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AN OBJECT-ORIENTED FRAMEWORK FOR ECO-HYDRAULIC SIMULATION IN COASTAL ENGINEERING

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The consideration of biological processes in hydro- and morphodynamic models is an important challenge for numerical simulation in coastal engineering. Vegetation greatly affects the hydro- and morphodynamic in coastal zones. This paper focused on the presentation of an object-oriented holistic framework for eco-hydraulic simulation. The numerical approximation is performed by a stabilized finite element method for hydro- and morphodynamic processes, to solve the related partial differential equations, and by a cell-oriented model for the simulation of ecological processes, which is based on a fuzzy logic rule-based system. The fundamental differences between these different model paradigms require special transfer and coupling methods. Case studies on seagrass prediction in the North Sea show main effects and influences on a changed hydro- and morphodynamic and demonstrate the applicability of the coupled approach in ecohydraulic modeling.

INTRODUCTION

Coastal zones are characterized by complex hydro-, morphodynamic and ecological processes. Hydraulic engineering projects and coastal protection measures interfere with the environment, mostly restricting natural processes. The aim of coastal engineering is to estimate these effects. In recent years especially numerical simulation models have been proven as a valuable tool in coastal engineering. For the description of the physical processes, a variety of hydro- and morphodynamic models have been developed. These models typically based on systems of partial differential equations (PDE's), which are usually solved approximately using FEM, FVM or FDM.

However, the interaction between vegetation and hydro- and morphodynamic processes is not sufficiently considered. Benthic ecosystems like seagrass and mussel beds greatly affect the hydro- and morphodynamic. Influences of seagrass beds on tidal current velocities and sediment texture were studied in different experiments (see [1] [2]) where a substantial reduction of vertical velocity profiles, stabilizing effects to sediment and wave damping effects could be observed. For a better representation of natural processes, the extension of numerical models by ecological model components is necessary.

HYDRODYNAMIC-NUMERICAL MODEL

The numerical model system MARTIN is based on a holistic modeling approach for hydro- and morphodynamic phenomenas (see [5]). Each of the subsystems for waves (W), current (U) and sediment transport processes (S) can be transformed into a uniform mathematical formulation:

$$\frac{\partial W}{\partial t} + L_W W + Q_W = 0 \qquad \text{(wave model)}$$

$$\frac{\partial U}{\partial t} + L_U U + Q_U = 0 \qquad \text{(current model)} \qquad (1)$$

$$\frac{\partial S}{\partial t} + L_S S + Q_S = 0 \qquad \text{(sediment transport model)}$$

The numerical approximation is performed by a stabilized finite element method [5]. In order to find a solution of the time-depended equations in (1) with the finite element method, the domain $\mathbf{\Omega}$ is discretized into n_{el} finite elements $\mathbf{\Omega}_e$. A semi-discrete approach is used, which is separated in a domain integration step and a time integration step. The domain integration is implemented with a predictor-corrector procedure based on the combination of standard Galerkin approximation and least squares approximation. This can be described for the differential equations in (1) as follows:

$$\int_{\Omega} (U_t + LU + S) \cdot \varphi \, d\Omega + \sum_{e=1}^{n_{el}} \tau_e \int_{\Omega^e} (L \cdot \varphi)(U_t^G + LU + S) \, d\Omega^e = 0 \qquad (2)$$

For the consideration of influences of biotic factors the holistic model system MARTIN was extended by ecological model components.

DISCRETE CELL-ORIENTED ECOLOGICAL MODEL

The existence of benthic ecosystems, like seagrasses and mussel beds, has strong effects on water motion and sediment dynamics. Ecological systems are usually described by rules and relationship-diagrams which show positive and negative dependencies between all relevant quantities. This rule-based formulation is typical for the description of biological processes. For the analysis and description of spatial and time variant processes in ecology, discrete cell-oriented models have been proven as suitable simulation tools (see [4],[7]).

