A Numerical Model for Fluid Mud Dynamics in Estuarine Systems – Overview and Outlook

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Summary

Fluid mud is a mixture of fine, mainly cohesive sediments, water and organic substances. The rheological behaviour of fluid mud is that of a non-Newtonian fluid; fluid mud is thus subject to its own dynamic compared to a water body with low suspended matter concentration. The occurrence of fluid mud in estuaries and coastal zones may vary spatially, from a few centimetres in layer thickness to river sections with fluid mud layers which are several kilometres long. The time variability of physical processes, such as the formation, transport and dissipation of fluid mud extends from a few seconds for turbulent mixing to months for creeping mud layers (MEHTA et al. 2014).

The progressive extension and development of coastal waterways has led to an increase in siltation and the formation of fluid mud in sections of estuarine shipping channels, ports and port approaches in recent decades. The need for a better understanding and profound knowledge of fluid mud dynamics has increased and new maintenance strategies and renaturation measures now need to be developed in estuaries and existing ones optimized. Numerical simulations contribute to the evaluation of such strategies.

This paper summarizes the current capabilities and performance of a newly developed three-dimensional numerical model for simulating fluid mud dynamics in estuarine systems. Further possible developments of the numerical model are presented. Important aspects are the interaction of rheology and turbulence in estuaries and the influence of biological parameters.

Keywords

Fluid mud, three-dimensional numerical model, cohesive sediment suspension, rheology, isopycnal model

Zusammenfassung

Flüssigschlick ist ein Gemisch aus feinen vorwiegend kohäsiven Sedimenten, Wasser und organischen Bestandteilen. Die rheologischen Eigenschaften sind die eines nicht-Newtonschen Fluides, somit unterliegt der Flüssigschlick einer eigenen Dynamik im Vergleich zum Wasserkörper mit geringer Schwebstoffkonzentration. Das Vorkommen von Flüssigschlick in Ästuaren und Küstenregionen kann sehr unterschiedliche räumliche Ausdehnungen von wenigen Zentimetern Schichtdicke zu kilometerlangen Flussabschnitten mit Flüssigschlickschichten annehmen. Gleichzeitig reicht die zeitliche Skala der physikalischen Prozesse wie die Entstehung, Transport und Resuspension von Flüssigschlick von Sekunden bei der turbulenten Durchmischung bis zu Monaten bei kriechenden Schlickschichten (MEHTA et al. 2014).

In den letzten Jahrzehnten hat der fortschreitende Ausbau von Seeschifffahrtsstraßen zu einer Zunahme der Verschlickung und Entstehung von Flüssigschlick in Bereichen der ästuarinen Schifffahrtstraßen, *Häfen und Hafeneinfahrten geführt. Der Bedarf an fundierten Kenntnissen über die Flüssigschlickdynamik wächst, um neue Unterhaltungsstrategien und Renaturierungsmaßnahmen in Ästuaren zu entwickeln und bestehende zu optimieren. Numerische Modelle dienen als Werkzeug zur Beurteilung dieser Strategien und Maßnahmen.*

In diesem Artikel werden die derzeitigen Möglichkeiten und die Leistungsfähigkeit eines neu entwickelten dreidimensionalen numerischen Modells zur Simulation der Flüssigschlickdynamik im ästuarinen Bereich zusammengefasst. Weiterhin werden Wege zur Weiterentwicklung des numerischen Modells aufgezeigt. Wichtige Aspekte sind hier Interaktion von Rheologie und Turbulenz in Ästuaren und der Einfluss von biologischen Parametern.

Schlagwörter

Flüssigschlick, 3D numerisches Modell, kohäsive Sedimentsuspension, isopyknisches Modell, Rheologie

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1 Introduction

Siltation in estuarine systems has increased in recent decades as shipping channels and harbours have been progressively developed and expanded. While cohesive suspended sediments are transported by turbulent currents, particles settle and accumulate on the bed in regions of quiescent flow or during periods of low currents, e.g. during slack water in tidal currents. Fluid mud then forms where there is an adequate supply of suspended matter. Fluid mud affects navigation and reduces the water quality. This increases the amount of maintenance required in estuarine waterways e.g. in the Ems estuary.

