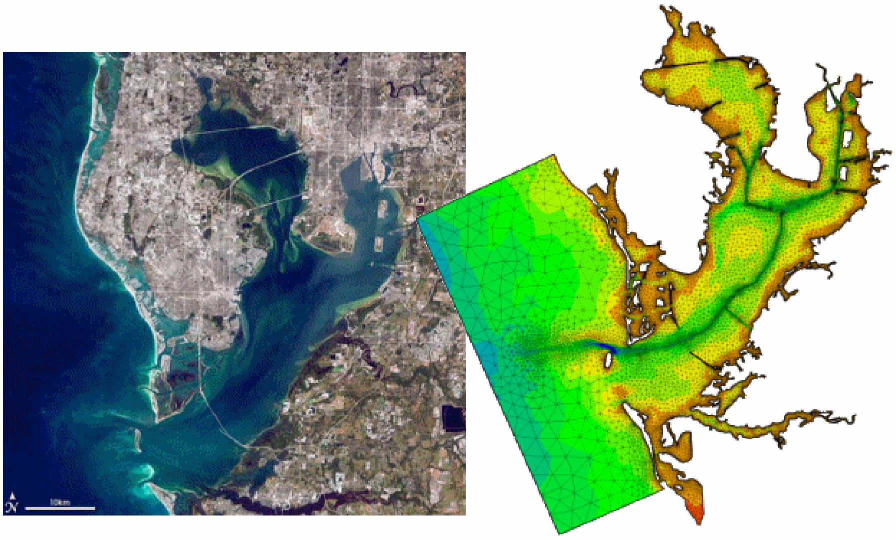


MIKE 21 & MIKE 3 FLOW MODEL FM

Hydrodynamic Module

Short Description

DHI Water & Environment

Agern Allé 5

DK-2970 Hørsholm

Denmark

Tel: +45 4516 9200

Fax: +45 4516 9292

E-mail: dhi@dhi.dk

Web: www.dhi.dk

MIKE213_FM_Short_Descrption.doc/HKJ/AJS/BHM/MSD0602.lsm – 2006-02-10

MIKE 21 & MIKE 3 Flow Model FM

The Flow Model FM is a new comprehensive modelling system for two- and three-dimensional water modelling developed by DHI Water & Environment. The new 2D and 3D models carry the same names as the classic DHI model versions MIKE 21 & MIKE 3 with an 'FM'added that refers to the type of model grid - Flexible Mesh.

The modelling system has been developed for complex applications within oceanographic, coastal and estuarine environments. However, being a general modelling system for 2D and 3D free-surface flows it may also be applied for studies of inland surface waters, e.g. overland flooding and lakes or reservoirs.

MIKE 21 & MIKE 3 Flow Model FM is a new general hydrodynamic flow modelling system based on a finite volume method on an unstructured mesh

DHI's new Flexible Mesh (FM) series includes the following:

Flow Model FM modules:

- Hydrodynamic Module, HD
- Transport Module, TR
- Ecology and water quality Module, ECO Lab
- Sand Transport Module, ST
- Mud Transport Module, MT

Wave module:

- Spectral Wave Module, SW

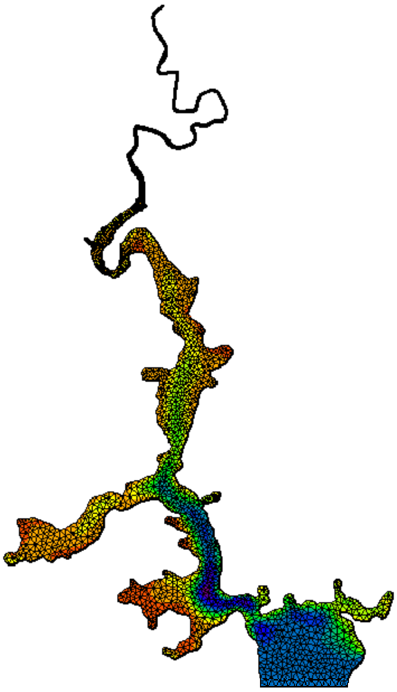
The FM Series meets the increasing demand for realistic representations of nature, both with regard to 'look alike' and to its capability to model coupled processes, e.g. coupling between currents, waves and sediments. Coupling of modules is managed in the Coupled Model FM.

All modules are supported by new advanced user interfaces including efficient and sophisticated tools for mesh generation, data management, 2D/3D visualization, etc. In combination with comprehensive documentation and support, the new FM series forms a unique professional software tool for consultancy services related to design, operation and maintenance tasks within the marine environment.

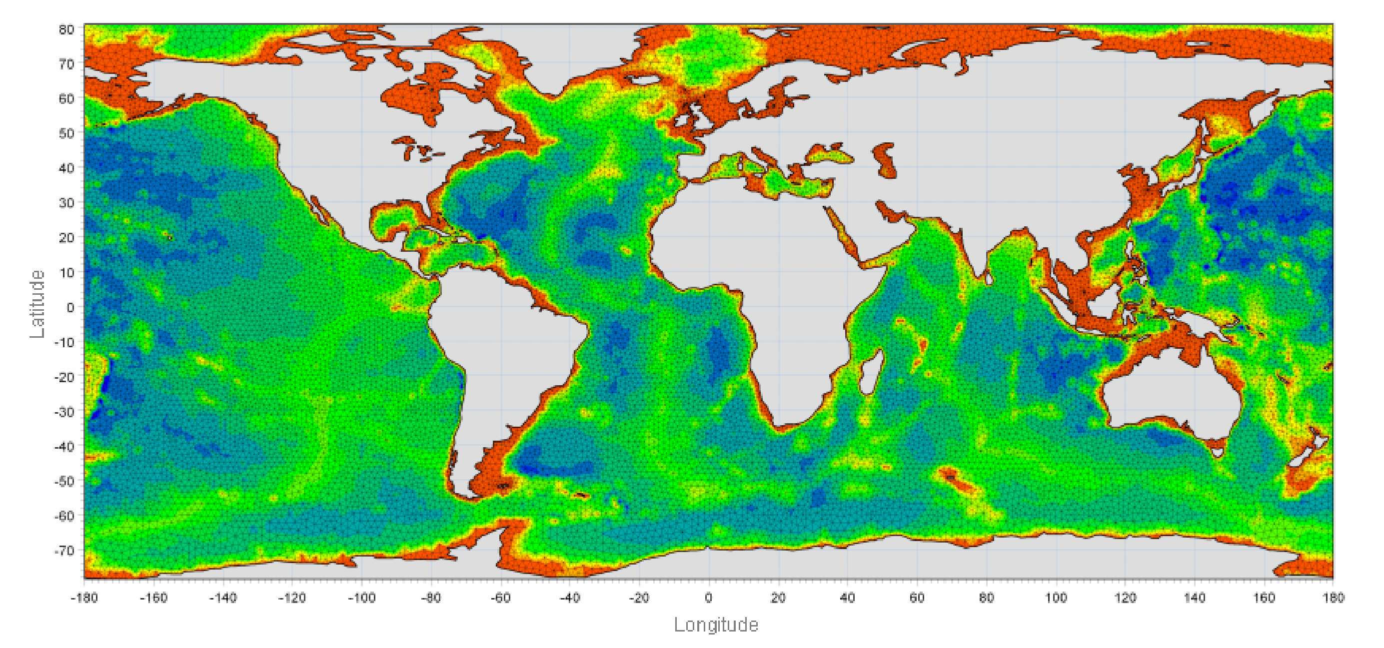
An unstructured grid provides an optimal degree of flexibility in the representation of complex geometries and enables smooth representations of boundaries. Small elements may be used in areas where more detail is desired, and larger elements used where less detail is needed, optimising information for a given amount of computational time.

The spatial discretisation of the governing equations is performed using a cell-centred finite volume method. In the horizontal plane an unstructured grid is used while a structured mesh is used in the vertical domain (3D).

This document provides a short description of the Hydrodynamic Module included in MIKE 21 & MIKE 3 Flow Model FM.



Example of computational mesh for Tamar Estuary, UK



MIKE 21 & MIKE 3 FLOW MODEL FM supports both Cartesian and spherical coordinates. Spherical coordinates are usually applied for regional and global sea circulation applications. The chart shows the computational mesh and bathymetry for the planet Earth generated by the MIKE Zero Mesh Generator

MIKE 21 & MIKE 3 Flow Model FM - Hydrodynamic Module

The Hydrodynamic Module provides the basis for computations performed in many other modules, but can also be used alone. It simulates the water level variations and flows in response to a variety of forcing functions on flood plains, in lakes, estuaries and coastal areas.

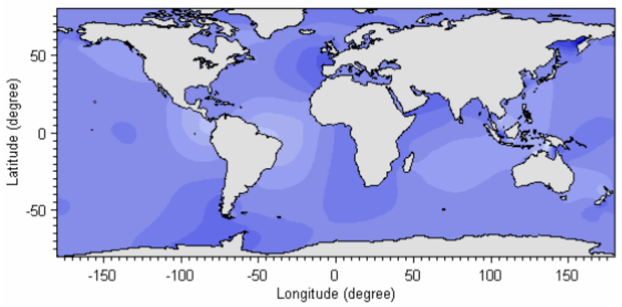
Application Areas

The Hydrodynamic Module included in MIKE 21 & MIKE 3 Flow Model FM simulates unsteady flow taking into account density variations, bathymetry and external forcings.

The choice between 2D and 3D model depends on a number of factors. For example, in shallow waters, wind and tidal current are often sufficient to keep the water column well-mixed, i.e. homogeneous in salinity and temperature. In such cases a 2D model can be used. In water bodies with stratification, either by density or by species (ecology), a 3D model should be used. This is also the case for enclosed or semi-enclosed waters where wind-driven circulation occurs.