The interactions and vegetation dynamics for a seagrass model are included in the basic ecological model, illustrated in figure 1. For the simulation in cell-based models, the flow domain has to be decomposed into a computation grid with a large number of small cells. The decomposition consists of $m \times n$ unique cells. Each cell c_k contains different state variables $\hat{u}(c_k)$ for all relevant quantities and represents a small section of the sea. For the description of relationships and dependencies among the state variables the use of fuzzy techniques and rule-based systems has been proven to process expert knowledge received from biologist and ecologist to determine the dynamics of ecosystems adequately [4].

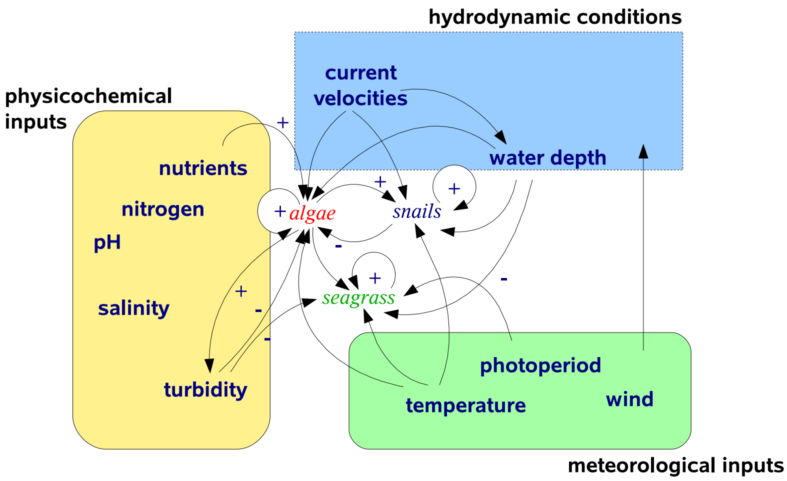

Figure 1. Basic interaction in the ecological model of seagras beds in the North Sea.

Fuzzy-based approach

The main difficulty in ecological modeling is that the knowledge about the evolution of populations and vegetation contains uncertainties. This shows the necessity of handling uncertainties in the variables and rules. The fuzzy set theory is the best tool to handle those uncertainties. Like numerical variables represent numerical values, in fuzzy set theory, linguistic variables represent values that are words (linguistic terms) with associated degrees of membership. The information represented in the fuzzy rule base, which is applied for every cell, can be formulated as if-then rules.

MODEL COUPLING

Eco-hydraulic simulation requires the use of different model paradigms. The fundamental differences between these models make it necessary to have special transfer and coupling methods. For a holistic consideration of biological and non-biological processes both directions have to be considered.

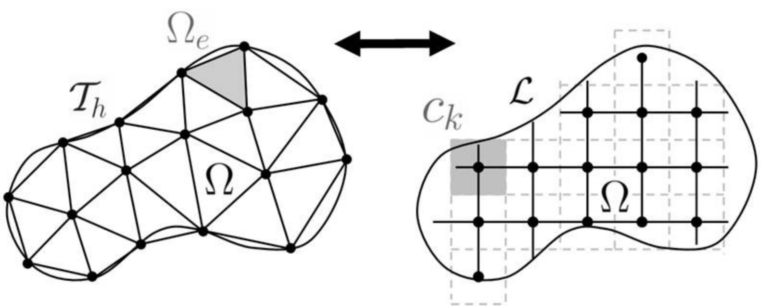

Figure 3: Schematic coupling between a FE-discretization and a cell-decomposition.