Fluid mud (high-concentration mud suspension) is a suspension consisting of mineral particles, organic substances, water and in some cases small amounts of gas. Owing to the cohesive properties of clay particles, the fraction of clay particles determines the specific flow behaviour of fluid mud. Fluid mud describes a state in which mud is capable of flowing in spite of very high concentrations of suspended matter in the range of several 10 g/l. The flow behaviour of fluid mud depends on the shear state and can be described as viscoelastic with a yield stress. By comparison, water is characterized as an ideal viscous Newtonian fluid. Fluid mud, being a non-Newtonian fluid, is therefore governed by a different rheology than clear water.

A profound understanding of the process of the formation, development and transport of fluid mud and the description of its rheological behaviour is required for the evaluation, planning and optimisation of construction work, maintenance work and activities designed to reduce siltation. Today, the required detailed investigations and prognoses of the behaviour and reaction of water systems are supported by numerical modelling. This was the rationale for the initiation of the research project MudSim (03KIS66/67 - funded by the German Coastal Engineering Research Council (KFKI) under the auspices of the Federal Ministry of Education and Research (BMBF)). In recent years, a numerical model for simulating fluid mud dynamics (MudSim) has therefore been developed in cooperation between the Federal Waterways Engineering and Research Institute and Prof. A. Malcherek from the University of the German Armed Forces in Munich. A hydrodynamic numerical model in isopycnal coordinates has been extended to enable the simulation of fluid mud dynamics in coastal areas, estuaries and harbours. The MudSim model has been continually developed since then by the BAW. The fluid mud model is outlined in brief and a projection of future developments is provided in the following.

2 Strategy for simulating fluid mud dynamics

The numerical modelling of estuaries is carried out using three-dimensional models which take account of physical processes such as suspended sediment transport, salt transport, density-induced currents, and turbulence. These conventional models are based on the assumption of a Newtonian fluid. However, highly concentrated mud suspensions exhibit distinctly non-Newtonian behaviour and a module to simulate and predict the dynamics of fluid mud therefore had to be developed.

There is usually a strong density gradient in the transition zone between a fluid mud layer and the body of water above it. This transition zone is known as a lutocline. The two fluid layers exhibit very different flow behaviours and interact by virtue of the shear forces acting in the transition zone. A common approach is therefore to model the fluid mud as a two-dimensional, depth-averaged layer. Processes such as the formation and resuspension of fluid mud lead to changes in the density gradient and to the development of a system with multiple layers. For example, in the Ems estuary fluid mud layers of several meters in thickness appear in the maximum turbidity zone, especially during ebb tide as a result of tidal asymmetry. This was observed during a field survey in 2009 (see Fig. 1) during which multiple mud-suspension layers of different densities were detected.

An isopycnal approach, in which mud suspensions are resolved three-dimensionally by means of layers of constant density, has therefore been chosen for the numerical model to improve the resolution of such mechanisms and has proved to be promising. An existing three-dimensional hydrodynamic isopycnal model approach based on CASULLI (1997) was extended to model fluid mud dynamics. This model is called *MudSim*. The numerical method has the following characteristics:

- isopycnal discretization permits a three-dimensional resolution of the fluid mud body with a low degree of discretization and little computational effort
- the isopycnal approach resolves the density stratification and the velocity profile within the fluid mud body
- layer thicknesses vary with the transition to different states of suspension, thereby permitting simulation of the formation, resuspension, settling, and advective and gravitational transport of fluid mud

- the numerical implementation is based on a numerical discretisation in the vertical direction by ρ-layers, and in the horizontal direction by unstructured grids and in time
- interaction of the isopycnal layers is realized on the basis of momentum transfer, vertical mass transfer and interfacial shear stresses

