MIKE 21 & MIKE 3 Flow Model FM

Mud Transport Module

Short Description

DHI headquarters
Agern Allé 5
DK-2970 Hørsholm
Denmark

+45 4516 9200 Telephone
+45 4516 9333 Support
+45 4516 9292 Telefax

mike@dhigroup.com
www.mikepoweredbydhi.com

MIKE213_MT_FM_ShortDescription.docx / AJS/HKH/ULU / 2017-10-03

MIKE 21 & MIKE 3 Flow Model FM – Mud Transport Module

This document describes the Mud Transport Module (MT) under the comprehensive modelling system for two- and three-dimensional flows, the Flexible Mesh series, developed by DHI.

The MT module includes a state-of-the-art mud transport model that simulates the erosion, transport, settling and deposition of cohesive sediment in marine, brackish and freshwater areas. The module also takes into account fine-grained non-cohesive material.

Example of spreading of dredged material in Øresund, Denmark

The MT module is an add-on module to MIKE 21 & MIKE 3 Flow Model FM. It requires a coupling to the hydrodynamic solver and to the transport solver for passive components (Advection Dispersion module). The hydrodynamic basis is obtained with the MIKE 21 or MIKE 3 FM HD module. The influence of waves on the erosion/deposition patterns can be included by applying the Spectral Wave module, MIKE 21 FM SW.

With the FM series it is possible to combine and run the modules dynamically. If the morphological changes within the area of interest are within the same order of magnitude as the variation in the water depth, then it is possible to take the morphological impact on the hydrodynamics into consideration. This option for dynamic feedback between update of seabed and flow may be relevant to apply in shallow areas, for example, where long term effects are being considered. Furthermore, it may be relevant in shallow areas where capital or considerable maintenance dredging is planned and similarly at sites where disposal of the dredged material takes place.

Example of sediment plume from a river near Malmö, Sweden

Application Areas

The MT module is used in a variety of cases where the erosion, dispersion, and deposition of cohesive sediments are of interest. Fine-grained sediment may cause impacts in different ways. In suspension, the fines may shadow areas over a time span, which can be critical for the survival of light-depending benthic fauna and flora. The fine-grained sediment may deposit in areas where deposition is unwanted, for instance in harbour inlets.

Furthermore, pollutants such as heavy metals and TBT are prone to adhere to the cohesive sediment. If polluted sediment is deposited in ecologically sensitive areas it may heavily affect local flora and fauna and water quality in general.

Example of resuspension in the nearshore zone. Caravelas, Brazil. Assessment of resuspension may be relevant in, for example, dredging projects to identify sources and levels of background turbidity

The estimation of siltation rates is an area where the MT module often is applied and also an important aspect to consider when designing new approach channels or deepening existing channels to allow access for larger vessels to the ports. Simulations of fine-grained sediment dynamics may contribute to optimise the design with regard to navigation and manoeuvrability on one hand and minimising the need for maintenance dredging on the other.

The MT module has many application areas and some of the most frequently used are listed below:

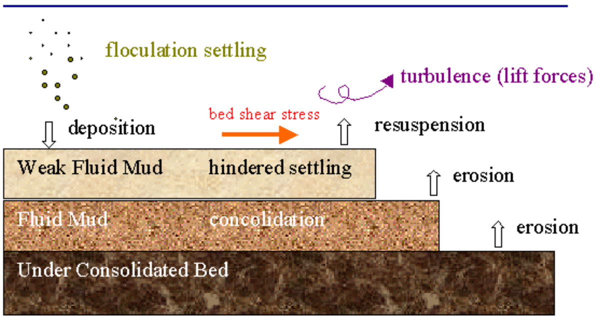
- Dispersion of dredged material
- Optimisation of dredging operations
- Siltation of harbours
- Siltation in access channels
- Cohesive sediment dynamics and morphology
- Dispersion of river plumes
- Erosion of fine-grained material under combined waves and currents
- Sediment laden gravity flows and turbidity currents
- Studies of dynamics of contaminated sediments