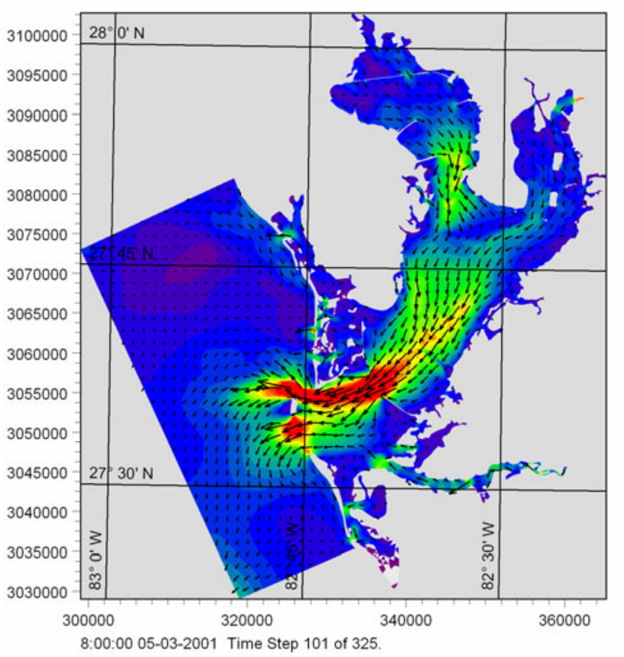
Typical application areas are

- Assessment of hydrographic conditions for design, construction and operation of structures and plants in stratified and non-stratified waters
- Environmental impact assessment studies
- Coastal and oceanographic circulation studies
- Optimization of port and coastal protection infrastructures
- Lake and reservoir hydrodynamics
- Cooling water, recirculation and desalination
- Coastal flooding and storm surge
- Inland flooding and overland flow modelling
- Forecast and warning systems

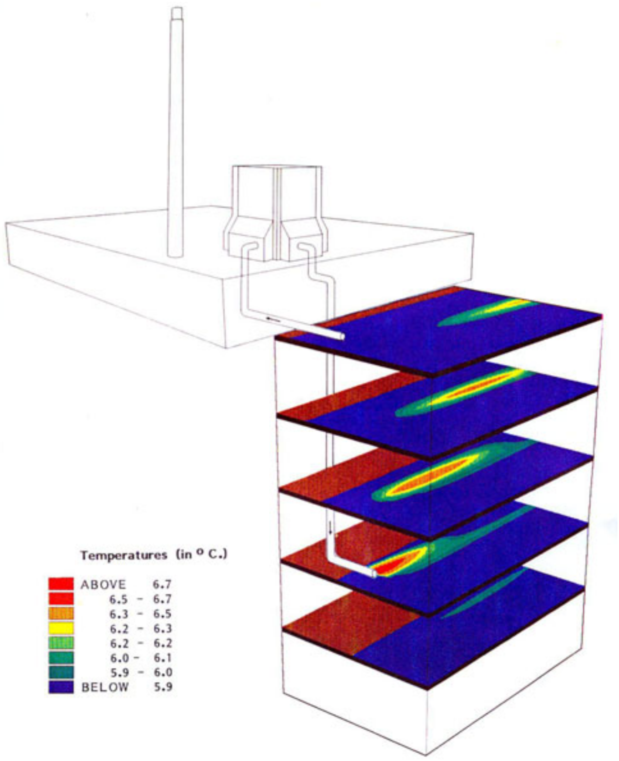


Example of a global tide application of MIKE 21 Flow Model FM. Results from such a model can be used as boundary conditions for regional scale forecast or hindcast models

The MIKE 21 & MIKE 3 Flow Model FM also support spherical coordinates, which makes both models particularly applicable for global and regional sea scale applications.



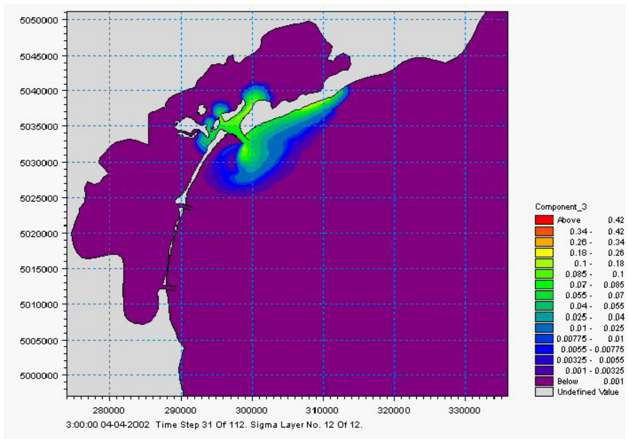
Example of a flow field in Tampa Bay, FL, simulated by MIKE 21 Flow Model FM



Study of thermal recirculation

Typical applications with the MIKE 21 & MIKE 3 Flow Model FM include cooling water recirculation and ecological impact assessment (eutrophication)

The Hydrodynamic Module is together with the Transport Module (TR) used to simulate the spreading and fate of dissolved and suspended substances. This module combination is applied in tracer simulations, flushing and simple water quality studies.



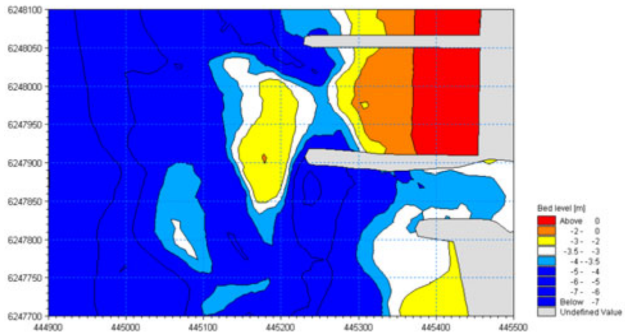
Tracer simulation of single component from outlet in the Adriatic, simulated by MIKE 21 Flow Model FM HD+TR

Prediction of ecosystem behaviour using the MIKE 21 & MIKE 3 Flow Model FM together with ECO Lab

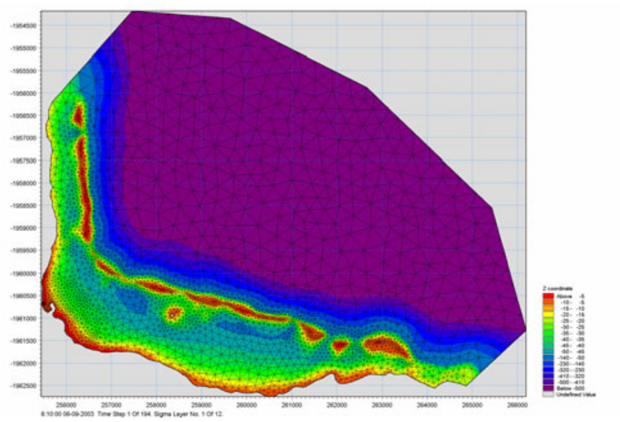
The Hydrodynamic Module can be coupled to the Ecological Module (ECO Lab) to form the basis for environmental water quality studies comprising multiple components.

Furthermore, the Hydrodynamic Module can be coupled to sediment models for the calculation of sediment transport. The Sand Transport Module and Mud Transport Module can be applied to simulate transport of non-cohesive and cohesive sediments, respectively.

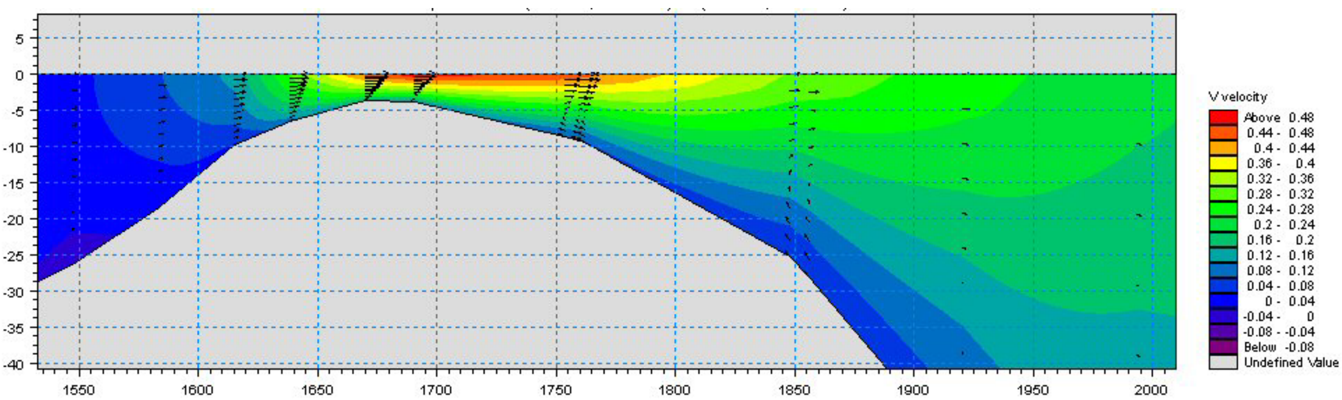
In the coastal zone the transport is mainly determined by wave conditions and associated wave-induced currents. The wave-induced currents are generated by the gradients in radiation stresses that occur in the surf zone. The Spectral Wave Module can be used to calculate the wave conditions and associated radiation stresses.



Coastal application (morphology) with coupled MIKE 21 HD, SW and ST, Torsminde harbour Denmark



Model bathymetry of Taravao Bay, Tahiti



Example of Cross reef currents in Taravao Bay, Tahiti simulated with MIKE 3 Flow Model FM. The circulation and renewal of water inside the reef is dependent on the tides, the meteorological conditions and the cross reef currents, thus the circulation model includes the effects of wave induced cross reef currents

Computational Features

The main features and effects included in simulations with the MIKE 21 & MIKE 3 Flow Model FM – Hydrodynamic Module are the following:

- Flooding and drying
- Momentum dispersion
- Bottom shear stress
- Coriolis force
- Wind shear stress
- Barometric pressure gradients
- Ice coverage
- Tidal potential
- Precipitation/evaporation
- Wave radiation stresses
- Sources and sinks

Model Equations

The modelling system is based on the numerical solution of the two/three-dimensional incompressible Reynolds averaged Navier-Stokes equations subject to the the assumptions of Boussinesq and of hydrostatic pressure. Thus, the model consists of continuity, momentum, temperature, salinity and density equations and it is closed by a turbulent closure scheme. The density does not depend on the pressure, but only on the temperature and the salinity.