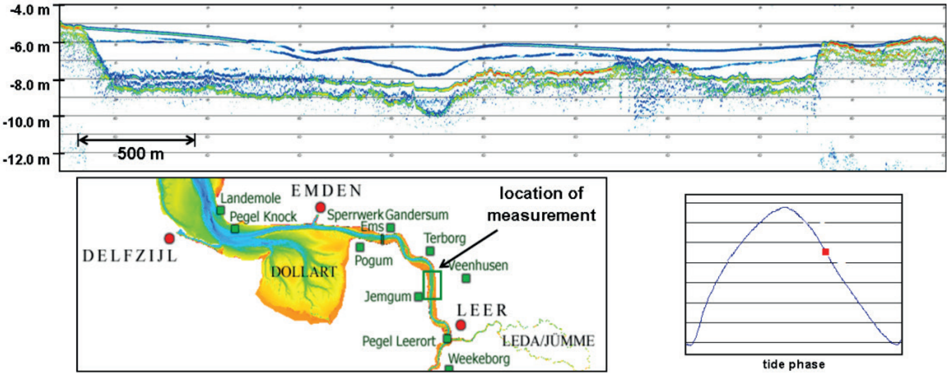

Figure 1: Multi-layer system of fluid mud detected by means of sediment echo sounding measurements (parametric sub-bottom profiler for shallow water) during an ebb tide. The longitudinal section is located between Terborg and Leer in the river Ems. The blue lines indicate strong density gradients and the horizon in red to yellow indicates the sediment bed. The field survey was carried out in July 2009 by the Federal Waterways Engineering and Research Institute (BAW).

It has also been extended to include an approximation of the inner stresses in a non-Newtonian fluid and by considering a parameterized approach for the description of the specific rheological behaviour of fluid mud.

A method is described for the integration of non-Newtonian flow behaviour in a numerical model based on the Reynolds-averaged Navier-Stokes equations. The model simulates the non-Newtonian flow of fluid mud by introducing a rheological viscosity to parameterize the rheology according to shear impact and particle concentration. The rheological model describes the structural break-up and recovery of aggregates in a mud suspension (outlined in Malcherek and Cha (2011) and in Wehr (2012)). The rheological viscosity is no longer a constant, such as the molecular viscosity, but is now a time-dependent and process-descriptive parameter. It is possible to apply different rheological models in this way. Internal friction and interfacial shear stresses are now related to the rheological behaviour of the mud suspension and are taken into account in the numerical solution.

The rheology of fluid mud is described as a viscoplastic shear-thinning fluid by applying a parameterized Worrall-Tuliani model (Worrall and Tuliani 1964; Knoch and Malcherek 2011; Malcherek and Cha 2011). This model considers a yield stress and the break-up and recovery of the microscopic structure (aggregates of cohesive sediments). These parameters are calculated as a function of the shear impact and solid volume concentration. The entire water column is modelled by adopting this approach, as it not only covers the non-Newtonian behaviour of high-concentration suspensions, but also the Newtonian behaviour of low-concentration suspensions and clear water. The shear-thinning behaviour has been studied phenomenologically and it was possible to reproduce it in a study of the Ems river section from Rhede to the weir at Herbrum, in which stratified flow in a tidally-influenced system was investigated (WEHR 2012; WEHR and MALCHEREK 2012). The influence of rheological behaviour on high-concentration flow was analysed in a study of flow on an inclined plane (WEHR 2012; WEHR and MALCHEREK 2012). This effect was compared to the influence of gravitational forcing due to density differences, which has proved to be the dominant process for this test case.

Furthermore, major subprocesses of the fluid mud transport are taken into account by parameterizations in the MudSim model. Vertical transport processes, which lead to the formation and resuspension of fluid mud, are mainly governed by hindered settling and entrainment. This requires variation in the thickness of the density layers over time and in accordance with instantaneous mass transport rates.