Example of muddy estuary. Caravelas, Brazil

Computational Features

The main features of the MIKE 21 & MIKE 3 Flow Model FM Mud Transport module are:

- Multiple sediment fractions
- Multiple bed layers
- Flocculation
- Hindered settling
- Inclusion of non-cohesive sediments
- Bed shear stress from combined currents and waves
- Waves included as wave database or 2D time series
- Consolidation
- Morphological update of bed
- Tracking of sediment spills



Example of modelled physical processes

Model Equations

The governing equations behind the MT module are essentially based on Mehta et al. (1989). The impact of waves is introduced through the bed shear stress. The cohesive sediment transport module or mud transport (MT) module deals with the movement of mud in a fluid and the interaction between the mud and the bed.

The transport of the mud is generally described by the following equation (e.g. Teisson, 1991):

$$\frac{\partial c^i}{\partial t}+\frac{\partial uc^i}{\partial x}+\frac{\partial vc^i}{\partial y}+\frac{\partial wc^i}{\partial z}-\frac{\partial w_S c^i}{\partial z}=$$

$$\frac{\partial}{\partial x}\left(\frac{\upsilon_{Tx}}{\sigma^i_{Tx}}\frac{\partial c^i}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{\upsilon_{Ty}}{\sigma^i_{Ty}}\frac{\partial c^i}{\partial y}\right)+\frac{\partial}{\partial z}\left(\frac{\upsilon_{Tz}}{\sigma^i_{Tz}}\frac{\partial c^i}{\partial z}\right)+S^i$$

The transport of the cohesive sediment is handled by a transport solver for passive components (AD-module). The settling velocity w_s is a sedimentological process and as such it is described separately with the extra term $\frac{\partial w_s C^i}{\partial z}$ using an operator splitting technique.

Symbol list

t	time
x, y, z	Cartesian co-ordinates
u, v, w	flow velocity components
D_v	vertical turbulent (eddy) diffusion coefficient
c^i	the i'th scalar component (defined as the mass concentration)
w_s^i:	fall velocity
σ_{Tx}^i	turbulent Schmidt number
υ_{Tx}	anisotropic eddy viscosity
S^i	source term

The bed interaction/update and the settling velocity terms are handled in the MT module.

The sedimentological effects on the fluid density and viscosity (concentrated near-bed suspensions) are not considered as part of the mud process module. Instead they are provided as separate sub-modules as they are only relevant for higher suspended sediment concentrations (SSC).

Mud plains in Loire River, France

Settling velocity

The settling velocity of the suspended sediment may be specified as a constant value. Flocculation is described as a relationship with the suspended sediment concentration as given in Burt (1986). Hindered settling can be applied if the suspended sediment concentration exceeds a certain level. To distinguish between three different settling regimes, two boundaries are defined, c_{floc} and $c_{hindered}$, being the concentrations where flocculation and hindered settling begins, respectively.

Constant settling velocity

Below a certain suspended sediment concentration the flocculation may be negligible and a constant settling velocity can be applied:

$$w_s = k \qquad c < c_{floc}$$

where w_s is the settling velocity and k is the constant.

Flocculation

After reaching c_{floc}, the sediment will begin to flocculate. Burt (1986) found the following relationship:

$$w_s = k \times \left(\frac{c}{\rho_{sediment}}\right)^{\gamma} \qquad c_{floc} > c > c_{hindered}$$

In which k is a constant, $\rho_{sediment}$ is the sediment density, and γ is a coefficient termed settling index.

Hindered settling

After a relatively high sediment concentration ($c_{hindered}$) is reached, the settling columns of flocs begin to interfere and hereby reducing the settling velocity. Formulations given by Richardson and Zaki (1954) and Winterwerp (1999) are implemented.