Geometric coupling

Standard interpolation could lead to discontinuities and inconsistent results during the coupling procedure. Therefore, extended conservative interpolation methods are focused in the following. The continuous values $u_h(x)$ of the hydrodynamic model have to be interpreted in the rules of the discrete cell-oriented model. This can be obtained by a weighted integral formulation for each cell c_k:

$$\hat{u}(c_k) = \frac{1}{\mu^*(c_k)} \int_x u_h(x)\, dc_k \tag{3}$$

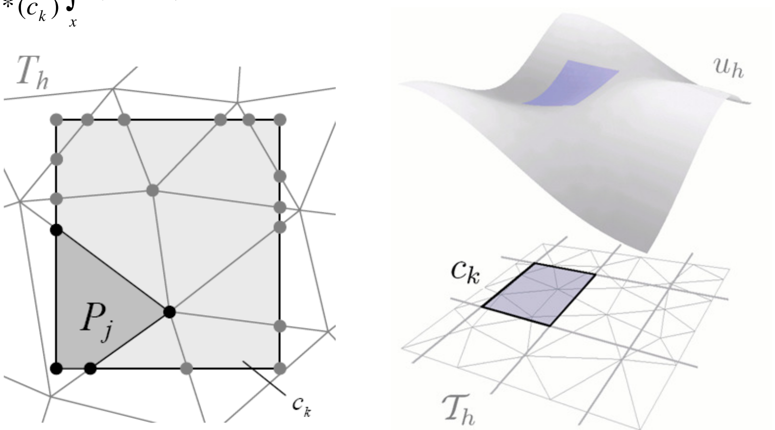

Figure 4. Coupling by integration of the FE-approximation over each cell-region c_k.

On the other hand the quasi-discrete ecological values $\hat{u}(c_k)$ have to be transferred into continuous parameters for a processing in the finite element model. This is based on the voronoi-decomposition of the domain $\boldsymbol{\Omega}$. This way every node is influenced by the cells c_i in the voronoi-region $VR(p_k)$:

$$u_k = \frac{1}{\mu^*(VR(p_k))} \int_x \hat{u}(x)\, dVR(p_k) = \frac{\sum \mu^*(VR(p_k) \cap c_i) \cdot \hat{u}(c_i)}{\sum \mu^*(VR(p_k))} \tag{4}$$

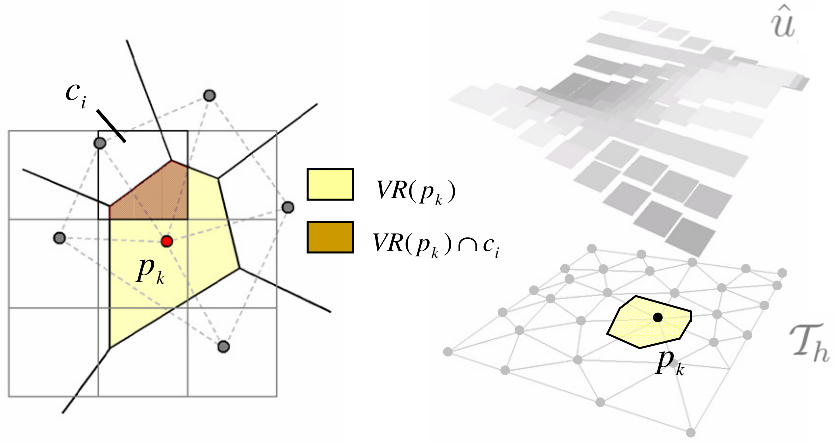

Figure 5. Consideration of all cells c_i in the voronoi-region $VR(p_k)$ for FE-Cell coupling.

In this way a uniform conservative geometric coupling method can be presented, which considers the structural differences of both models and warranties a correct and consistent transfer of all system parameters.

