1 © IWA Publishing 2008 Journal of Hydroinformatics | xx.not known | 2008

# A holistic approach and object-oriented framework for eco-hydraulic simulation in coastal engineering

P. Milbradt and T. Schonert


## ABSTRACT

The consideration of biological processes in hydro- and morphodynamic models is an important challenge for numerical simulation in coastal engineering. Eco-hydraulic aspects will play a major role in engineering tools and planning processes for the design of coastal works. Vegetation greatly affects the hydro- and morphodynamic models in coastal zones. Most hydrodynamic numerical models do not consider influences by ecological factors.

This paper focuses 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 rule system. The fundamental differences between these model paradigms require special transfer and coupling methods. Case studies on seagrass prediction in the North Sea around the island of Sylt show the main effects and influences on changed hydro- and morphodynamic processes and demonstrate the applicability of the coupled finite element fuzzy cell-based approach in eco-hydraulic modeling.


**Key words** | fuzzy based modeling, hydro-ecological simulation, object-oriented design, stabilized finite elements

**P. Milbradt** (correspoding author)
**T. Schonert**
Institute of Computer Science in Civil Engineering,
Leibniz University of Hanover,
Callinstrasse 34, Hannover D-30167,
Germany
E-mail: *milbradt@bauinf.uni-hannover.de*

## INTRODUCTION

Coastal zones are characterized by complex hydro- and morphodynamic as well as ecological processes. Tides and waves attack the shore lines and cause changes of position and the shape of coasts. Hydraulic engineering projects and coastal protection measures interfere with the environment, mostly restricting natural processes with far-reaching consequences on coastal systems and their surrounding areas. 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 (Horikawa 1988; Abbott & Minns 1998). They allow the estimation and quantification of effects concerning changed hydrodynamic conditions and sediment transport processes caused by man-made structures already during the planning stage. In the future, eco-hydraulic aspects, and especially the estimation of the effects of man-made structures on the environment, will play a major role in the process of planning in coastal engineering. In order to answer a wide spectrum of questions concerning hydro- and morhopdynamic conditions, water quality, transport processes with chemical reactions as well as biological and ecological processes as it is stipulated in the requirements of the European Water Framework Directive and in the Integrated Coastal Zone Management, suitable eco-hydraulic simulation models are necessary (Mynett 2002; Imberger & Mynett 2006).

For the description of the physical processes, a variety of hydro- and morphodynamic models have been developed. These models are typically based on systems of partial differential equations, which are usually solved

doi: 10.2166/hydro.2008.029

approximately using finite element methods, finite volume methods or finite difference approximations. In contrast, discrete simulation models on the basis of cellular automata have proved to be an appropriate tool in situations where dependences and effect relationship rules are formulated, as in biology and ecology (Hogeweg 1988; Chen 2004). In addition, a variety of processes in nature and technology can be described only with a certain degree of fuzziness. A fundamental approach to the description of blur is the fuzzy theory, where linguistic variables are used to describe the system behavior (Salski & Sperlbaum 1991). The holistic modeling and simulation of such coupled problems require coupling mechanisms, which consider the different model specifications and guarantee a consistent transfer of the system parameters.

Benthic ecosystems like seagrass and mussel beds significantly affect the hydro- and morphodynamic models. Influences of seagrass beds on tidal current velocities and sediment texture were studied in different experiments (see Fonseca *et al.* 1982; Cox *et al.* 2003) where a substantial reduction of the vertical velocity profile, stabilizing effects to sediment and wave damping effects could be observed. On the other side, hydrodynamic conditions are attributed to represent an important effect on biological and ecological processes.

Case studies on seagrass prediction in the North Sea around the Island of Sylt show the main effects and influences on a changed hydro- and morphodynamic model and demonstrate the fundamental coupling algorithms.

## METHODS

The focus of this study lies in the presentation of a holistic ecological, hydro- and morphodynamic model approach. The numerical approximation is performed by a stabilized finite element method for hydro- and morphodynamic processes as well as advection–reaction ecological processes to solve the related partial differential equations, and by a cell-oriented fuzzy model for the benthic ecological processes. The fundamental differences between these different model paradigms require special transfer and coupling strategies.

The essential coupling strategies and algorithms are presented for the example of the interaction of the benthic ecosystem seagrass with the hydro- and morphodynamic processes.

## HYDRO- AND MORPHODYNAMIC MODEL

The hydro- and morphodynamic module is based on the numerical model system MARTIN (Milbradt 2002*a*,*b*). The mathematical formulation of these physical processes leads, for example, to a system of nine time-dependent partial differential equations.