Deposition

The deposition is described as (Krone, 1962):

$$S_D = w_s c_b p_D$$

where w_s is the settling velocity of the suspended sediment (m s^{-1}), c_b is the suspended sediment concentration near the bed, and p_d is an expression of the probability of deposition:

$$p_d = 1 - \frac{\tau_b}{\tau_{cd}}$$

In the three-dimensional model, c_b is simply equal to the sediment concentration in the water cell just above the sediment bed.

In the two-dimensional model, two different approaches are available for computing c_b. If the Rouse profile is applied, the near bed sediment concentration is related to the depth averaged sediment concentration by multiplying with a constant centroid height:

$$c_b = \bar{c} \times (\text{centroid height})$$

Teeter (1986) related the near bed concentrations to the Peclet number (P_e), the bed fluxes, and the depth averaged suspended sediment concentrations. In this case, the near bed sediment concentration is described as:

$$c_b = \bar{c} \times \left(1 + \left(\frac{P_e}{1.25 + 4.75\left(p_d{}^{2.5}\right)}\right)\right)$$

where P_e is the Peclet number:

$$P_e = \frac{w_s h}{D_z}$$

where h is the water depth, D_z is the eddy diffusivity, both computed by the hydrodynamic model.

Erosion

Erosion features the following two modes.

Hard bed

For a consolidated bed the erosion rate can be written as (Partheniades, 1965):

$$S_E = E\left(\frac{\tau_b}{\tau_{ce}} - 1\right)^n \qquad \tau_b > \tau_c$$

Where E is the erodibility (kg m^{-2} s^{-1}), n is the power of erosion, τ_b is the bed shear stress (N m^{-2}) and τ_{ce} is the critical shear stress for erosion (N m^{-2}).
S_E is the erosion rate (kg m^{-2} s^{-1}).

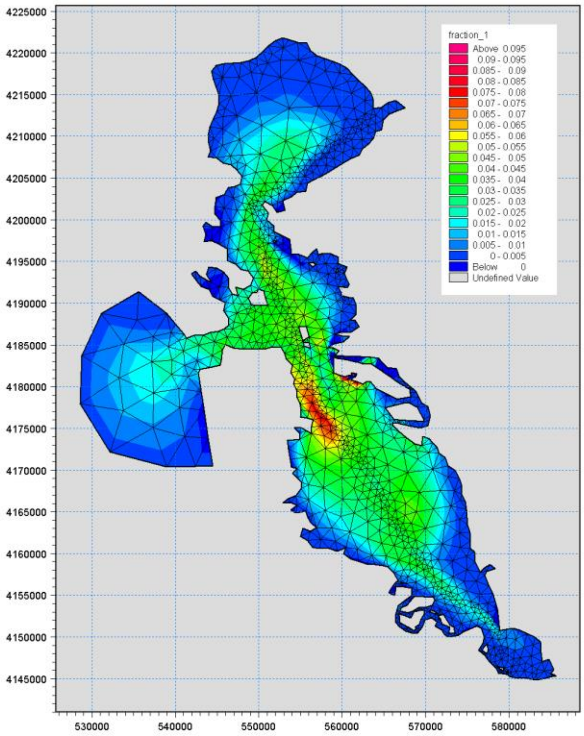
Soft bed

For a soft, partly consolidated bed the erosion rate can be written as (Parchure and Mehta, 1985):

$$S_E = E\left(e^{\alpha\sqrt{(\tau_b - \tau_c)}}\right) \qquad \tau_b > \tau_c$$

Consolidation

When long term simulations are performed consolidation of deposited sediment may be an important process. If several bed layers are used a transition rate (T_i) can be applied. This will cause sediment from the top layers to be transferred to the subsequently lower layers.



The MT module is a tool for estuary sediment management in complex estuaries like San Francisco bay, California, USA

Solution Technique

The solution of the transport equations is closely linked to the solution of the hydrodynamic conditions.

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. In the horizontal plane an unstructured grid is used while in the vertical domain in the 3D model a structured mesh is used. 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.