For the 3D model, the free surface is taken into account using a sigma-coordinate transformation approach.

Below the governing equations are presented using Cartesian coordinates.

The local continuity equation is written as

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=S$$

and the two horizontal momentum equations for the x- and y-component, respectively

$$\frac{\partial u}{\partial t}+\frac{\partial u^2}{\partial x}+\frac{\partial vu}{\partial y}+\frac{\partial wu}{\partial z}=fv-g\frac{\partial \eta}{\partial x}-$$
$$\frac{1}{\rho_0}\frac{\partial p_a}{\partial x}-\frac{g}{\rho_0}\int_z^\eta \frac{\partial \rho}{\partial x}dz+F_u+\frac{\partial}{\partial z}\left(\nu_t\frac{\partial u}{\partial z}\right)+u_sS$$

$$\frac{\partial v}{\partial t}+\frac{\partial v^2}{\partial y}+\frac{\partial uv}{\partial x}+\frac{\partial wv}{\partial z}=-fu-g\frac{\partial \eta}{\partial y}-$$
$$\frac{1}{\rho_0}\frac{\partial p_a}{\partial y}-\frac{g}{\rho_0}\int_z^\eta \frac{\partial \rho}{\partial y}dz+F_v+\frac{\partial}{\partial z}\left(\nu_t\frac{\partial v}{\partial z}\right)+v_sS$$

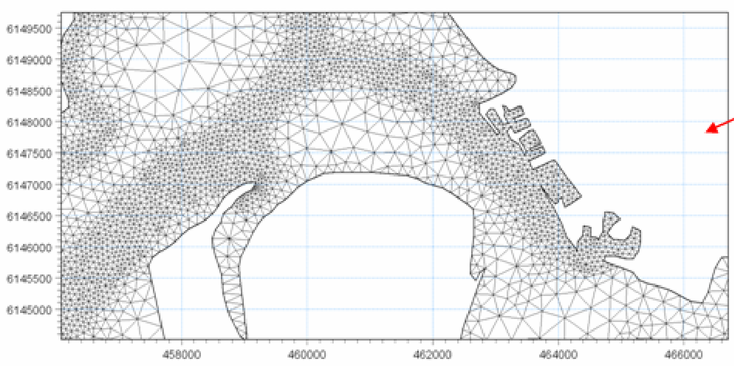
Temperature and salinity

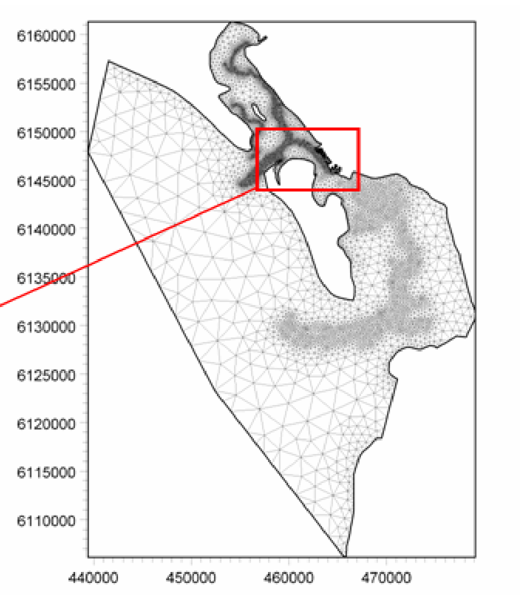
In the Hydrodynamic Module, calculations of the transports of temperature, *T*, and salinity, *s* follow the general transport-diffusion equations as

$$\frac{\partial T}{\partial t}+\frac{\partial uT}{\partial x}+\frac{\partial vT}{\partial y}+\frac{\partial wT}{\partial z}=F_T+\frac{\partial}{\partial z}\left(D_v\frac{\partial T}{\partial z}\right)+\hat{H}+T_sS$$

$$\frac{\partial s}{\partial t}+\frac{\partial us}{\partial x}+\frac{\partial vs}{\partial y}+\frac{\partial ws}{\partial z}=F_s+\frac{\partial}{\partial z}\left(D_v\frac{\partial s}{\partial z}\right)+s_sS$$

Unstructured mesh technique gives the maximum degree of flexibility, for example: 1) Control of node distribution allows for optimal usage of nodes 2) Adoption of mesh resolution to the relevant physical scales 3) Depth-adaptive and boundary-fitted mesh. Below is shown an example from Ho Bay Denmark with the approach channel to the Port of Esbjerg





The horizontal diffusion terms are defined by

$$\left(F_T, F_s\right) = \left[\frac{\partial}{\partial x}\left(D_h \frac{\partial}{\partial x}\right) + \frac{\partial}{\partial y}\left(D_h \frac{\partial}{\partial y}\right)\right]\left(T, s\right)$$

The equations for two-dimensional flow are obtained by integration of the equations over depth.

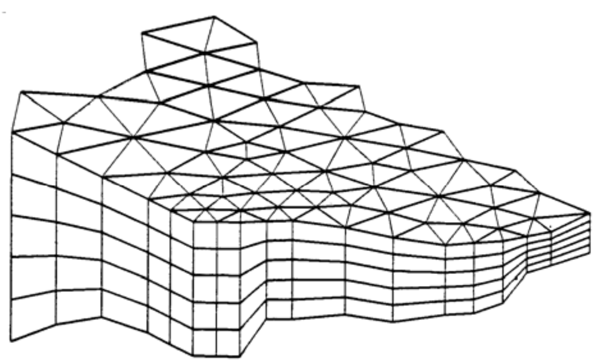
Heat exchange with the atmosphere is also included.

Symbol list

t	*time*
x, y, z:	*Cartesian coordinates*
u, v, w:	*flow velocity components*
T, s:	*temperature and salinity*
D_v :	*vertical turbulent (eddy) diffusion coefficient*
$\hat{H}$:	*source term due to heat exchange with atmosphere*
S:	*magnitude of discharge due to point sources*
T_s, s_s :	*temperature and salinity of source*
F_T, F_s, F_c :	*horizontal diffusion terms*
D_h :	*horizontal diffusion coefficient*
h :	*depth*

Solution Technique

The spatial discretisation of the primitive equations is performed using a cell-centred finite volume method. The spatial domain is discretised by subdivision of the continuum into non-overlapping elements/cells.



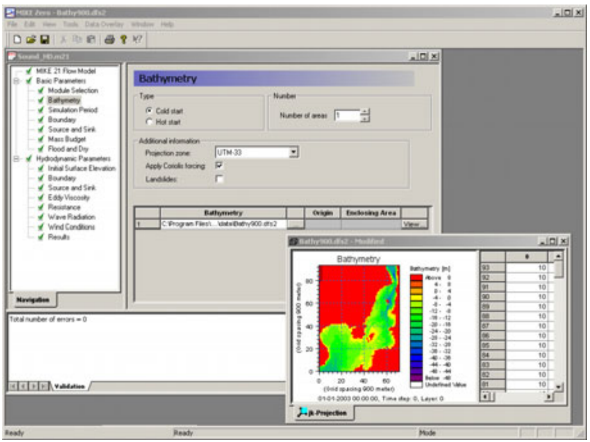
Principle of 3D mesh

In the horizontal plane an unstructured mesh is used while a structured mesh is used in the vertical domain of the 3D model. In the 2D model the elements can be triangles or quadrilateral elements. In the 3D model the elements can be prisms or bricks whose horizontal faces are triangles and quadrilateral elements, respectively.

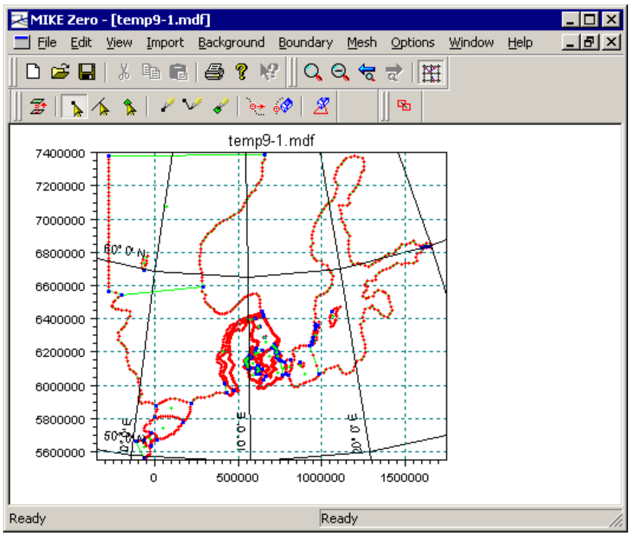
Model Input

Input data can be divided into the following groups:

- Domain and time parameters:
  - computational mesh (the coordinate type is defined in the computational mesh file) and bathymetry
  - simulation length and overall time step
- Calibration factors
  - bed resistance
  - momentum dispersion coefficients
  - wind friction factors
- Initial conditions
  - water surface level
  - velocity components
- Boundary conditions
  - closed
  - water level
  - discharge
- Other driving forces
  - wind speed and direction
  - tide
  - source/sink discharge
  - wave radiation stresses