The hyperbolic wave model:

$$\frac{\partial K_i}{\partial t} = -\frac{\partial \sigma_a}{\partial x_i} + C_{\mathrm{g}} \frac{K_j}{k}\left(\frac{\partial K_j}{\partial x_i} - \frac{\partial K_i}{\partial x_j}\right) \tag{1}$$

$$\frac{\partial \sigma}{\partial t} = -(u_i + C_{\mathrm{g}_i})\frac{\partial \sigma}{\partial x_i} - k_{\mathrm{x}_i}\frac{\partial u_i}{\partial t} + f\frac{\partial h}{\partial t} \tag{2}$$

$$\frac{\partial a}{\partial t} = -\frac{1}{2a}\frac{\partial}{\partial x_i}(u_i + C_{\mathrm{E}_i})a^2 - \frac{S_{ij}}{\rho g a_{\mathrm{g}}}\frac{\partial u_i}{\partial x_i} + \frac{u_i(T_i - T_{\mathrm{i}}^{\mathrm{B}})}{\rho g a} + \frac{\varepsilon_{\mathrm{B}}}{\rho g a} \tag{3}$$

with the wavenumber vector $K$, the angular frequency $\sigma$, the wave amplitude frequency $\rho$ and the wave amplitude $a$. Here $C_{\mathrm{g}}$ is the group velocity, $S_{ij}$ describes the radiation stresses, $f$ is the influence of the bottom change and $\varepsilon_{\mathrm{B}}$ the energy loss by wave breaking.

The **shallow water equations** are used to describe the mean water elevation $\eta$ and depth integrated velocities $u$:

$$\frac{\partial \eta}{\partial t} = -\frac{\partial u_j d}{\partial x_j} \tag{4}$$

$$\frac{\partial u_i}{\partial t} = -u_j\frac{\partial u_i}{\partial x_j} - g\frac{\partial \eta}{\partial x_i} - \frac{1}{\rho d}\frac{\partial S_{ij}}{\partial x_i} + \frac{1}{\rho d}(T_i - T_{\mathrm{i}}^{\mathrm{B}} + T_{\mathrm{i}}^{\mathrm{W}}) \tag{5}$$

where $d$ the total water depth, $T$ describes turbulence, $T^{\mathrm{B}}$ the bottom friction and $T^{\mathrm{W}}$ the energy input by wind. To model the **sediment transport** and the changes of the sea bottom the following equations are used:

$$\frac{\partial C}{\partial t} = -u_i \frac{\partial C}{\partial x_i} + \frac{\partial}{\partial x_i}\left(\tau_i \frac{\partial C}{\partial x_i}\right) + S \tag{6}$$

$$q_i = \int_{-h}^{n} u_i C \, \mathrm{d}z + q_\mathrm{b} \tag{7}$$

$$\frac{\partial h}{\partial t} = -\frac{1}{1-n}\frac{\partial q_i}{\partial x_i} \tag{8}$$

where $C$ the concentration of the suspended sediment, $q_\mathrm{b}$ the bed load transport rate, $n$ the porosity as well as $h$ the sea bottom.

The numerical approximation is performed by a stabilized finite element method. In order to find a solution of the time-dependent equations with the finite element method, the domain $\Omega$ is discretized into $n_\mathrm{el}$ finite elements $\Omega_\mathrm{e}$. A semi-discrete approach is used, which is separated into a domain integration 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. By introducing suitable differential operators:

$$L \equiv L_\mathrm{adv} + L_\mathrm{diff} = A_\mathrm{vi}\frac{\partial}{\partial x_i} - \frac{\partial}{\partial x_i}\left(K_\mathrm{vij}\frac{\partial}{\partial x_j}\right) \tag{9}$$

and source and sink terms $S$, each of the subsystems for waves, currents and sediment transport processes can be transformed into a uniform mathematical formulation and approximated with

$$\int_{\Omega}(U_\mathrm{t}+LU+S)\cdot\varphi \, \mathrm{d}\Omega + \sum_{\mathrm{e}=1}^{n_\mathrm{el}} \tau_\mathrm{e} \int_{\Omega^\mathrm{e}} (L\cdot\varphi)(U_\mathrm{t}^\mathrm{G}+LU+S)\,\mathrm{d}\Omega^\mathrm{e} = 0 \tag{10}$$

The first integral contains the Galerkin approximation and the second term contains the least-squares stabilization. For each time step the time derivatives $U_\mathrm{t}^\mathrm{G}$ are determined by the standard Galerkin method in the predictor step. In the corrector step the time derivatives are corrected by the least squares, where the element stabilization parameter $\tau_\mathrm{e}$ weights the portion of the least squares part to the Galerkin part of the method. The time integration step can be performed by universal time integration schemes (e.g. Euler, Heun, Runge-Kutta).