The time integration is performed using an explicit scheme.

Model Input

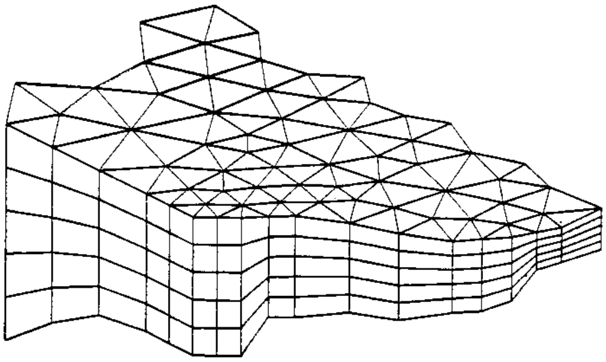
The generic nature of cohesive sediment dynamics reveals a numerical model that will always call for tremendous field work or calibration due to measurements performed. The following input parameters have to be given:

- Settling velocity
- Critical shear stress for erosion
- Critical shear stress for deposition
- Erosion coefficients
- Power of erosion
- Suspended sediment
- Concentration at open boundaries
- Dispersion coefficients
- Thickness of bed layers or estimate of total amount of active sediment in the system
- Transition coefficients between bed layers
- Dry density of bed layers

Model Output

The main output possibilities are listed below:

- Suspended sediment concentrations in space and time
- Sediment in bed layers given as masses or heights
- Net sedimentation rates
- Computed bed shear stress
- Computed settling velocities
- Updated bathymetry



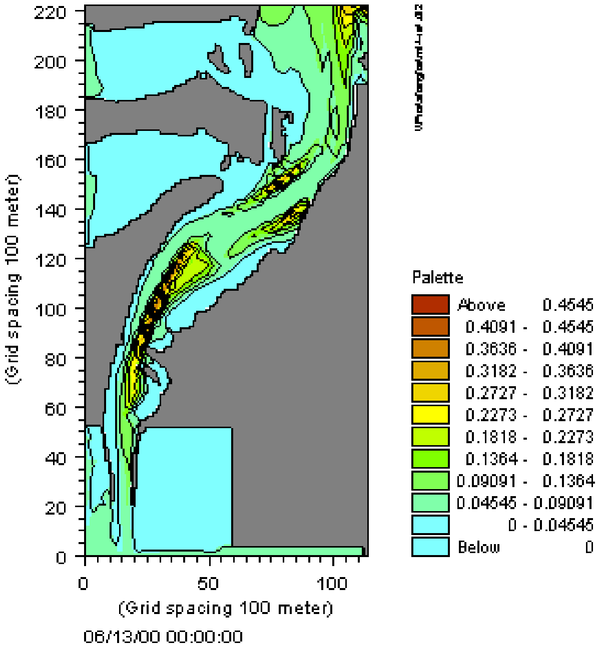
Principle of 3D mesh

Validation

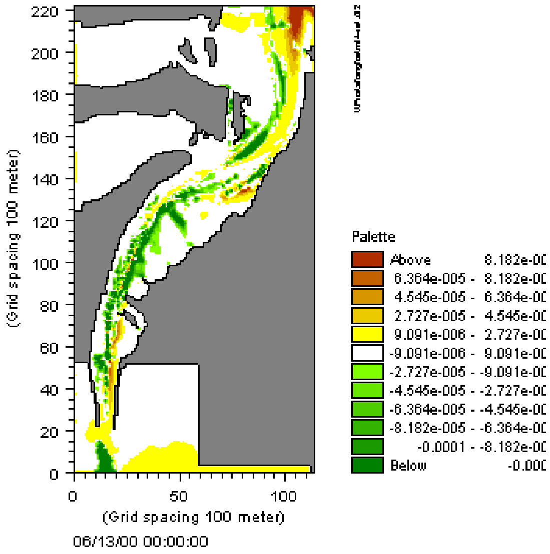
The model engine is well proven in numerous studies throughout the world:

The Rio Grande estuary, Brazil

In 2001, the model was applied for a 3D study in the Rio Grande estuary (Brazil). The study focused on a number of hydrodynamic issues related to changing the Rio Grande Port layout. In addition the possible changes in sedimentation patterns and dredging requirements were investigated.

