Modeling the Mekong Delta at Three Different Scales

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LONG-TERM GOALS

The long-range goals of the project are to learn about the characteristics and behavior of tropical hydrodynamic and morphological systems including large-scale mangrove vegetation, and to build a long-term collaboration between Vietnamese and ONR researchers through joint field research and modeling.

OBJECTIVES

To provide modeling support to Vietnamese and US researchers and to carry out additional model development in order to enhance the understanding of the hydrodynamic and morphological behavior of the Mekong delta at a range of scales. Specifically, the focus in this project will threefold: (1) on modeling flooding of agricultural areas; (2) on long-term morphological change of the main tributaries of the Mekong in Vietnam; (3) the feedback between mangroves and estuarine and open coast morphology.

APPROACH

The Delft consortium is provides access to and training in open-source models, i.e. Delft3D, XBeach and the new unstructured grid model DFlow-FM (Flexible Mesh). Some developments are foreseen to accommodate specific research questions or useful functionalities. The Delft team will liaise with other ONR research groups involved in field research or modeling and facilitate the use of models to enhance understanding and provide synoptic representations, linking in situ observations, which are necessarily limited in space and remote sensing imagery, which is often of limited quantitative accuracy. An important activity is the training and research collaboration with Vietnamese research groups, through 2 workshops in Vietnam and special programs at UNESCO-IHE in Delft, i.e. to collaborate in development and validation of new functionalities. We envisage the following activities:

WORKSHOPS

A introductory workshop was held in Vietnam during which all interested ONR and VN parties got together to discuss plans for field experiments and model application and development, and to establish what field experiments need in terms of modeling and vice versa. A first 1-2 day modeling short course was part of the program.
In order to promote the optimal use of a combination of field studies, remote sensing and modeling a mid-term workshop was held in Vietnam devoted to an exchange between the different scientists, where modeling results may lead to new ideas on data analysis and trends from data may point towards new modeling ideas or point out weaknesses in the models.

Special programme selected Vietnamese scientists in the Netherlands
A very effective way to build modeling capacity and strengthen collaboration in our experience is to invite researchers over to Delft for approximately 3 month periods during which, apart from some formal training, they work alongside our staff in developing models for their area of interest and/or help develop and validate new functionality.

Development of Mekong Delta unstructured model
As part of a multi-million euro Next Generation Software project at Deltares, an unstructured-grid, finite volume model accommodating both quadrilateral and triangular cells has been under development for several years and is now in a state where it is being applied and validated in large research projects such as the USGS-led CASCADE II project which looks into future climate and water use impacts on the San Francisco Bay and Delta area. The model approach combines accurate representation of bending channels with extreme flexibility in modeling very complex areas and can handle any combination of 1D networks and 2DH or 3D areas. Like the Sacramento-San Joaquin delta the Mekong delta consists of a combination of very complex networks and larger water bodies with distinctly 3D features. Using the experience at UNESCO-IHE, the development team at Deltares and local Vietnamese know-how on the river network an effective and efficient model for the whole system can be developed.

As part of this project, two developments will be implemented:

(1) Optimizing 1D network generation and conversion tools. Given the complexity and sheer number of branches and nodes it is very helpful to be able to import and convert existing network schematizations or GIS layers into a Delft3D Flexible Mesh schematization. Vietnamese modelers will have a leading role here, and will be assisted by Deltares developers for support regarding Delft3D Flexible Mesh model setup and file formats.

(2) Implementing vegetation effects in Delft3D Flexible Mesh. There is substantial experience with modeling effects of vegetation on hydrodynamics and morphology in Delft3D; this can be readily implemented and the formulations, which have so far mainly been used in flood plains and salt marshes in moderate climates, will be adapted to typical mangrove vegetation characterizations. The latter is a task for the Vietnamese modelers.

We expect an important part of the actual modeling effort to be carried out by the Vietnamese partners, for a large part during their respective stays in Delft. Guidance and education is provided for the largest part by UNESCO-IHE, and by Deltares where Delft3D Flexible Mesh is involved.