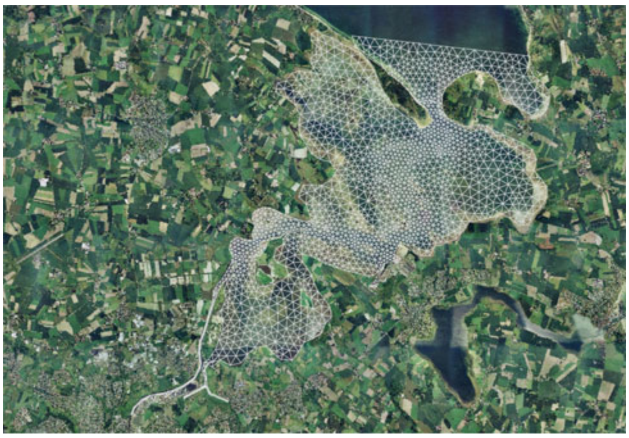


View button on all the GUIs in MIKE 21 & MIKE 3 FM HD for graphical view of input and output files



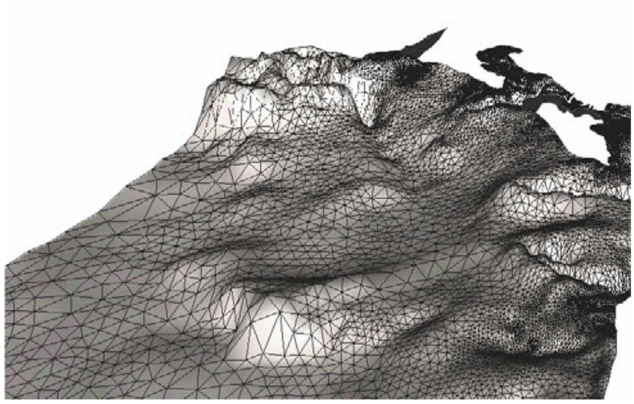
The Mesh Generator is an efficient MIKE Zero tool for the generation and handling of unstructured meshes, including the definition and editing of boundaries

Providing MIKE 21 & MIKE 3 Flow Model FM with a suitable mesh is essential for obtaining reliable results from the models. Setting up the mesh includes the appropriate selection of the area to be modelled, adequate resolution of the bathymetry, flow, wind and wave fields under consideration and definition of codes for defining boundaries.



2D visualization of a computational mesh (Odense Estuary)

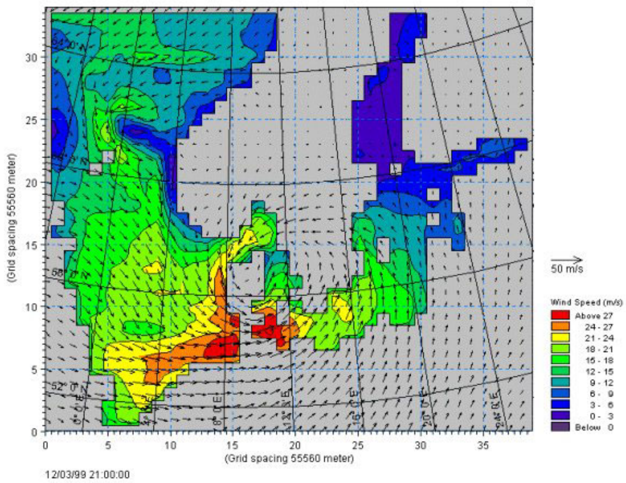
Bathymetric values for the mesh generation can e.g. be obtained from the DHI Software product MIKE C-Map. MIKE C-Map is an efficient tool for extracting depth data and predicted tidal elevation from the world-wide Electronic Chart Database CM-93 Edition 3.0 from C-Map Norway.



3D visualization of a computational mesh

If wind data is not available from an atmospheric meteorological model, the wind fields (e.g. cyclones) can be determined by using the wind-generating programs available in MIKE 21 Toolbox.

Global winds (pressure & wind data) can be downloaded for immediate use in your simulation. The sources of data are from GFS courtesy of NCEP, NOAA. By specifying the location, orientation and grid dimensions, the data is returned to you in the correct format as a spatial varying grid series or a time series. The link is: www.dhisoftware.com/mikemarine/onlinedata



The chart shows a hindcast wind field in the North Sea and Baltic Sea as wind speed and wind direction

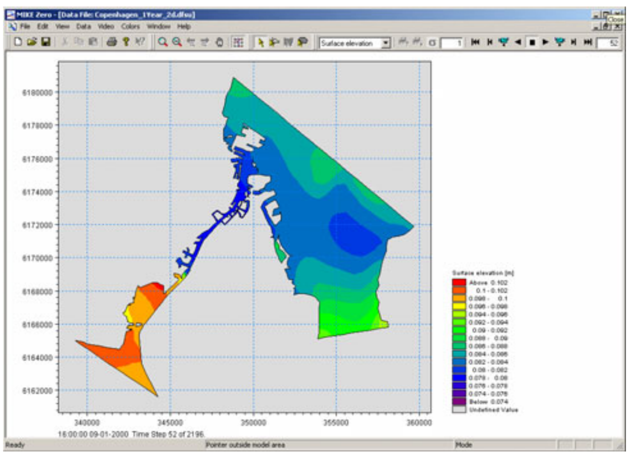
Model Output

Computed output results at each mesh element and for each time step consist of:

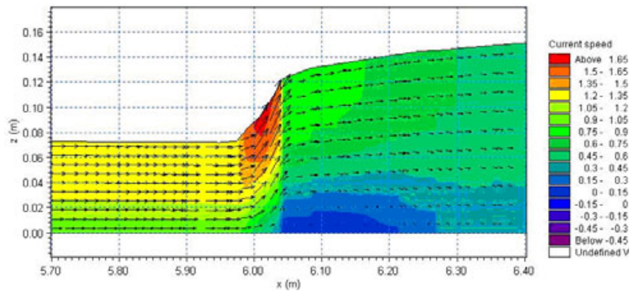
- Basic variables
  - water depth and surface elevation
  - flux densities in main directions
  - velocities in main directions
  - densities, temperatures and salinities
- Additional variables
  - Current speed and direction
  - Wind velocities
  - Air pressure
  - Drag coefficient
  - Precipitation/evaporation
  - Courant/CFL number
  - Eddy viscosity

The output results can be saved in defined points, lines and areas. In the case of 3D calculations the results are saved in a selection of layers.

Output from MIKE 21 & MIKE 3 Flow Model FM is typically post-processed using the Data Viewer available in the common MIKE Zero shell. The Data Viewer is a tool for analysis and visualization of unstructured data, e.g. to view meshes, spectra, bathymetries, results files of different format with graphical extraction of time series and line series from plan view and import of graphical overlays.



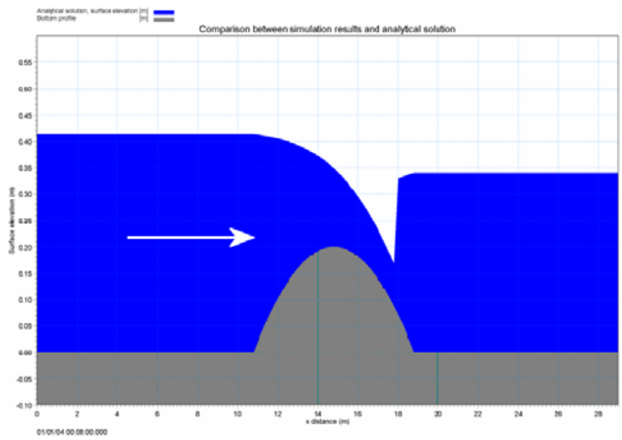
The Data Viewer in MIKE Zero – an efficient tool for analysis and visualization of unstructured data including processing of animations. Above screen dump shows surface elevations from a model setup covering Port of Copenhagen



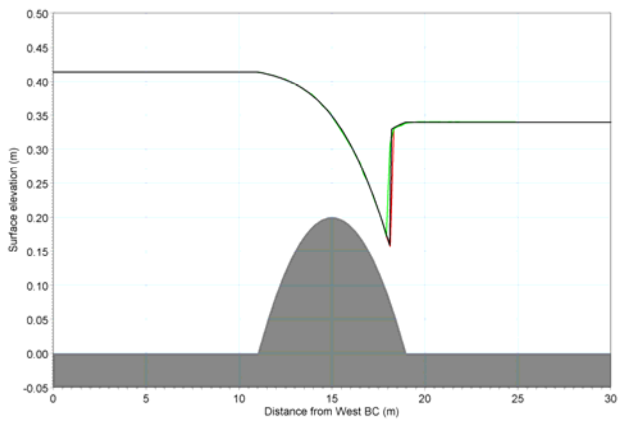
Vector and contour plot of current speed at a vertical profile defined along a line in Data Viewer in MIKE Zero

Validation

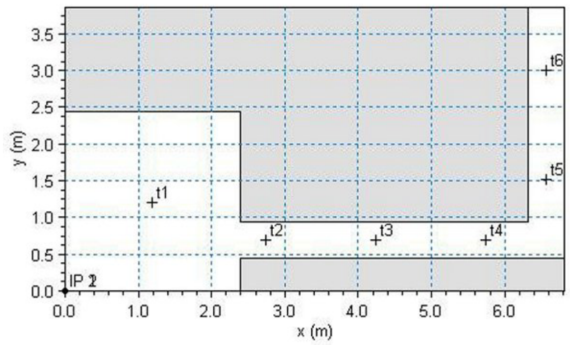
Before the first release of MIKE 21 & MIKE 3 Flow Model FM the model was successfully applied to a number of rather basic idealized situations for which the results can be compared with analytical solutions or information from the literature.