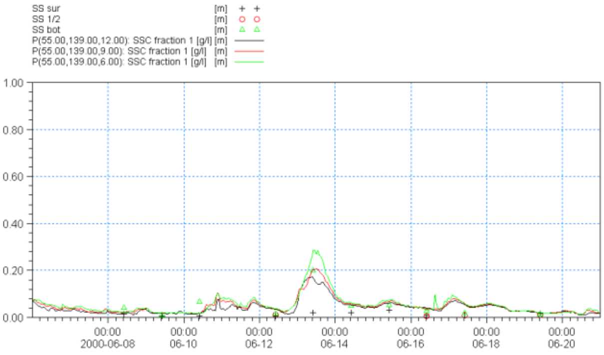


SSC in surface layer (kg/m^3), Rio Grande, Brazil



Instantaneous erosion (kg/m^2/s), Rio Grande, Brazil

The figure below shows the most common calibration parameter, which is the suspended sediment concentration (SSC). The results are reasonable given the large uncertainties connected with mud transport modelling.



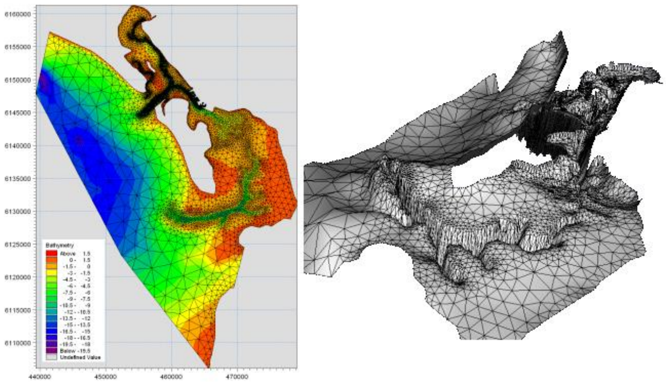
Suspended sediment concentrations, Rio Grande, Brazil

The Graadyb tidal inlet, Denmark

The MT module has also been used in the Graadyb tidal inlet located in the Danish part of the Wadden Sea. In this area, the highest tidal range reaches 1.7 m at springs, but the storm surge in the area can be as high as 2-4 metres.

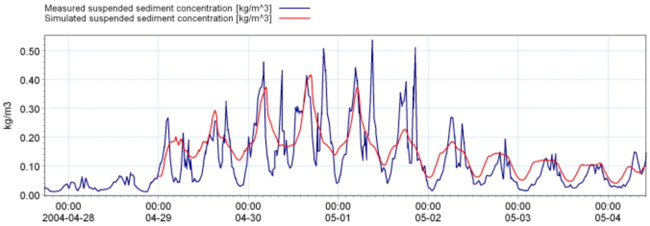
The maximum current in the navigation channel leading to the harbour of Esbjerg is in the range of 1-2 m/s. The depth in the channel is 10-12 m at mean sea level.

