid of 36 x 21 points in the horizontal plane. The gridsize was 1200 m, the vertical representation was made by five layers of 1 m, and the bottom layer was taken at 1.5 m. The timestep was 7.5 minutes.

Even with the limited depth the concentration distributions at the surface and near the bottom are quite different as is shown in Figure 3.
Particularly during the first few days, considerable differences in concentrations over the vertical exist in the southern part of the lake as is shown in the timehistories of the concentrations in Figure 4.

Developments

The above presented computation method for flow- and transport computation is now being used by the Dutch Rijkswaterstaat and by Delft Hydraulics.
Further developments with this scheme are:
- The incorporation of (curvilinear-) transformations

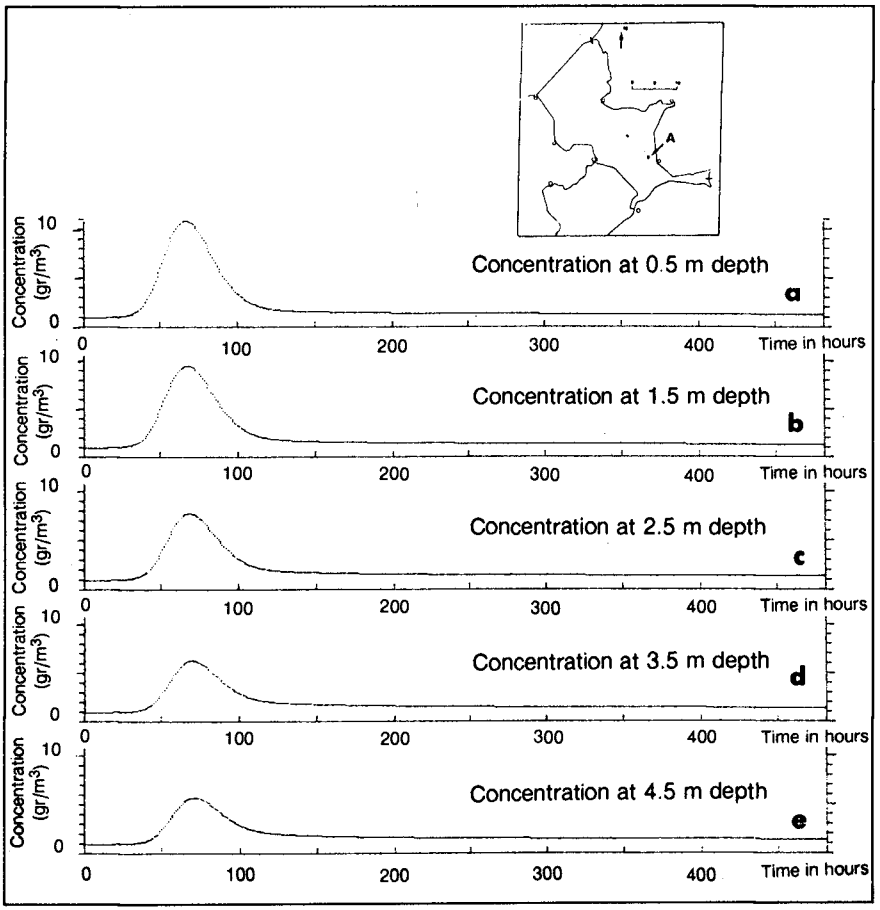

Figure 4.: Computed time-series of the concentration at station A at 0.5 m depth (a), 1.5 m depth (b), 2.5 m depth (c), 3.5 m depth (d), and 4.5 m depth (e) (timestep=7.5 min.)

in the horizontal direction and (sigma-) transformations in the vertical direction (de Vriend, 1990),

- The use of a higher order approximation for the advection in the vertical with a different computation method,
- The incorporation of a turbulent energy (K-epsilon) model for vertical diffusion,
- The incorporation of vertical field accelerations for near field computations.

Conclusions

With the presented (ADI) computation method, implicit three-dimensional flow- and transport-computations can be made which are stable and second order accurate.
Large timesteps can be used, compared to explicit codes for small-scale and fine-grid applications, therefor the algorithm is effective in CPU-demand.

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