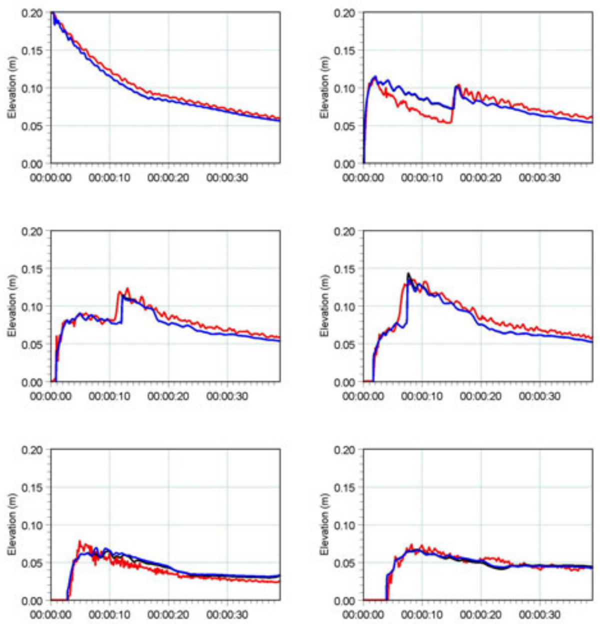
The domain is a channel with a parabola-shaped bump in the middle. The upstream (western) boundary is a constant flux and the downstream (eastern) boundary is a constant elevation. Below: the total depths for the stationary hydraulic jump at convergence. Red line: 2D setup, green line: 3D setup, black line: analytical solution



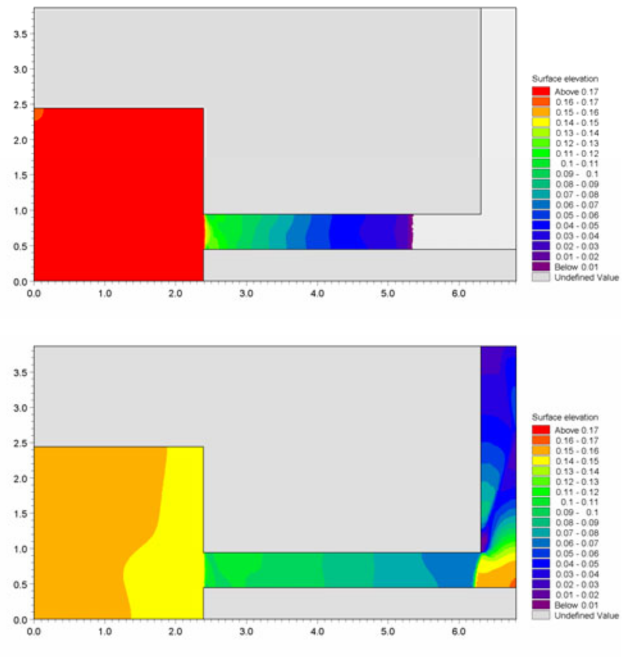
A dam-break flow in an L-shaped channel (a, b, c):



a) *Outline of model setup showing the location of gauging points*

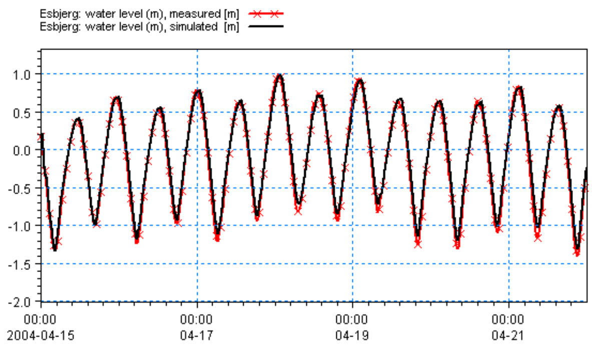


b) *Comparison between simulated and measured water levels at the six gauge locations. (Blue) coarse mesh (black) fine mesh and (red) measurements*

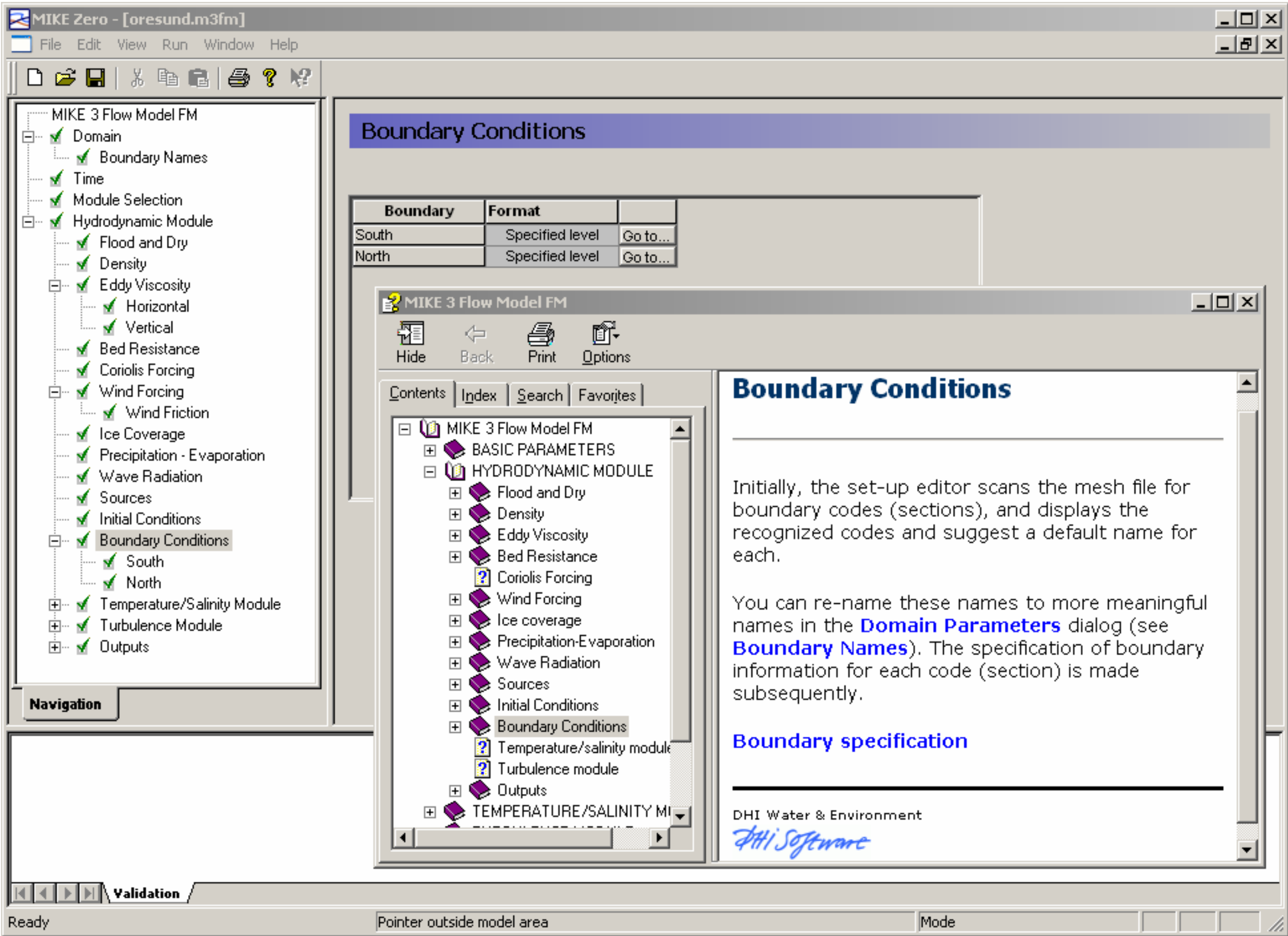


c) *Contour plots of the surface elevation at T = 1.6 s (top) and T = 4.8 s (bottom)*

Example from Ho Bay, a tidal estuary (barrier island coast) in South-West Denmark with access channel to the Port of Esbjerg. Below: Comparison between measured and simulated water levels



The model has also been applied and tested in more natural geophysical conditions; ocean scale, inner shelves, estuaries, lakes and overland, which are more realistic and complicated than academic and laboratory tests.

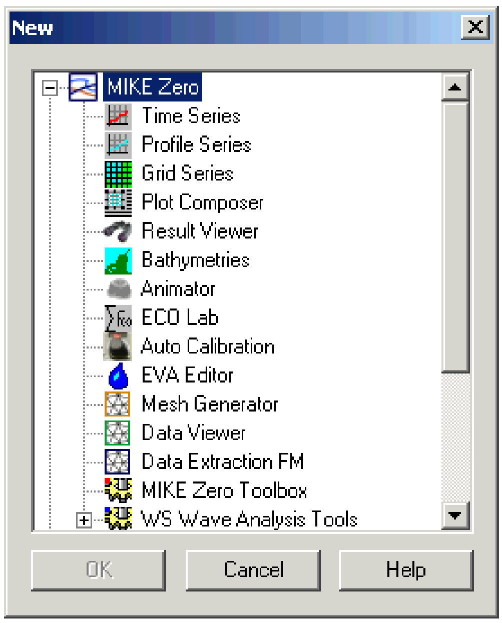


The user interface of the MIKE 21 and MIKE 3 Flow Model FM (Hydrodynamic Module), including an example of the extensive Online Help system

Graphical User Interface

The MIKE 21 & MIKE 3 Flow Model FM are operated through a fully Windows integrated graphical user interface (GUI). Support is provided at each stage by an Online Help system.

The common MIKE Zero shell provides entries for common data file editors, plotting facilities and a toolbox for/utilities as the Mesh Generator and Data Viewer.



Overview of the common MIKE Zero utilities

Hardware and Operating System Requirements

The MIKE 21 & MIKE 3 Flow Model FM are available for PCs with Microsoft Windows XP Professional Edition, Microsoft Windows 2000 and Microsoft Windows XP Professional x64 Edition. Microsoft Internet Explorer (IE) is required for network license management as well as for accessing the Online Help.