Graadyb tidal inlet (Skallingen), Denmark

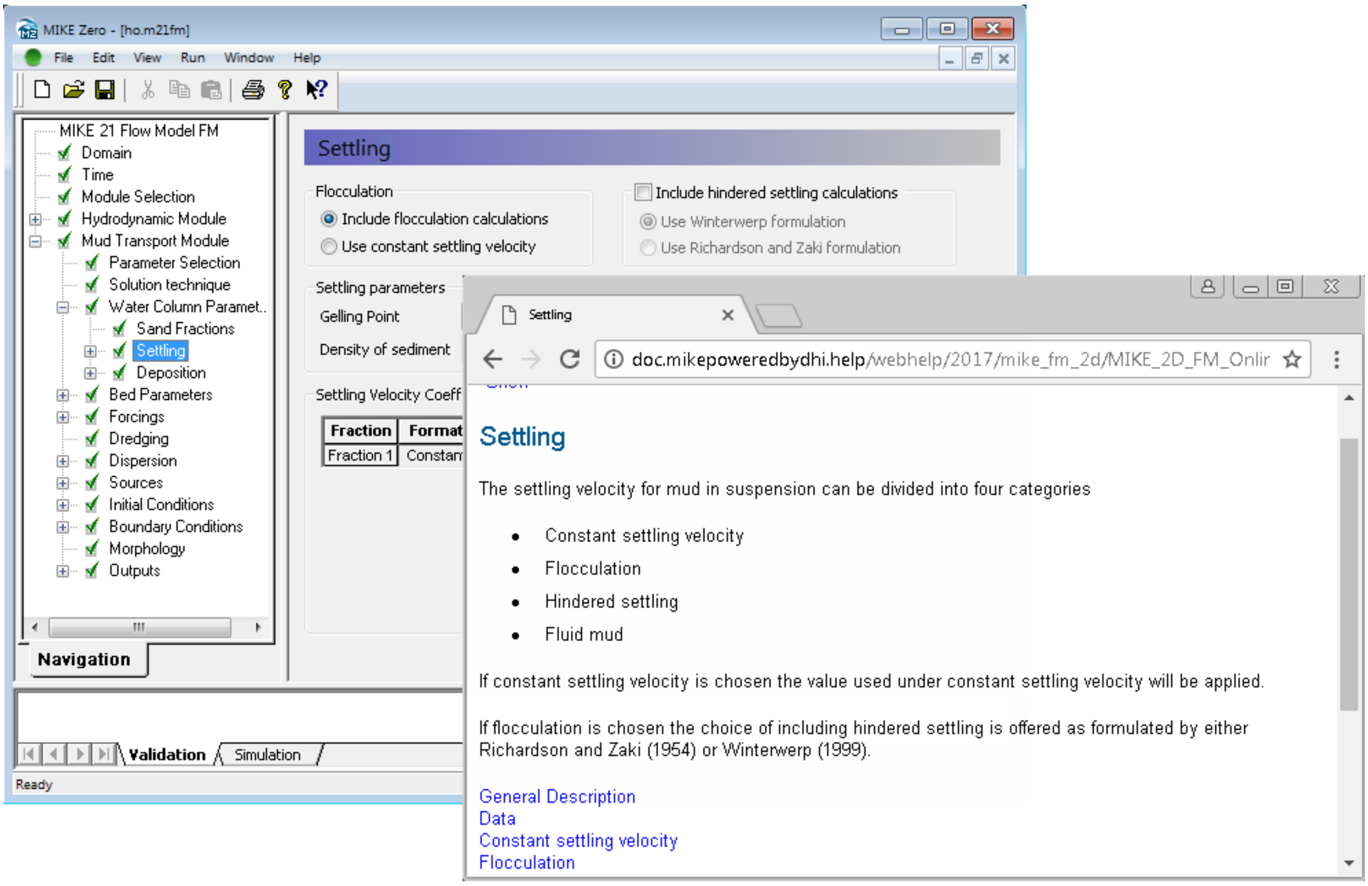


Bathymetry and computational mesh for the Graadyb tidal inlet, Denmark

A comparison between measured and simulated SSC time series is shown below. The overall comparison is excellent.



Comparison between measured and simulated suspended sediment concentrations, Graadyb tidal inlet, Denmark



Flocculation

● Include flocculation calculations

○ Use constant settling velocity

☐ Include hindered settling calculations

○ Use Winterwerp formulation

○ Use Richardson and Zaki formulation

Settling

The settling velocity for mud in suspension can be divided into four categories

- Constant settling velocity
- Flocculation
- Hindered settling
- Fluid mud

If constant settling velocity is chosen the value used under constant settling velocity will be applied.