The method for simulating fluid mud dynamics is presented in detail in WEHR (2012) as well as in WEHR and MALCHEREK (2012).

3 Achievements and applications of the three-dimensional numerical fluid mud model

Fluid mud dynamics under the influence of tidal currents has been investigated for two model domains: the Ems estuary and the Weser estuary in WEHR (2012) as well as in WEHR and MALCHEREK (2012):

- Fluid mud formation, advective and gravitational transport, and resuspension are periodic processes in tidal systems.
- Highly-stratified flow develops during slack water at high tide and during the ebb tide in the shipping channel.
- The rheological viscosities determined as a function of the shear rate and density yield plausible results and influence the velocities of the stratified flow.
- A qualitative comparison of simulated fluid mud formation and the observed development of the lutocline in the river sections of the Ems and Weser estuaries show similar results.

The latter aspect is presented in the following as a short representative result of simulating fluid mud dynamics with the MudSim model. The numerical model MudSim was applied on the river section Rhede to the weir Herbrum. The comprehensive description of the application and their results is presented in WEHR and MALCHEREK (2012). A characteristic result of the three-dimensional simulation with 16 density layers is shown. The sediment transport in this region is dominated by mud suspensions. The fine sediments are mainly carried into this region by tidal pumping. The fluid mud transport and development under tidal currents were evaluated qualitatively by comparing the simulation results with observations of the lutocline development according to WANG (2010). This is illustrated in Fig. 2. The observations were carried out over several tidal cycles at a specific location in the turbidity zone of the Ems estuary (Leerort). The simulation results are taken from a position between Rhede and Herbrum. Apart from these different locations, the hydrodynamic conditions are not the same in each case and only a phenomenological comparison is therefore possible. However, simulated and observed results both show the typical asymmetrical tide with high flood currents, long slack water at high tide as well as a long ebb phase. The different freshwater discharge conditions in the simulations demonstrate the effect of variable hydrodynamic conditions. The observed lutocline was obtained from ADCP measurements by analysing the backscatter signal. A high backscatter gradient indicates a high-density gradient in the water column.