The recommended minimum hardware requirements for executing MIKE 21 & MIKE 3 Flow Model FM are:

Processor:	Pentium, AMD or compatible processor; 2 GHz (or higher)
Memory (RAM):	512 MB (or higher)
Hard disk:	20 GB (or higher)
Monitor:	SVGA, resolution 1024x768
Graphic card:	32 MB RAM (or higher), 24 bit true colour
CD-ROM/DVD drive:	for installation of software

Support

News about new features, applications, papers, updates, patches, etc. are available at the MIKE 21 Website located at:

http://www.dhisoftware.com/mike21

For further information please contact your local DHI Software agent or the Software Support Centre at DHI:

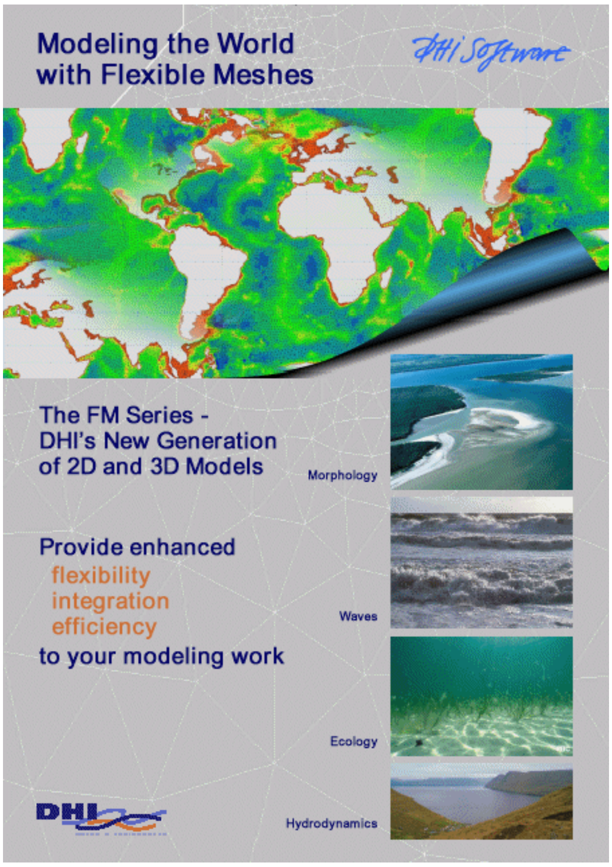
DHI Software Support Centre
DHI Water & Environment
Agern Allé 5
DK-2970 Hørsholm
Denmark

Tel: +4545169333
Fax: +4545169292
Web: www.dhisoftware.com
E-mail: software@dhi.dk

References

The MIKE 21 & MIKE 3 Flow Model FM are provided with comprehensive user guides, online help, scientific documentation, application examples and step-by-step training examples.

The MIKE 21 & MIKE 3 Flow Model FM have been, and are, extensively used in DHI consultancy services (some 50 studies in 20 different countries) and in several research projects.



Petersen, N.H., Rasch, P. "Modelling of the Asian Tsunami off the Coast of Northern Sumatra", presented at the 3rd Asia-Pacific DHI Software Conference in Kuala Lumpur, Malaysia, 21-22 February, 2005

French, B. and Kerper, D. Salinity Control as a Mitigation Strategy for Habitat Improvement of Impacted Estuaries. 7th Annual EPA Wetlands Workshop, NJ, USA 2004.

DHI Note, "Flood Plain Modelling using unstructured Finite Volume Technique" January 2004 – download from http://www.dhisoftware.com/mike21/Download/Papers_Docs/M21FM_Floodplain.pdf

MIKE 3/21 FM

Estuarine and Coastal Hydraulics and Oceanography

Hydrodynamic Module

Flexible Mesh Version

DHI Software 2002

DHI Water & Environment
Agern Allé 11
DK-2970 Hørsholm
Denmark

Tel:	+45 4516 9200
Fax:	+45 4516 9292
E-mail:	dhi@dhi.dk
Web:	www.dhi.dk

2002-07-09/MIKE_321_FM_Scientific_Doc.doc/OSP

PLEASE NOTE

LIMITED LIABILITY

The liability of DHI is limited as specified in Section III of your 'DHI Software Licence Agreement':

'IN NO EVENT SHALL DHI OR ITS REPRESENTATIVES (AGENTS AND SUPPLIERS) BE LIABLE FOR ANY DAMAGES WHATSOEVER INCLUDING, WITHOUT LIMITATION, SPECIAL, INDIRECT, INCIDENTAL OR CONSEQUENTIAL DAMAGES OR DAMAGES FOR LOSS OF BUSINESS PROFITS OR SAVINGS, BUSINESS INTERRUPTION, LOSS OF BUSINESS INFORMATION OR OTHER PECUNIARY LOSS ARISING OUT OF THE USE OF OR THE INABILITY TO USE THIS DHI SOFTWARE PRODUCT, EVEN IF DHI HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES. THIS LIMITATION SHALL APPLY TO CLAIMS OF PERSONAL INJURY TO THE EXTENT PERMITTED BY LAW. SOME COUNTRIES OR STATES DO NOT ALLOW THE EXCLUSION OR LIMITATION OF LIABILITY FOR CONSEQUENTIAL, SPECIAL, INDIRECT, INCIDENTAL DAMAGES AND, ACCORDINGLY, SOME PORTIONS OF THESE LIMITATIONS MAY NOT APPLY TO YOU. BY YOUR OPENING OF THIS SEALED PACKAGE OR INSTALLING OR USING THE SOFTWARE, YOU HAVE ACCEPTED THAT THE ABOVE LIMITATIONS OR THE MAXIMUM LEGALLY APPLICABLE SUBSET OF THESE LIMITATIONS APPLY TO YOUR PURCHASE OF THIS SOFTWARE.'

PRINTING HISTORY

July 2002 .... Edition 2002

CONTENTS

1 INTRODUCTION

The MIKE 21/3 FM modelling system is a general hydrodynamic model, aimed at applications within oceanographic, coastal and estuarine environments. The system comprises both 2 dimensional vertically averaged equations (MIKE 21FM) and 3-dimensional hydrostatic equations (MIKE 3FM).

This note provides the mathematical and numerical background for MIKE 21/3 FM models. In general, the physical processes and features are similar to the implementation in the MIKE 21 nested. Therefore is this note focused on differences from the nested, finite difference model.

2 MATHEMATICAL FORMULATION

The model is based on the solution of the 3-dimensional incompressible Reynolds averaged Navier-Stokes equations, subject to the assumptions of Boussinesq and of a hydrostatic pressure.
The general approach is to use a generalised wave equation, derived from the depth averaged continuity and momentum equations, to describe the free surface while the local momentum equations for the two horizontal components describe the vertical profiles, given the pressure gradients. The solution approach basically follows (Lynch and Werner, 1993).

The local continuity equation is written as

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \tag{2.1}$$

and the two horizontal momentum equations for x- and y-component respectively,

$$\begin{aligned}&\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}=\\&-\frac{\partial}{\partial x}(g\eta+p_A/\rho)+fV-\frac{\partial}{\partial z}(\nu_T\frac{\partial u}{\partial z})+A_X-\frac{g}{\rho}\int_z^\eta\frac{\partial\rho}{\partial x}\end{aligned} \tag{2.2}$$

$$\begin{aligned}&\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}=\\&-\frac{\partial}{\partial y}(g\eta+p_A/\rho)-fU-\frac{\partial}{\partial z}(\nu_T\frac{\partial v}{\partial z})+A_Y-\frac{g}{\rho}\int_z^\eta\frac{\partial\rho}{\partial y}\end{aligned} \tag{2.3}$$

where
ρ : density
u,v,w : velocities in x,y,z directions
f : Coriolis parameter
ϕ,λ : latitude, longitude
υ_t : turbulent eddy viscosity
S : source/sink terms with
η : ELEVATION
p_A : atmospheric pressure
A_X : horizontal stress terms

The horizontal stress terms are described using a gradient-stress relation as

$$A_X = \frac{\partial}{\partial x}(K_{XY}\frac{\partial u}{\partial x}) + \frac{\partial}{\partial y}(K_{XY}\frac{\partial u}{\partial y})$$

where K_{XY} is an eddy viscosity.

Depth averaging of the local equations reads for the continuity equation

$$\frac{\partial \eta}{\partial t} + \frac{\partial UH}{\partial x} + \frac{\partial VH}{\partial y} = 0 \qquad (2.3)$$

and for the two horizontal momentum equations

$$\frac{\partial U}{\partial t} + U\frac{\partial U}{\partial x} + V\frac{\partial U}{\partial y} - fV = -g\frac{\partial}{\partial x}[\eta + \eta_A] + \frac{\tau_{sx} - \tau_{bx}}{\rho H} + A_X + B_X \qquad (2.3)$$

$$\frac{\partial V}{\partial t} + U\frac{\partial V}{\partial x} + V\frac{\partial V}{\partial y} + fU = -g\frac{\partial}{\partial y}[\eta + \eta_A] + \frac{\tau_{sy} - \tau_{by}}{\rho H} + A_Y + B_Y \qquad (2.4)$$

where τ_s is surface stress and τ_b the bed stress, A_X and A_Y are horizontal stress terms and B_X , B_Y are depth averaged baroclinic pressure gradients. For reasons of numerical stability a generalised wave equation is derived for the free surface (Lynch and Werner, 1987). This can be derived by once differentiating the continuity equation eq. 2.3, adding τ_o times the continuity and combining with the momentum equations (2.4 and 2.5). This yields

$$\frac{\partial \eta}{\partial t} + \tau_o\frac{\partial \eta}{\partial t} + \frac{\partial}{\partial x}(\frac{\partial UH}{\partial t} + \tau_o UH) + \frac{\partial}{\partial y}(\frac{\partial VH}{\partial t} + \tau_o VH) + G = 0 \qquad (2.5)$$

where $G = UH\frac{\partial \tau_o}{\partial x} + VH\frac{\partial \tau_o}{\partial y}$

The wind induced surface stress originates from the vertical shear term assuming a balance between the wind shear and the water shear at the surface

$$\tau_{sx} = \rho_{AIR} C_W W W_x$$

where ρ_{AIR} is the density of air, W the wind speed, W_X the x-component of the windspeed, C_W the wind drag coefficient. The wind friction factor is calculated in accordance with Smith and Banke (1975), see Figure 7.2.