Wave transformation modelling in mangrove forests
We propose to investigate the effects of cyclone waves on the mangrove forests of the Mekong Delta. Since, especially on the open coast, both incident-band and infragravity waves are likely to be important in understanding and modeling storm erosion, we propose to use the Delft3D Flow model with wave forcing by the online-coupled XBeach, which was recently developed with ONR funding, and to adapt both short-wave and long-wave dissipation formulations for the effect of mangrove
vegetation. Moreover, these formulations will be tested against in-situ data that are partly already available in Vietnam. Infragravity wave data will have to be collected.

WORK COMPLETED

Special programme selected Vietnamese scientists in the Netherlands
Over the last 12 months, UNESCO-IHE welcomed a number of Vietnamese scientists for a stay of a number of weeks/months in the framework of the capacity building part of the project. The purpose of their visit was to get acquainted with the Delft3D FLOW and Delft3D Flexible Mesh modeling software, and to assist them in applying the code in their own work. This was done by a combination of a dedicated short course and hands-on work with assistance of UNESCO-IHE staff:

- Nguyen Hoang Phong of VNU - University of Science focused on developing a Delft3D FLOW model able to simulate the hydrodynamics on the Mekong shelf;
- Vo Quoc Thanh of Can Tho University - College of Environment and Natural Resources started to build an unstructured model of the estuarine parts of the Delta, with special focus on the Bassac river. He was accompanied by Van Pham Dang Tri, who joined a week long modeling short course as a visiting scientist.
- In the meantime Vo Quoc Thanh has enrolled as a PhD student at UNESCO-IHE and will carry out a large part of the modeling work in the second phase of the project.

Final workshop
A final 7-day workshop was held in Ho Chi Minh City on 13-20 September 2015, hosted by the University of Science. During this workshop progress in the model development was presented and a detailed methodology to convert sparse cross-section data to full 2D grid coverage was outlined. Subsequently, during 5 days 25 scientists from HCMC, Hanoi, US and New Zealand were trained in the use of Delft3D.

Figure 1 Impression of Delft3D training workshop: groups of students preparing presentations of the model results they created during the training.
**Code development Delft3D-FM**

In order to attain the objective of building a numerical model that is capable of simulating the longer term morphological development, UNESCO-IHE has started with the implementation of sediment transport and morphodynamic update capability within the Delft3D Flexible Mesh code.

The foundation of this effort was an existing generically operating fortran morphology module, which is currently also used in well-tested models such as SOBEK and Delft3D. Within the scope of this project, the coupling was developed between the morphology module and the native Delft3D FM code. This provides the modeling framework with a large variety in sediment transport formulations for cohesive sediment, sand and gravel (Table 1). The default sediment transport calculation follows the formulations by Van Rijn (1993) with additions by Van Rijn&Walstra (2003).

**Table 1: Available sediment transport formulations in the Delft3D morphology module (Deltares, 2015)**

<table>
<thead>
<tr>
<th>Reference</th>
<th>Transport mode</th>
<th>Waves included</th>
</tr>
</thead>
<tbody>
<tr>
<td>Van Rijn (1993)</td>
<td>Bedload + suspended</td>
<td>Yes</td>
</tr>
<tr>
<td>Van Rijn (2004)</td>
<td>Bedload + suspended</td>
<td>Yes</td>
</tr>
<tr>
<td>Engelund-Hansen (1967)</td>
<td>Total transport</td>
<td>No</td>
</tr>
<tr>
<td>Meyer-Peter-Muller (1948)</td>
<td>Total transport</td>
<td>No</td>
</tr>
<tr>
<td>Ackers - White (1973)</td>
<td>Total transport</td>
<td>No</td>
</tr>
<tr>
<td>General formula</td>
<td>Total transport</td>
<td>No</td>
</tr>
<tr>
<td>Bijker (1971)</td>
<td>Bedload + suspended</td>
<td>Yes</td>
</tr>
<tr>
<td>Van Rijn (1984)</td>
<td>Bedload + suspended</td>
<td>No</td>
</tr>
<tr>
<td>Soulsby/Van Rijn (1997)</td>
<td>Bedload + suspended</td>
<td>Yes</td>
</tr>
<tr>
<td>Soulsby (1997)</td>
<td>Bedload + suspended</td>
<td>Yes</td>
</tr>
<tr>
<td>Ashida–Michiue (1974)</td>
<td>Total transport</td>
<td>No</td>
</tr>
<tr>
<td>Wilcock–Crowe (2003)</td>
<td>Bedload</td>
<td>No</td>
</tr>
<tr>
<td>Gaeuman et al. (2009)</td>
<td>Bedload</td>
<td>No</td>
</tr>
<tr>
<td>Partheniades-Krone (1965)</td>
<td>Suspended</td>
<td>No</td>
</tr>
</tbody>
</table>