Physical-phenomenological coupling

The majority of research on vegetative flow resistance is based on theory and experiments with rigid cylindrical elements (see [3]). However, seagrass is a very flexible material with a low flexural stiffness and far from this simplification. Pasche [6] presented an approach for numerical simulation of flexible vegetative roughness in seagrass meadows. The flexible seagrass elements have been considered as sources of surface roughness as well as drag resistance.

$$F_R = F_{D,\perp} + F_{S,\parallel} = \frac{1}{2}\rho \cdot u^2 \cdot C_D \cdot LAI \cdot l_p b_p \cdot \sin\theta + \frac{1}{8}\rho \cdot u^2 \cdot \lambda_p \cdot LAI \cdot l_p b_p \cdot \cos\theta \qquad (5)$$

To reproduce the behaviour of flexible seagrass plants and to consider the roughness caused by vegetation adequately in the depth-integrated hydrodynamic model system, an approximation of the method by Pasche can be used to determine equivalent Strickler friction coefficients k_{St} :

$$k_{St} = \rho_p k_{St,p} + (1-\rho_p) k_{St,b}$$

$$k_{St,p} = A\ \cos(k\theta) + B \quad \text{with} \quad A = \frac{k_{St,g}^{=} - k_{St,g}^{\perp}}{2}, B = \frac{k_{St,g}^{=} + k_{St,g}^{\perp}}{2}, k = 3.0 \qquad (6)$$

where ρ_p - the density of the seagrass plants; $k_{St,g}^{\perp}$ - equivalent friction coefficient for upright seagrass elements; $k_{St,g}^{=}$ - equivalent friction coefficient for bended seagrass and $k_{St,b}$ - the bottom friction factor. The influence of the vegetation slope θ and the density of the vegetation layer ρ_p to the equivalent Strickler friction coefficient k_{St} are illustrated in figure 7.

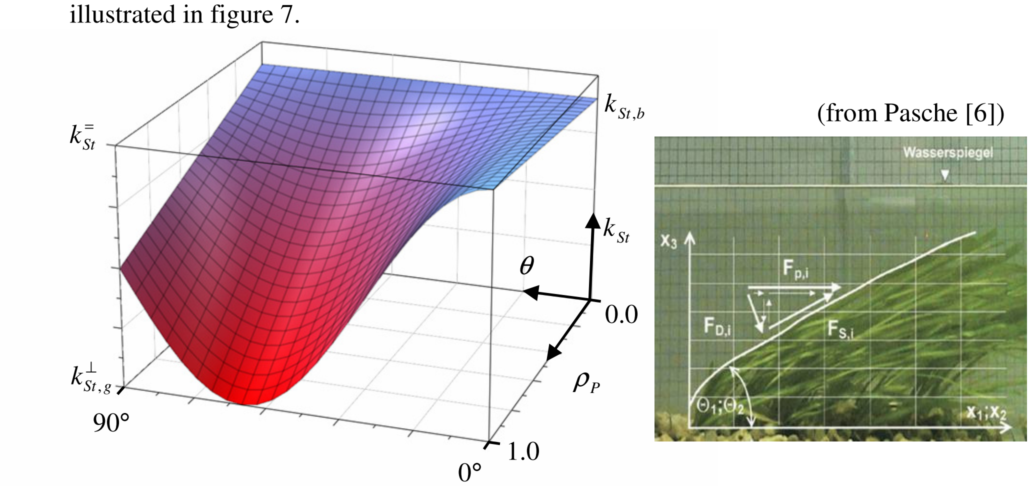

Figure 7. Dynamic equivalent roughness parameters k_{st} reproduce the flexible behaviour of seagrass plants as additional resistance in hydrodynamic-numerical models.

OBJECT-ORIENTED FRAMEWORK

A reusable and extendable software design facilitates the development of eco-hydraulic simulation models in coastal engineering. This can be achieved by developing an object-oriented framework that is a reusable software architecture represented by a set of classes and their interactions.

The class libraries of the coupled eco-hydraulic simulation framework are structured into three packages *Finite Element Model*, *Cellbased Model* and *Geometrical Model*. Each package consists of several modules and classes (see figure 8). The package *FEM* contains classes such as *FEDOF*, *FEModelData*, *FEModel*, *FEDecomposition* and *FEApproximation*. The linking to physical problem definitions takes place by means of the implementation of the interface *FEModel* and the allocation of the model data to the class *FEDOF*. An analogue structure can be found for the *Cellbased Model* package, where classes *CellDOF*, *CellModelData*, *CellModel*, *CellDecomposition*, *CellNeighbourhoodRelation* and *CellApproximation* are realized to facilitate the generation of ecological models. The classes for description of geometry as for example *PointNd*, *Polyhedron* and *DomainDecomposition*, belong to the package *Geometry*.