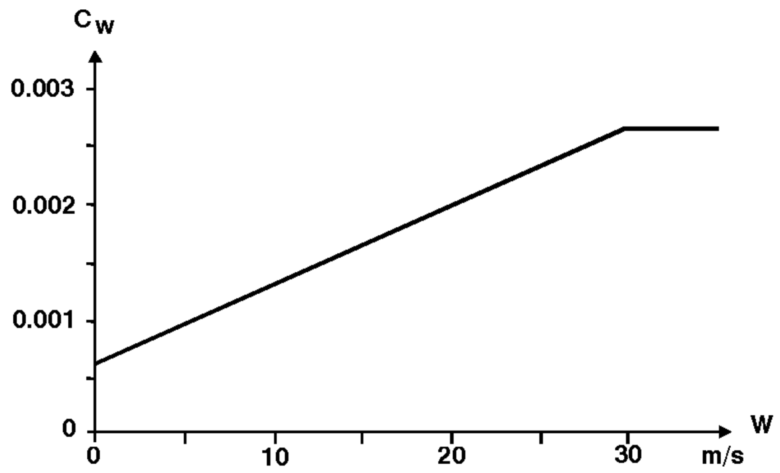


Fig. 7.2 *Wind friction factor (Smith and Banke, 1975)*

$$C_w = \begin{cases} C_{w0} & for \quad W < W_0 \\ C_{w0} + \dfrac{W - W_0}{W_1 - W_0} \cdot \left(C_{w1} - C_{w0}\right) & for \quad W_0 \le W \le W_1 \\ C_{w1} & for \quad W > W_1 \end{cases} \tag{7. 1}$$

where

$$\begin{aligned} C_{w0} &= 0.0013, \; W_0 = 0 \; m/s \\ C_{w1} &= 0.0026, \; W_1 = 24 \; m/s \end{aligned} \tag{7. 2}$$

2.1.1 Bed Resistance

Similar to the wind friction the bed resistance originates from the vertical shear term as a boundary condition.
The vertical discretization in MIKE 3 FM, place the uppermost nodes at the free surface and the lowermost at the seabed. In the calculation of the bed resistance a partial slip boundary is used, where it is assumed that the lowermost node rests on top of the (thin) boundary layer. The thickness of this layercan be given either as *i)* a constant thickness over the whole domain *ii)* a fraction of the still water depth or *iii)* a fraction of the thickness of the lowermost element.

In MIKE 3 FM the bed shear can be calculated using

- constant linear drag where $\tau_b = \rho C_L \left| u(z_b) \right|$

- constant quadratic drag where $\tau_b = \rho C_D \left| Q(z_b) u(z_b) \right|$
- Chezy number where $C_D = \dfrac{g}{C_z^2}$
- Manning number where $C_D = \dfrac{g}{M^2 h^{2/3}}$
- Equivalent roughness and the log-law where $C_D = \left[\dfrac{1}{\kappa} \log(\dfrac{30 z_b}{k_s}) \right]^{-2}$

where κ is von Kármán's constant, k_s the bed roughness, Q the current speed, u is the current velocity (in 2D these are depth averaged values), z_b the distance above the seabed, C_L is a linear drag coefficient, C_D is a quadratic drag coefficient and h the water depth.

If in a 3D setup, resistance is specified as Chezy or Manning numbers, these are converted into an equivalent roughness using for Chezy's law $k_s = H(25.4/C_z)^6$ and for Mannings law $k_s = (25.4/M)^6$ and vice-versa if the roughness is specified in a 2D setup.

The transports of salt or temperature follow the general transport-diffusion equations as

$$\frac{\partial c}{\partial t}+u\frac{\partial c}{\partial x}+v\frac{\partial c}{\partial y}+w\frac{\partial c}{\partial z}=\frac{\partial}{\partial x}(\Gamma_{XY}\frac{\partial c}{\partial x})+\frac{\partial}{\partial y}(\Gamma_{XY}\frac{\partial c}{\partial y})+\frac{\partial}{\partial z}(\Gamma_{Z}\frac{\partial c}{\partial z})+S \quad (2.6)$$

where c can be salinity or temperature, Γ_{XY} and Γ_Z are the diffusivity in horizontal and vertical directions and S are additional source terms, e.g. point sources, heat exchange with the atmosphere or contributions from precipitation.

The temperature and salinity variations are linked to the hydrodynamics using an equation of state, here the UNESCO equation is used.

The turbulence is modelled assuming isotropic turbulence following a gradient-stress or gradient-flux relation. Several options exist, the most complete being a standard k-ε model (Rodi, 1984), where the eddy-viscosity is derived from turbulence parameters k and ε as

$$\nu_T = C_\nu k^2/\varepsilon \quad (2.6)$$

The turbulent kinetic energy k is estimated from a transport equation as

$$\frac{Dk}{Dt}=\frac{\partial}{\partial x}(\Gamma^k_{XY}\frac{\partial k}{\partial x})+\frac{\partial}{\partial y}(\Gamma^k_{XY}\frac{\partial k}{\partial y})+\frac{\partial}{\partial z}(\Gamma^k_{Z}\frac{\partial k}{\partial z}) +\nu_T(S^2+N^2/\sigma_T)-\varepsilon \quad (2.7)$$

and the dissipation of TKE from

$$\frac{D\varepsilon}{Dt}=\frac{\partial}{\partial x}(\Gamma^\varepsilon_{XY}\frac{\partial \varepsilon}{\partial x})+\frac{\partial}{\partial y}(\Gamma^\varepsilon_{XY}\frac{\partial \varepsilon}{\partial y})+\frac{\partial}{\partial z}(\Gamma^\varepsilon_{Z}\frac{\partial \varepsilon}{\partial z}) +\frac{\varepsilon}{k}(\nu_T(C_{1\varepsilon}S^2+C_{3\varepsilon}N^2/\sigma_T)-C_{2\varepsilon}\varepsilon) \quad (2.8)$$

where σ_T is a turbulent Prandtl number and S is the shear, which can be written in tensor notation as

$$S^2=\frac{\partial u_i}{\partial x_j}(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}) \quad (2.9)$$

and N^2 the Brunt-Vaisala frequency

$$N^2 = \frac{g}{\rho}\frac{\frac{\partial \rho}{\partial z}}{\left(\frac{\partial u}{\partial z}\right)^2} \qquad (2.10)$$

For the horizontal stress terms, can be used a Smagorinsky sub-grid scale eddy coefficient, which is calculated as

$$K_{XY} = c_s l^2 |S| \qquad (2.11)$$

where c_S is a constant and l is the linear extent of the element, estimated as $l = \sqrt{A_{element}}$

3 NUMERICAL SOLUTION

Meshes
The numerical solution is based on linear prismatic finite elements and a standard Galerkin weak formulation of the integral equations. The spatial discretization is based on an unstructured mesh of linear triangular elements in the horizontal and a layered vertical mesh using a generalised sigma transformation .

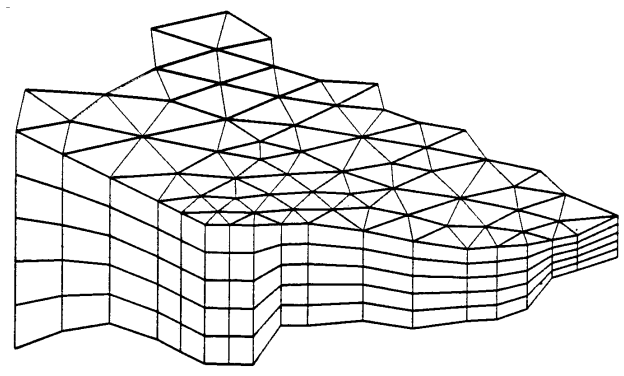


Figure 1. Principles of meshing

Generally, the field variable u is approximated by

$$u(x,y,z)=\sum_{i=1}^{N}u_i\Pi_i(x,y,z) \qquad (2.11)$$

where Π_i is the so-called shape function, describing the spatial variation of u within element i.
With the present choice of spatial discretization the three-dimensional shape function can be written as a horizontal and a vertical part, thus

$$\Pi_i = W_i(x,y)E_i(z)$$

where W is a linear triangular shape function and E is a one dimensional chapeau function.

Numerical solution
The solution of the generalized wave equation is based on a Standard Galerkin weak formulation with nodal quadrature. The time marching is semi implicit, with the gravity terms being time centred and the remaining terms explicit. The momentum equations are solved afterwards, using a procedure where horizontal terms are explicit and vertical terms are time centred.

The vertical velocity is finally derived from the z-derivative of the local continuity equation. Auxiliary parameters as e.g. viscosity and density, are updated at the beginning of each timestep.

The transport equations for salt, temperature and turbulence are solved after the free surface and the velocity field in a way similar to the momentum equations.

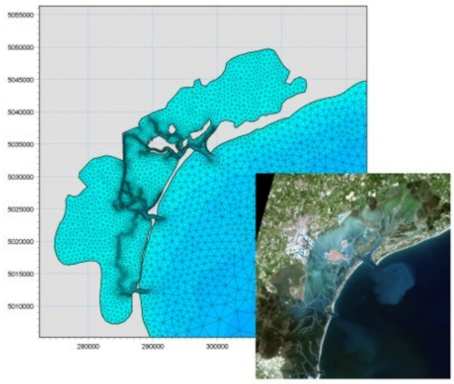
4 REFERENCES

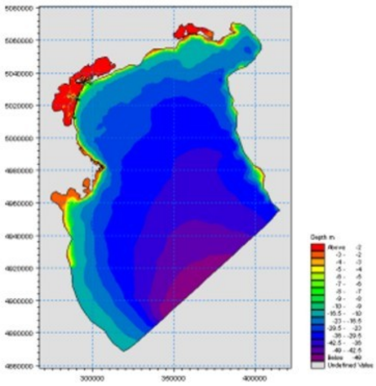
Lynch, D. R. and Werner, F. E. (1987). Three-dimensional hydrodynamics on finite elements, Part II. *International Journal for Numerical Methods in Fluids,* **12**, 507-533.