Sediment transport can be modeled using different fractions. Each one of these fractions can be defined as bedload, suspended non-cohesive load or suspended cohesive load. These transport modes are all being calculated separately. Different sediment fractions can be assigned different transport formulations. Fractions interact through their relative availability for erosion and transport, and through hiding-exposure. They feed into a bed composition module, that is able to model the behaviour of well-mixed sediment composed of different fractions, or the bed stratigraphy itself.

**Bedload and total load transport**

Bedload represents the sediment movement in the wave boundary layer, or the total transport in case of a total load formulation. The available formulations are capable of taking into account the effects of currents, (non-linear) wave effects and the wave-current angle. The effect of secondary (spiral) flow can be included. Transports are calculated in the water level points, then transferred to the velocity points, and are then corrected for bed-slope effects, and upwind bed composition and sediment
availability. The longitudinal bed slope has an effect on the transport rate, while the transverse slope changes the direction of the bed load transport. The available formulations for these corrections are (Deltres 2015):

- Bagnold (1966) - Ikeda (1982, 1988);
- Koch - Flokstra (1980);
- Parker - Andrews (1985)

**Suspended load transport**
The present depth-averaged suspended transport formulation uses the approach of Galappatti and Vreugdenhil (1985) to calculate the source and sink terms for the depth integrated suspended sediment transport. In this approach, a relaxation time represents the time which the suspended sediment needs to diffuse vertically through the water column to attain an equilibrium sediment concentration profile.

\[ \frac{\partial hc}{\partial t} + \frac{\partial hcu}{\partial x} + \frac{\partial hcv}{\partial y} - \frac{\partial}{\partial x} \left( D \frac{\partial hc}{\partial x} \right) - \frac{\partial}{\partial y} \left( D \frac{\partial hc}{\partial y} \right) = h \left( c - c_{eq} \right) / T, \]

where \( h \) is the water depth, \( c \) is the depth-averaged concentration, \( u \) and \( v \) are the depth-averaged velocities, \( D \) is the horizontal diffusivity, \( T \) is the relaxation period. This relaxation period is a function of the fall velocity, local water depth and the local shear velocity (Galappatti, 1983). The equilibrium concentration \( c_{eq} \) follows from the sediment transport formula used: \( c_{eq} = \frac{|S|}{|u| h} \). Here \( S \) is the depth-averaged sediment transport vector, following from direct calculation or 1DV integration, depending on the transport formulation chosen.

**Bottom updating**
The bottom is optionally updated during every computational timestep. At each time-step, the change in the mass of bed material that has occurred as a result of the sediment sink and source terms and transport gradients is calculated. This change in mass is then translated into a bed level change based on the dry bed densities of the various sediment fractions. The start of the morphological updating can be delayed until the hydrodynamic spin-up period has passed. Morphodynamic simulations can be sped up using the morphological time scale factor (Roelvink, 2006). To avoid the excessive scouring of channels, and allow erosion of the dry beach and channel migration, dry cells next to flooded cells can set to start eroding. Part of the erosion flux that would occur in the neighbouring wet cell is then attributed to the dry cell surrounding it.