The element parameter $\tau_\mathrm{e}$ plays an important role in the stability and consistency as well as for the accuracy of the approximation (Hughes *et al.* 1989). For the determination of this coefficient the following generalization is used:

$$\tau_\mathrm{e} = \alpha_\mathrm{opt}\frac{1}{2}\frac{h_\mathrm{e}}{\|L_\mathrm{adv}\|} \tag{11}$$

with an optimality parameter $\alpha_\mathrm{opt}$, the characteristic element expansion $h_\mathrm{e}$ and the norm of the advection operator $\|L_\mathrm{adv}\|$. The optimality parameter $\alpha_\mathrm{opt}$ is computed by

$$\alpha_\mathrm{opt} := \coth(Pe) - \frac{1}{Pe} \tag{12}$$

based on the element Peclet number $Pe$, which depends on the operator norms of the advection and diffusion differential operator:

$$Pe := \frac{\|L_\mathrm{adv}\| h_\mathrm{e}}{\|L_\mathrm{diff}\|}. \tag{13}$$

The choice of a suitable operator norm has a significant influence on the quality of the solution. On the basis of the general definition (Kolmogorov & Fomin 1975) of the norm of the continuity operators in (Euclidian) normed spaces we define the following operator norm:

$$\|L_\mathrm{adv}\| := \sqrt{\sum \rho(A_i)^2} \tag{14}$$

where $\rho(A_i)$ is the spectral radius of the operator component

$$\rho(A_i) := \max\left|\lambda_j(A_i)\right| \tag{15}$$

Here $\lambda_\mathrm{max}$ $(A_i)$ is the largest absolute eigenvalue of the matrix $A_i$. This approach for the determination of the stabilization parameter leads to very good results for a large number of simulation models for hydro- and morphodynamic processes.

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

## BENTHIC ECOLOGICAL MODEL

The existence of benthic ecosystems, like seagrasses and mussel beds, has strong effects on water motion and sediment dynamics (see Figure 2). It was shown (Fonseca *et al.* 1982; Nepf 1999; Järvella 2004) that vegetation greatly affects the hydro- and morphodynamic processes in coastal zones. The vertical velocity profile in vegetation areas is divided into mainly two parts. There is an accelerated flow field above the vegetation layer whereas the flow velocities between the seagrass plants are strongly reduced (see Figure 1). In particular, the sensitivity of the water subsurface to erosion is primarily influenced by the existence of marine organisms and natural cover. This shows the necessity of considering ecological components in hydrodynamic numerical models.

Ecological systems are usually described by rules and relationship diagrams which show positive and negative dependences between all relevant quantities. This rule-based formulation is typical for the description of biological processes and differs basically from the mathematical description of physical processes. Therefore, special simulation methods are necessary in ecological modeling. 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 Hogeweg 1988; Marsili-Libelli & Guisti 2005; Schonert & Milbradt 2005).

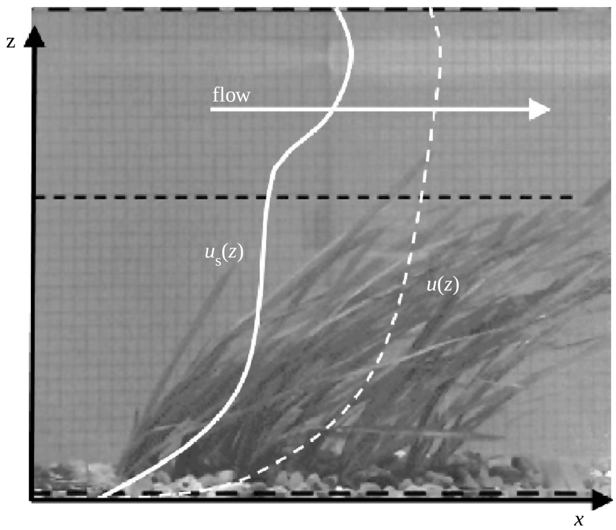



**Figure 1** | The influences of seagrass plants on the vertical velocity profile.

To exemplify the modeling of ecological systems, we consider seagrass beds and their dependences in the mudflats of the North Sea. Seaweeds are habitats for different kinds of species. Special experiments (Schanz 2003) showed that the complex interaction between hydrodynamic conditions, densities of algae and snail populations as well as temperature, turbidity and concentration of nutrients play an important role for the growth of *zostera marina* seagrass plants. The interactions and vegetation dynamics can be described by a graph, where influences can be positive or negative (illustrated in Figure 2).