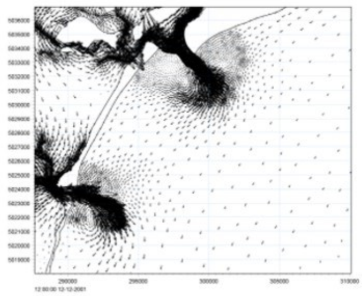
Lynch, D. R. and Namie, C. E. (1993). The M2 tide and its residual on the outerbanks of Gulf of Maine. *Continental Shelf Research*,**12**, 37-64.

Rodi, W. (1984). *Turbulence models and their applications in hydraulics.* IAHR, Delft, the Netherlands.

Location	Upper Adriatic Sea
Type of Project	Estuarine Circulation Study
Client	Consorzio Venezia Nuova (CVN)







Description

The purpose of the project is to establish a thermal and salinity model for near coastal waters of the Upper Adriatic Sea, capable of estimating temperature and salinity in front of the three inlets to Venice Lagoon.

The specific objective is to determine the distribution and origin of water masses off Venice Lagoon. The origin and pathways of the water masses are important for understanding the land-ocean interaction and the source of nutrients and sediments entering or being exchanged with Venice Lagoon. This information is needed in order to be able to establish nutrient and sediment budgets for the lagoon and to support the monitoring activities for measuring the exchange of water between Venice Lagoon and the Adriatic Sea.

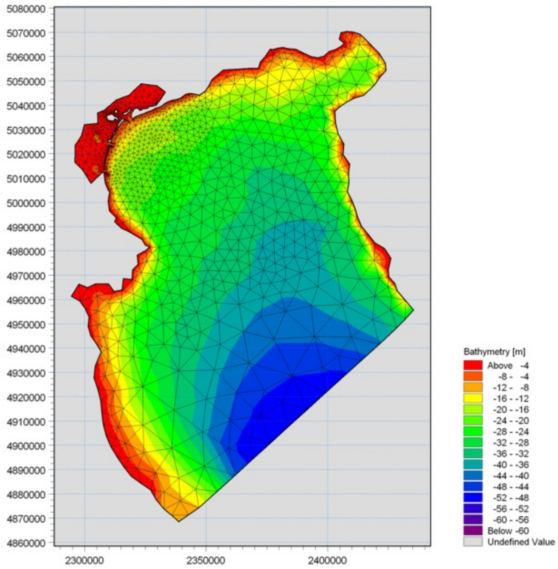
The model has been developed using MIKE 3 FM unstructured mesh model, describing the general circulation in the upper Adriatic Sea and inside the Venice Lagoon. The model describes hydrodynamics, salinity and temperature, and for the purpose of water mass identification transports of 10 conservative tracers are described. Travel times and pathways are further described using a Lagrangian particle tracking module. The model is forced with LAMBO hindcasted local area wind fields and uses meteorological and oceanographic data from the ADRICOSM project.

VENEZIA LONG SEA OUTFALL, ITALY (2005)

Location Venezia

Type of Project Hydraulic design

Client Thetis S.p.a.



Description

As part of the assessment of possible impacts on the environment from a planned long sea outfall into the Golfo di Venezia, DHI has developed a three-dimensional model of the Northern Adriatic Sea including the Laguna di Venezia. The model describes the short-term effects of for example dilution, E. Coli, dispersion or sediment deposition, and long-term effects on eutrophication and on heavy metal concentrations in the sea and the lagoon.

The model is based on the unstructured mesh model MIKE 3 FM and combines hydrodynamics, sediment transport and various ECO Lab templates. The model has been calibrated using a 1-year period of observations of hydrodynamics and water quality parameters. The model is used to describe the possible effects of the sea outfall during various 1-year scenarios.

HYDRODYNAMIC AND WATER QUALITY CHARACTERISTIC MATRIX

Item	SMS 8.1	RMA-10/11	EFDC	CE-QUAL-ICM	WASP4	QUAL 2E-UNCAS	MIKE 3	DELFT 3D	FLOW-3D
CURRENT STATUS	Have software and documentation readily available	Have software and documentation not readily available "testing stage"	Have software and documentation not readily available "testing stage"	Have software and documentation readily available	Have software and documentation readily available	Have software and documentation readily available	Have software and documentation readily available	Have software and documentation readily available	Have software and documentation readily available
DEVELOPER	Birmingham Young University Provo, Utah and RMA	US Waterways Experimental Station and RMA (Dr. Ian King)	Virginia Institute of Marine Science (Dr. John M. Hamrick)	US Waterways Experimental Station	US Environmental Protection Agency	US Environmental Protection Agency	DHI Water and Environment	WL/Delf Hydraulic	Flow Science Inc. (Dr. C. W. Hirt)
VENDOR OR CONTACT PERSON	Boss international Corporation 6612 Mineral Rd, Madison. WI 1-800-488-4775	Dr. Carl F. Cerco US Waterways Experimental Station, Corps of Engineers, 3909 Halls Ferry Road Vicksburg, Mississippi 601-634-3129	Applied Marine Science and Ocean Engineering The College Of William and Mary Gloucester Point, VA 23062	Dr. Carl F. Cerco US Waterways Experimental Station, Corps of Engineers, 3909 Halls Ferry Road Vicksburg, Mississippi 601-634-3129	Robert Ambrose Center for exposure Modelling 404-546-3593	Robert Ambrose Center for exposure Modelling 404-546-3593	Charles Kirsty DHI Water & Environment 301 S.State St. Newtown PA 18940 (215) 504 8497	Rotterdamseweg 185 P.O.Box 177 2600 MH Delf The Netherlands Telephone 31-15-285-8585	Flow Science Inc. P. O. Box 933 1257 40th Street Los Alamos, New Mexico 87544 505-662-2636
COMMERCIAL/PUBLIC DOMAIN	Commercial	Commercial	Public domain	Public domain	Public domain	Public domain	Commercial	Commercial	Commercial
MODEL DIMENSION	Two Dimensional Depth averaged	Three Dimensional	Three Dimensional	Three Dimensional	Three Dimensional	One-Dimensional	Three Dimensional	Three Dimensional	Three Dimensional
MODEL TYPE									
Hydrodynamic	x (RMA-2)	x	x	-	-	x	x	x	x
Water Quality	x (RMA-4)	x	x	x	x	x	x	x	x (Some modification)
Sediment Transport	x	-	-	-	-	-	x	x	-
ELEMENT CONFIGURATION									
Finite element	x	x	-	-	-	-	-	-	-
Finite Difference	-	-	x	-	x	x	-	x	x
Finite Volume	-	-	-	x	-	-	x	-	-
TRANSPORT TRANSFORMATION SCHEME									
Implicit	-	x	-	-	-	x	x	x	-
Explicit	x	-	-	x	x	-	-	-	-
Implicit/Explicit	x	x	x	x	-	-	-	-	x
COMPUTATIONAL SCHEME									
Lagrangian	x	x	-	-	-	-	-	-	-
Eluerian	-	-	-	-	x	x	x	x	x
Eluerian/Lagrangian	x	x	x	x	-	-	-	-	x
MODEL PROCESSING									
Pre-Processor	x	x	x	-	-	-	x	x	x
Solver	x	x	x	x	x	x	x	x	x
Post-Processor (GUI)	x	-	x (with limitation)	-	x	-	x	x	x
WATER QUALITY (Variables or Process)									
Dissolved Oxygen (DO)	x	-	-	x	x	x	x	x	-

HYDRODYNAMIC AND WATER QUALITY CHARACTERISTIC MATRIX

Item	SMS 8.1	RMA-10/11	EFDC	CE-QUAL-ICM	WASP4	QUAL 2E-UNCAS	MIKE 3	DELFT 3D	FLOW-3D
Organic Matter (BOD)	-	-	-	-	-	-	x	x	
Temperature	-	x	x	x	x	x	x	x	x
Salinity	-	x	x	x	x	-	x	x	x
Sediment	x	x	x	x	x	-	x	x	x (Some modification)
Ammonia		-	-	-	-	-	x	x	-
Nitrate	x	-	-	-	-	-	x	x	-
Phosphorus	x	-	-	-	-	-	x	x	-
Bacteria	-	-	-	-	-	-	x	x	-
Chlorophyll-a	-	-	-	-	-	-	x	x	-
Other Water Quality parametrs	x	-	-	x	x	x	x	x	x
EUTROPHICATION MODULE									
Carbon and Nutrient cycling	-	-	-	-	-	-	x	x	-
Growth of phytoplankton and zooplankton	-	-	-	-	-	-	x	x	-
Oxygen Balance	-	-	-	-	-	-	x	x	-
Benthic Vegetation	-	-	-	-	-	-	x	x	-
RIVER CONFIGURATION									
Reach	x	x	x	x	x	x	x	x	x
Branch	-	x	x	x	x	x	x	x	x
Network	-	x	x	x	x	x	x	x	x
IMPOUNDMENT CONFIGURATION									
Mixed	-	x	x	x	x	x	x	x	x
Stratified	-	x	x	x	x	-	x	x	x
BOUNDARY CONDITIONS									
Steady state	x	x	x	x	-	x	x	x	x
Transient (Dynamic)	x	x	x	x	x	-	x	x	x
Quasi-dynamic	-	x	x	-	-	-	-	-	x
TRANSPORT TYPE									
Advection	x	x	x	x	x	x	x	x	x
Diffusion	x	x	x	x	x	x	Dispersion	x	x
Souce /Sink	x	-	-	x	x	x	x	-	-
VARIABILITY									
Deterministic	x	x	x	x	x	x	x	x	x
Stochastic	-	-	x	-	-	-	-	-	x
HYDRODYNAMIC MODELLING HYDRAULIC APPLICATION									
River, harbor, estuary	x	x	x	x	x	x	x	x	x
Irregular floodplains	x	x	x	x	x	x	x	x	x