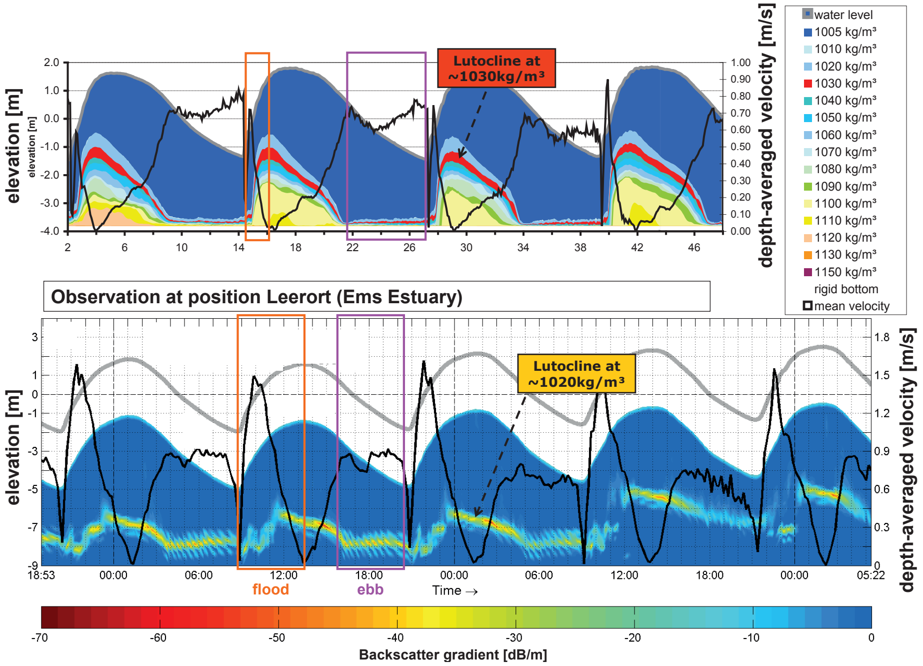

Figure 2: Tidal dynamics of the lutocline - comparison between simulation results (upper panel, simulation (1)) and observations based on 300 kHz ADCP measurements (lower panel).The density corresponding to the lutocline is 1030 kg/m³ in the simulations. The lutocline is indicated by a high backscatter gradient in the measurements. The water level is indicated in grey and the depth averaged velocity in black. It should be noted that the simulated and measured data relate to different locations and different hydrological situations. However, the characteristic development of the lutocline is very similar (illustration of observations by courtesy of Wang (2010)).

The suspended matter concentration just below the lutocline is in the range of 30 kg/m³ (density ~1020 kg/m³) during slack water at high tide, as reported by WANG (2010). The concentration increases downward to the bottom. The simulated density stratification is followed by the subsurface elevation of the density layers. The lutocline is defined as the transition between Newtonian and non-Newtonian behaviour and is accompanied by a sharp density gradient. This corresponds to the layer with a density of 1030 kg/m³ in the simulations as indicated in red in the graphics.

The fluid mud suspension is entrained into the water column during the flood tide. The observations show low backscatter gradients over the entire water column. This mixing process is indicated in the model results by a rapid increase in the layer thicknesses (subsurfaces) of the mud suspensions. The increasing layer thicknesses result from higher concentration layers being mixed with lower concentration layers due to entrainment and horizontal transport. A highly-stable stratified system is then attained in both cases during slack water. The fluid mud is carried downstream with the ebb currents, which decreases the lutocline elevation. The intensifying ebb velocities progressively lower the lutocline level as reflected in both the simulations and the observations. At the same time, the sharp transition between the fluid mud and the water body vanishes. The shapes of the simulated and observed lutoclines are very similar and reveal comparable reactions to the tidal flow, even though the mixing process should be intensified in the simulations.

These applications demonstrate that the developed numerical model approach permits the simulation of three-dimensional fluid mud dynamics. The developed numerical model is capable of simulating fluid mud dynamics in systems such as harbour basins and river sections where high-concentration flow and fluid mud formations dominate the system. Such simulations can contribute to classical 3D hydrodynamic and morphodynamic simulations of estuarine systems for evaluating sediment transport analysis and maintenance strategies.

4 Perspective

The presented numerical model applies an appropriate resolution of the fluid mud body using isopycnal layers. Each isopycnal layer represents a single phase fluid/suspension with a specific particle concentration and specific rheological properties. The isopycnal layer may become very thin or even attain zero thickness depending on the transport rate and the development of cohesive mud suspensions.

The three-dimensional isopycnal model is applied to the entire water column from the consolidated bed to the free surface in the presented model applications in WEHR (2012) and WEHR and MALCHEREK (2012). Simulations of the dynamics of highly-concentrated mud suspensions showed reasonable results. However, the numerical approach limits the flow to stable stratification. This assumption does not always apply in highly-turbulent flows with suspended sediments. In particular, the presence of suspended sediment transport and baroclinic processes may result in an unstable stratification in estuaries. Further investigations of the simulation of the low-concentrated water body are necessary to permit comprehensive modelling of estuarine systems. One possible way of arriving at a more sophisticated model of the water body is described in the following.

A solution can be achieved by coupling the isopycnal model with an existing and established three-dimensional hydrodynamic model such as UnTRIM (CASULLI and WALTERS 2000; CASULLI and LANG 2004), Telemac (HERVOUET and BATES 2000; ELECTRICITÉ DE FRANCE 2000) or Delft3D (LESSER et al. 2004; GERRITSEN et al. 2007). The isopycnal numerical model then functions as a module representing the fluid mud body. The suspended sediment and salt transport simulation is performed by the hydrodynamic model such as in WEILBEER (2014). The isopycnal fluid mud module would then become active in the case of fluid mud formation once the threshold from Newtonian to non-Newtonian flow or a specific mud concentration is exceeded. This module would only be activated in model domains with cohesive sediment accumulations, thereby reducing computational effort for large model domains with different transport regimes such as those in estuaries. This concept will require further developments, research and software engineering for the comprehensive modelling of estuarine systems. Communication between the models will require further investigations on software engineering as well as the description of physical processes. One aspect of the latter is outlined in the following.