### Cell-based approach

For the simulation of vegetation dynamics in seagrass plants a cell-based model is used. A cell-based model is characterized by a quasi-discrete structure of all its components *space*, *time* and *states*. It can be described as a tuple $(L, S, N, \delta)$, where $L$ is a regular grid of cells; $S$ is a quasi-finite set of states; $N \subseteq S^n$ is the neighborhood relation and $\delta{:}S^n \rightarrow S$ is the local transition function or a set of rules.

The domain can be decomposed into regular and non-regular polygonal cells (see Figure 3). 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 dependences among the state variables fuzzy techniques and rule-based systems have been proven to process expert knowledge derived by biologists and ecologists to determine the dynamics of ecosystems adequately (Chen 2004; Marsili-Libelli & Guisti 2005).

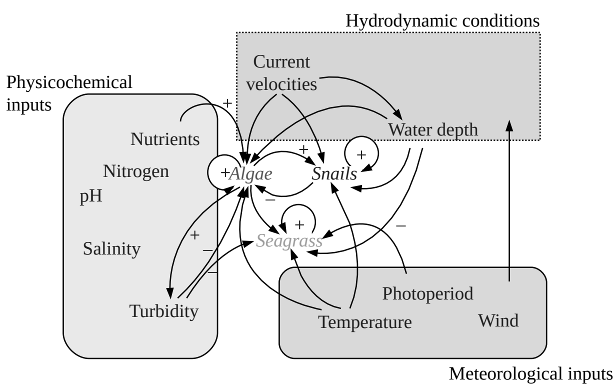
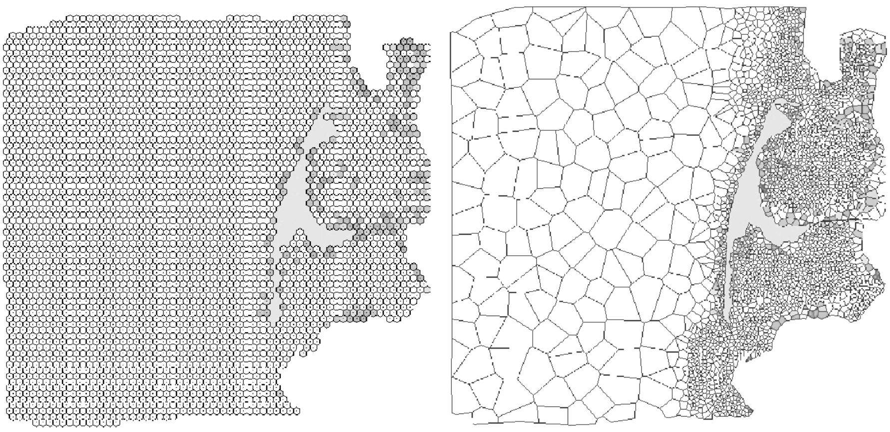



**Figure 2** | Basic interaction in the ecological model of seagrass beds in the North Sea.



Q2
**Figure 3** | Simulation of benthic seagrass by use of different cell decompositions.

In the presented model the temporal development of the ecological system variables is realized with a dynamic fuzzy system for each computational cell (see Figure 4).

## Fuzzy-based approach

The main difficulty in ecological modeling is that the knowledge about the evolution of populations and vegetation contains uncertainties. Human expertise can generally be uncertain and imprecise. This shows the necessity of handling uncertainties in the variables and rules. The modeling of uncertain processes is a very complex problem. The fuzzy set theory (Zadeh 1965) is the best tool to handle those uncertainties. Like numerical variables representing numerical values, in fuzzy set theory, linguistic variables represent values that are words (linguistic terms) with associated degrees of membership. Fuzzy logic provides the description of complex system dynamics with expert knowledge. The theory of fuzzy sets is based on the notion of partial membership: each element belongs partially or gradually to the fuzzy sets that have been defined. A fuzzy set $F$, like *the density of algae concentration is low*, has blurred boundaries and is well characterized by a function that assigns a real number out of the closed interval from 0 to 1 to each element $u$ in the set $U$. This function $\mu_F : U \rightarrow [0,1]$ is called a membership function and describes the degree that an element $u \in U$ belongs to the fuzzy set $F$. In this way fuzzy sets can be specified to define linguistic terms (*low*, *medium*, *high*) for each system variable (for example, population density). Figure 5 gives an example of these linguistic variables for the parameters population density and flow velocity.