**Additional features**
In addition to the coupling of the morphology module to the main Delft3D FM code, separate modules are being developed to perform dredging and dumping operations, and to calculate the generation and advection of bed forms.
**Validation**

Validation of the model outcomes of various newly implemented features was performed by a detailed comparison between the Delft3D Flexible Mesh and an equivalent structured Delft3D model. An example of one of these simulations is presented in Figure 3.

![Figure 2: Example of comparison between a curvilinear Delft3D model and an unstructured Delft3D FM model. Test case is the movement of a circular mound of sand as described by de Vriend (1987).](image)

**Development of Mekong Delta unstructured model**

Boundary conditions (discharge, salinity, water levels) from the upstream boundaries in Cambodia, land boundary data and terrain and bathymetric information for the unstructured grid model were obtained from the Mekong River Comission data portal, and other public domain data sources. The tidal boundary conditions were derived from a tidal inversion model (TMD, Egbert & Erofeeva, 2002).

Except for relatively small portions of the delta system, batymetry data is available at relatively sparse cross-sections, that are not always properly geo-referenced. In order to generate a bathymetry dataset for all the main branches that is fine enough to support a range of model schematizations at different resolutions an effort was made to create separate fine curvilinear grids along all reaches; an effective methodology was found to project the profile data onto these boundary-following grids, to interpolate the data in the transformed grid domain and to project the results back as fine sets of x,y,z samples. In Figure 3 below the steps to generate a fine bathymetric sample sets are outlined. This procedure was carried out for all the major branches of the Mekong, until well across the Cambodian border, up to Kratie and Tonle Sap lake. Figure 4 shows the extent of the compiled bathymetry dataset, which clearly shows the definition of all main channels and islands.
Figure 3 Steps in building a detailed bathymetry for the major Mekong delta branches

Figure 4 Overview of compiled bathymetry dataset
The complete large-scale unstructured grid is shown in Figure 5 and a detail in Figure 6. Depending on the calibration and validation of the discharges and water levels the grid may need to be locally adapted or refined but this will likely not induce major changes in the number of grid cells. As it is, the model can run simulations over half a year overnight on a laptop, so with the use of more computer power multi-year simulations are easily within reach. Results are scheduled to be presented at Ocean Sciences 2016 (Q.T. Vo et al.)
Development of Bassac (Hau) River Delft3D model

In order to study the 3D hydrodynamic and sediment processes in the Hau river branch, its estuary, Cu Lau Dung island and the shelf, a Delft3D model was set up with a domain extending upstream to 155 km from Cu Lau Dung and approx 150 km alongshore towards the southwest. The model was set up with a deliberately coarse grid to be able to quickly assess the dominant processes. Since the underlying bathymetry data is much finer it is relatively straightforward to refine the model according to needs. The model has 10 equidistant sigma layers and can run, including salinity and sediment processes, a spring-neap cycle in little more than an hour on a laptop, making it very suitable for a first assessment of processes and sensitivities to input parameters and forcing conditions. The model was used successfully during the final workshop to facilitate the connection between modeling and observations and resulting collaborative results (UNESCO-IHE, UW, NCSU, VNU) will be presented at the Ocean Sciences meeting in Feb 2016 (Roelvink et al.), connecting ADCP data on fixed moorings, ADCP and CTD profiles from ships in Bassac and on the shelf, with RS images of SSC.

Figure 7 Coarse-grid Delft3D model of Bassac and shelf and sample point output of time-varying velocity, salinity and sediment concentration
Wave transformation modelling in mangrove forests
To attain objective (3), Deltares has implemented dissipation formulations in XBeach with which it is possible to simulate the wave attenuation and water level set up in vegetation. The implementation is done as follows: XBeach (in hydrostatic mode) solves the wave action equation for the short waves separately from the momentum and mass equation for the (time-varying) water levels. In the wave action equation we implemented the Mendez & Losada (2004) formulation which governs the attenuation of the grouped short waves, and which has also been implemented in SWAN for stationary waves. In the flow momentum balance, the drag force term was adapted for the non-linearity of short and long waves.