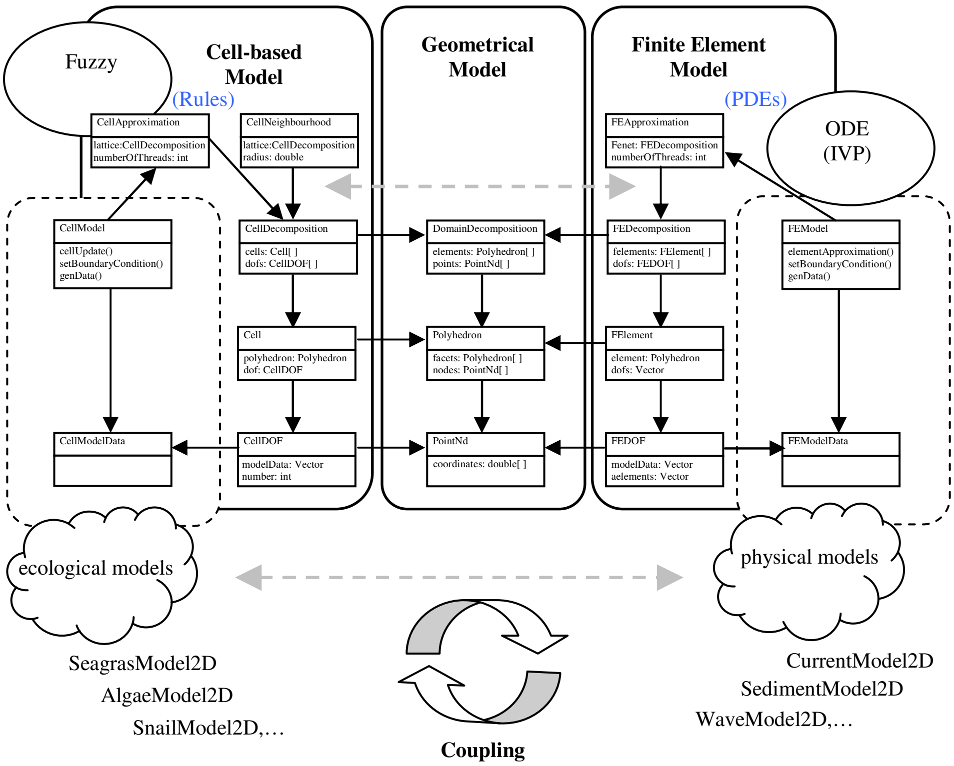

Figure 8. Class libraries of the object-oriented eco-hydraulic framework.

SIMULATION RESULTS

Case studies on seagrass prediction in the North Sea around the Island of Sylt show main effects and possible influences on a changed hydro- and morphodynamic. The simulation started with a stochastic distribution of seagrass, snails and algae. After a simulation period of 2 years, a typical organization of vegetation was achieved (figure 9).

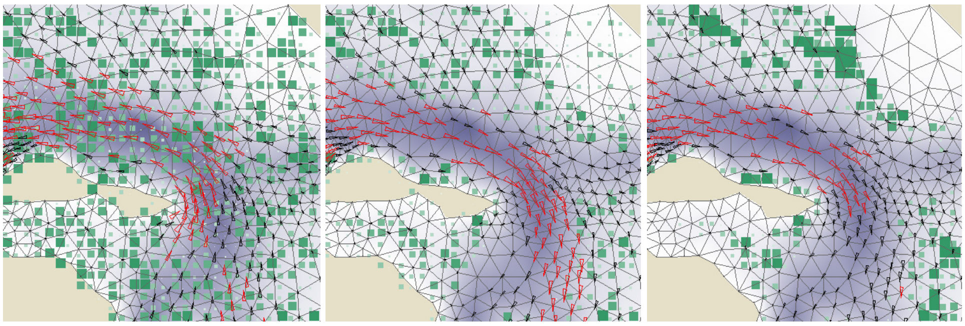

Figure 9. Result of the coupled eco-hydraulic simulation, where only seagrass variables are shown.