The developments had focused so far on the interfacial and internal friction resulting from rheological behaviour. However, the internal shear stresses are also influenced by turbulence.

In nature, fluid mud flows become laminar as the turbulence is destroyed due to density stratification. On the other hand, their rheological behaviour changes from non-Newtonian to Newtonian as mud concentration decreases in the water body, with the possible creation of turbulence. Turbulence interacts with the suspended particles due to turbulence damping and buoyancy effects, which in turn influence the settling velocity. Thus, in the high-concentration, stratified areas, flow behaviour is characterised by the rheological viscosity whereas, in low-concentration mixed areas, the turbulent viscosity is dominant. Both rheology and turbulence are modelled with a similar conceptual model as described in WEHR (2012). They are taken into account through a viscosity and result in a deceleration of the average velocity with increasing viscosities (internal friction). However, their physical effect is contradictory. Whereas rheological viscosity leads to laminar and stratified flow as its magnitude increases, increasing turbulent viscosity, on the other hand, intensifies turbulent mixing and may cause unstable stratifications. Accordingly, research on the interaction between rheological and turbulent viscosity will be important for progressive fluid mud and suspended sediment transport modelling. The focus should be on the transitional area between fluid mud and dilute suspension as well as on the formation process and the resuspension of fluid mud as both quantities may reach considerable magnitudes during resuspension or entrainment. A general approach based on viscosity should combine rheology and turbulence modelling and take account of the solids concentration, shear conditions and structural mechanisms (e.g. flocculation) for the overall water body.

Improvement of the turbulence model will also affect the entrainment of fluid mud which is basically induced by turbulent interfacial shear stresses. Another aspect which would be worth investigating is the influence of fluid mud formation in large areas and of sizable thickness on the internal friction in estuarine systems. Turbulence will be damped during periods of high stratification and internal friction is built up by the rheological viscosity. The shear-thinning behaviour of fluid mud may then lead to relatively small rheological viscosities once the fluid mud moves with the tidal currents. Compared to the magnitudes of the rheological viscosities, the turbulent viscosities can reach much higher magnitudes in a turbulence-dominated system. This aspect and the reduced bottom friction of the water body flowing above the fluid mud body may lead to a larger tidal range in estuaries (see description of tidal dynamics in MALCHEREK (2010)).

Further process-based improvements and validation of the fluid mud model will require additional comparisons with laboratory studies and field measurements. Observation of the development of fluid mud involves measurements not only of the lutocline movement but also of density stratification below the lutocline and velocity distribution inside the fluid mud body. These types of measurement are the objects of ongoing research into highly dynamic systems as it is difficult to perform measurements in high-concentration suspensions. These measurements should enable specific observed phenomena to be related to physical processes. Physical processes are strongly related to the tidal cycle in tidal systems and it is therefore necessary to obtain continuous information in tidal systems (e.g. at least one tidal cycle).

The characteristic flow behaviour of fluid mud can be reproduced by considering a mud suspension comprised solely of cohesive sediments and water as realised in the presented model. However, there are several aspects from which we can learn and gain a better understanding of flow behaviour under different conditions. One important aspect is the influence of organic matter content and biological activity on the formation and flow behaviour of fluid mud. Initial investigations on the simulation of biochemical interactions in estuarine systems have been undertaken as part of the BAW project "Interaction of sediment transport and water quality in three-dimensional estuarine models" with the perspective of further research on the interaction between biological activity and sediment transport.

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