The new model has been validated on a laboratory data set of wave attenuation and wave-induced set up, kindly provided by dr. Ozeren of the U. of Mississippi. The XBeach results show good agreement with data and moreover, XBeach is capable of reproducing the zero gradients in the water level.

The next steps are to implement the formulations such that it is possible to simulate emerging vegetation, and vegetation with vertically-varying properties such as mangroves which have a root, stem and canopy structure. Further testing of this model on academic and (if available) real observations of mangrove coasts will take place, with a scheduled manuscript on the model formulations.

RESULTS

In this study, the process-based storm impact model XBeach was extended with formulations for attenuation of sea-swell and IG waves as well as the effect on the wave setup, in two modes: the sea-swell wave phase-resolving (non-hydrostatic) and the phase-averaged (surfbeat) mode. In surfbeat mode a wave shape model was implemented to estimate the wave phase and to capture the intra-wave scale effect of emergent vegetation and nonlinear waves on the wave setup. Both modeling modes were validated using data from two flume experiments and show good skill in computing the attenuation of both sea-swell and IG waves as well as the effect on the wave-induced water level setup. In surfbeat mode, the prediction of nearshore mean water levels greatly improved when using the wave shape model, while in non-hydrostatic mode this effect is directly accounted for. Subsequently, the model was used to study the influence of the bottom profile slope and the location of the vegetation field on the computed wave setup with and without vegetation. It was found that the reduction is wave setup is strongly related to the location of vegetation relative to the wave breaking point, and that the wave setup is lower for milder slopes.

The extended version of XBeach developed within this study can be used to study the nearshore hydrodynamics on coasts fronted by vegetation such as mangroves. It can also serve as tool for storm impact studies on coasts with aquatic vegetation, and can help to quantify the coastal protection function of vegetation. The results and conclusions of the study are summarized in Van Rooijen et al. (2015a) and Van Rooijen et al. (in preparation).

IMPACT/APPLICATIONS

It is clear that a morphodynamic model which covers the entire Mekong Delta, and which is sufficiently efficient to simulate a few years of change without input schematisation is invaluable for integrated coastal zone and estuarine management purposes. Moreover, we aim at making this model a community model, meaning that we will make it widely available to all interested parties to apply,
improve and extend. The fact that Delft3D Flexible Mesh is envisaged to become open source and freely available in 2015 will provide an additional boost to this initiative.

The Delft3D model of the Hau river branch has been developed as an easy tool to demonstrate and study the interaction between river flow, tides, saline/fresh water interactions and tide-, wave-, and wind-driven flows on the shelf.

The improved flow momentum balance for vegetated environments will allow to study the morphodynamics of mangrove forest, not only during modal conditions when tidal pumping is the main input mechanism for sediment in these areas, but mainly during tropical cyclones, when infragravity waves are likely the dominating mechanism for the import of fines in tidal wetlands.

**RELATED PROJECTS**

All the modeling efforts within this project benefit from the field data gathered by the other partners in the DRI and collaborative papers are planned with UW, NCSU, MDA. A follow-up proposal 'Mekong Modeling Phase 2' has been accepted for administrative processing and is awaiting formal acceptance. This project will be a direct continuation and will make the step to fully implemented methods and validated models.

The development of the Delft3D-Flexible Mesh code and the vegetation algorithms will allow much more robust and accurate model schematizations in many complex estuaries and river systems of interest to ONR.

Core funding for the generic development of Delft3D-FM code has come from the Next Generation Hydro Software programme led jointly by the Dutch government (Rijkswaterstaat) and Deltares, with a funding of over 10 M€.

**ABSTRACTS SUBMITTED TO OCEAN SCIENCES 2016**

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Thanh Quoc Vo, UNESCO-IHE Institute for Water Education, Delft, Netherlands

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