If flocculation is chosen the choice of including hindered settling is offered as formulated by either Richardson and Zaki (1954) or Winterwerp (1999).

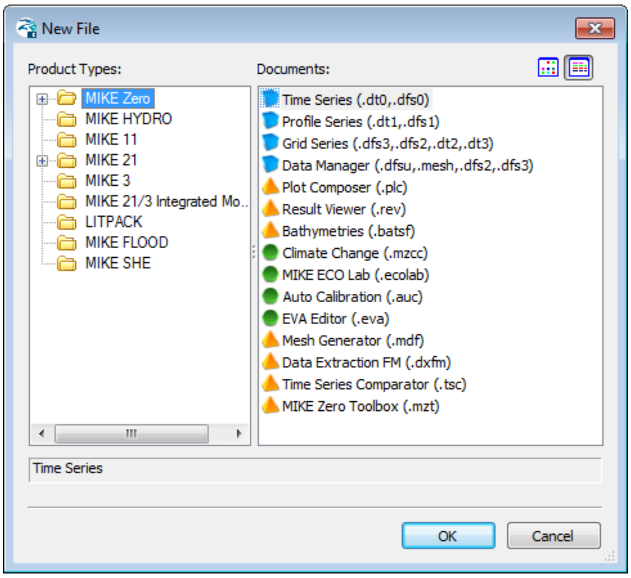
General Description
Data
Constant settling velocity
Flocculation

Graphical user interface of the MIKE 21 Flow Model FM, Mud Transport Module, including an example of the Online Help System

Graphical User Interface

The MIKE 21 & MIKE 3 Flow Model FM, Mud Transport Module is operated through a fully Windows integrated Graphical User Interface (GUI). Support is provided at each stage by an Online Help System.

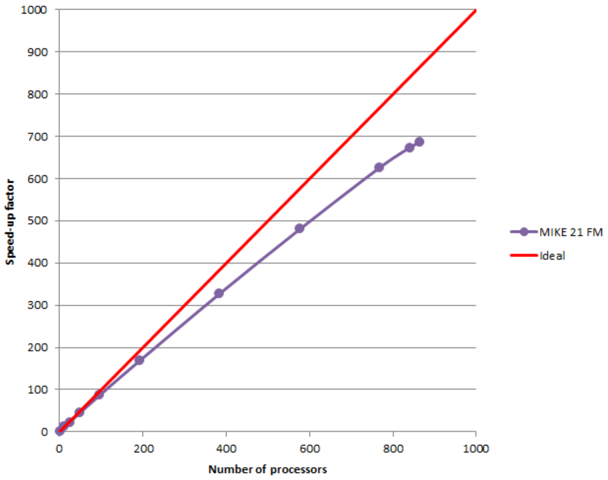
The common MIKE Zero shell provides entries for common data file editors, plotting facilities and a toolbox for/utilities as the Mesh Generator and Data Viewer.



Overview of the common MIKE Zero utilities

Parallelisation

The computational engines of the MIKE 21/3 FM series are available in versions that have been parallelised using both shared memory as well as distributed memory architecture. The latter approach allows for domain decomposition. The result is much faster simulations on systems with many cores.



Example of MIKE 21 HD FM speed-up using a HPC Cluster with distributed memory architecture (purple)

Hardware and Operating System Requirements

The MIKE Zero Modules support Microsoft Windows 7 Professional Service Pack 1 (64 bit), Windows 10 Pro (64 bit), Windows Server 2012 R2 Standard (64 bit) and Windows Server 2016 Standard (64 bit).

Microsoft Internet Explorer 9.0 (or higher) is required for network license management. An internet browser is also required for accessing the web-based documentation and online help.