Due to the evolution and existence of the natural cover, changes of the hydrodynamic conditions occurred. The left side of figure 10 shows the distribution of seaweeds after a simulation period of 2 years. The consideration of the vegetation layer as source of additional roughness leads to a change of friction coefficients in the hydrodynamic-numerical model. The right side of figure 10 presents velocity differences compared to simulation without consideration of ecological processes. These first simulations show general influences of ecological components to the hydrodynamic model and vice versa.

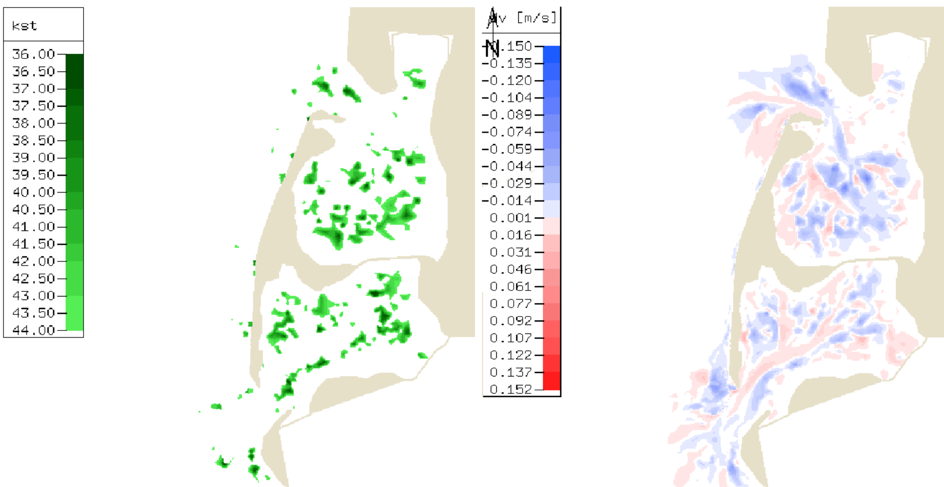

Figure 10. Equivalent friction coefficients for flexible vegetation (left) and velocity differences (right) due to the existence and consideration of seaweeds.

CONCLUSIONS AND PERSPECTIVES

The paper focused on the presentation of a holistic object-oriented framework for eco-hydraulic simulation. It consists of class libraries and packages which allow a holistic concept for the use of numeric methods in coastal engineering. The numerical approximation is performed by a stabilized finite element method for hydro- and morphodynamic processes and by a cell-oriented model for the simulation of ecological processes, which is based on a fuzzy logic rule-based system. The use of fuzzy techniques has been proven to process expert knowledge received from biologists and ecologists and to describe the dynamics of ecosystems adequately. Special transfer and coupling strategies based on conservative interpolation are presented which allow the coupling of these fundamental different models.

In this way hydrodynamics and ecology are integrated into a holistic model in which physical processes are directly considered in an ecological seagrass model. Depending on the presence of vegetation friction coefficients have to be adapted which in turn is a decisive factor for hydro- and morphodynamic processes.

Future work could focus on improvements and extensions of the holistic model. An objective for further investigations should be the extension to hierarchical or polygonal bounded cell decompositions for achieving refinements of interesting regions in the ecological model. Open questions are the adaption of sedimentological parameters for adequate physical coupling between vegetation and morphodynamic as well as long term simulation with regard to different temporal scales of physical and ecological processes.

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