The recommended minimum hardware requirements for executing the MIKE Zero modules are:

Processor:	3 GHz PC (or higher)
Memory (RAM):	2 GB (or higher)
Hard disk:	40 GB (or higher)
Monitor:	SVGA, resolution 1024x768
Graphics card: (GUI and visualisation)	64 MB RAM (256 MB RAM or higher is recommended)

Support

News about new features, applications, papers, updates, patches, etc. are available here:

www.mikepoweredbydhi.com/Download/DocumentsAndTools.aspx

For further information on MIKE 21 & MIKE 3 Flow Model FM software, please contact your local DHI office or the support centre:

MIKE Powered by DHI Client Care
Agern Allé 5
DK-2970 Hørsholm
Denmark

Tel: +45 4516 9333
Fax: +45 4516 9292

mike@dhigroup.com
www.mikepoweredbydhi.com

Documentation

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

References

Burt, N., 1986. Field settling velocities of estuary muds. In: Estuarine Cohesive Sediment Dynamics, edited by Mehta, A.J. Springer-Verlag, Berlin, Heidelberg, NewYork, Tokyo, 126–150.

Krone, R.B., 1962. Flume Studies of the Transport of Sediment in Estuarine Shoaling Processes. Final Report to San Francisco District U. S. Army Corps of Engineers, Washington D.C.

Mehta, A.J., Hayter, E.J., Parker, W.R., Krone, R.B. and Teeter, A.M., 1989. Cohesive sediment transport. I: Process description. Journal of Hydraulic Engineering – ASCE 115 (8), 1076–1093.

Parchure, T.M. and Mehta, A.J., 1985. Erosion of soft cohesive sediment deposits. Journal of Hydraulic Engineering – ASCE 111 (10), 1308–1326.

Partheniades, E., 1965. Erosion and deposition of cohesive soils. Journal of the hydraulics division Proceedings of the ASCE 91 (HY1), 105–139.

Richardson, J.F and Zaki, W.N., 1954. Sedimentation and fluidization, Part I, Transactions of the institution Chemical Engineers 32, 35–53.

Teeter, A.M., 1986. Vertical transport in fine-grained suspension and newly deposited sediment. In: Estuarine Cohesive Sediment Dynamics, edited by Mehta, A.J. Springer-Verlag, Berlin, Heidelberg, NewYork, Tokyo, 170–191.

Teisson, C., 1991. Cohesive suspended sediment transport: feasibility and limitations of numerical modelling. Journal of Hydraulic Research 29 (6), 755–769.

Winterwerp, J.C., 1999. “Flocculation and settling velocity”, TU delft. pp 10-17.

References on applications

Edelvang, K., Lund-Hansen, L.C., Christiansen, C., Petersen, O.S., Uhrenholdt, T., Laima, M. and Berastegui, D.A., 2002. Modelling of suspended matter transport from the Oder River. Journal of Coastal Research 18 (1), 62–74.

Lumborg, U., Andersen, T.J. and Pejrup, M., 2006. The effect of *Hydrobia ulvae* and microphytobenthos on cohesive sediment dynamics on an intertidal mudflat described by means of numerical modelling. Estuarine, Coastal and Shelf Science 68 (1-2), 208–220.

Lumborg, U. and Pejrup, M., 2005. Modelling of cohesive sediment transport in a tidal lagoon – An annual budget. Marine Geology 218 (1-4), 1–16.

Petersen, O. and Vested, H.J., 2002. Description of vertical exchange processes in numerical mud transport modelling. In: Fine Sediment Dynamics in the Marine Environment, edited by Winterwerp, J.C. and Kranenburg, C. Elsevier, Amsterdam, 375–391.

Petersen, O., Vested, H.J., Manning, A.J., Christie, M. and Dyer, K., 2002. Numerical modelling of mud transport processes in the Tamar Estuary. In: Fine Sediment Dynamics in the Marine Environment, edited by Winterwerp, J.C. and Kranenburg, C. Elsevier, Amsterdam, 643–654.

Valeur, J.R., 2004. Sediment investigations connected with the building of the Øresund bridge and tunnel. Danish Journal of Geography 104 (2), 1–12.