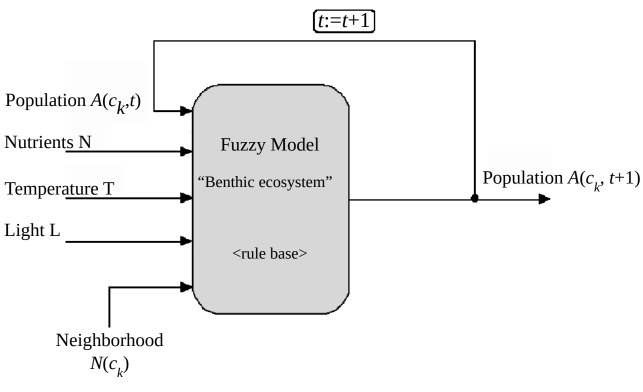



**Figure 4** | Structure of the fuzzy-based model for a cell.

Such fuzzy formulation of parameters can be used to represent ecological expert knowledge in the form of a fuzzy rule base. The information represented in the fuzzy rule base, which is applied for every cell, can be formulated as linguistic if–then rules, such as:

> Rule 1: **if** the quantity of algae in a specific cell is *high* **and** the quantity of snails is *low*, **then** the growth of the snail population is *high*.
> Rule 2: **if** the quantity of algae in a specific cell is *medium* **and** the quantity of snails is *very high*, **then** the growth of the algae population is *negative high*.

The general form of a fuzzy rule consists of a set of premises $A_i$ and a conclusion $B$:

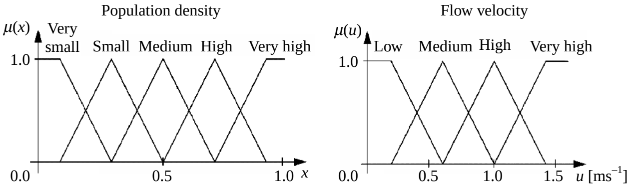



**Figure 5** | Definition of fuzzy sets for ecological and physical parameters.

if $A_1$ and … and $A_n$ then $B$

Rules like these can be derived from the relationship graph illustrated in Figure 2. The complete set of fuzzy if–then rules represents the expert knowledge about relationships and dependences between all relevant state variables. Fuzzy logic provides concepts of approximate reasoning, where imprecise conclusions can be deduced from imprecise premises. Such fuzzy reasoning allows the application of fuzzy information and simulation of dynamic systems. The basic mathematical concept consists of the generalized *modus ponens* with a suitable fuzzy implication operator. There are several fuzzy implication operators (for further details see Ruan & Kerre 1993). In most cases the Mamdami operator is used ($R{:}\mu_{A\to B}(x,y) = \min(\mu_A(x),\mu_B(y))$) to determine a fuzzy relation $R$ between premise and conclusion variables. The deduction of imprecise conclusions from uncertain premises is performed by max-$t$-composition:

$$\mu_{B'}(y) = \max(t(\mu_{A'}(x), \mu_{A\to B}(x,y))) \tag{16}$$

where $t$ is a $t$-norm ($t$:[0,1] × [0,1] → [0,1]). The general inference procedure can be described as follows:

| | | |
|---|---|---|
| (Premise): | X is $A'$ | $A'$ |
| (Implication): | **if** $X$ is $A$, **then** $Y$ is $B$ | $A \to B$ |
| (Conclusion): | $Y$ is $B'$ | $B'$ |
| | $A'(x)$ | $\mu_{A'}(x)$ |
| | $R(x,y)$ | $\mu_R(x,y) = \mu_{A\to B}(x,y)$ |
| | $B'(y) = R(x,y)\circ A'(x)$ | $\mu_{B'}(y) = \max(t(\mu_{A'}(x), \mu_{A\to B}(x,y)))$ |

## MODEL COUPLING

The use of these different model paradigms requires special transfer and coupling methods. Both directions have to be considered. On the one hand, the continuous values from the hydro- and morphodynamic model must be used in the discrete fuzzy model and, on the other hand, the discrete linguistic terms must be transferred in the continuous finite element model. Additionally, conservative transfer algorithms between different geometrical resolutions as well as different time scales must be realized. Finally some aspects of the physical–phenomenological coupling are described.

### Fuzzification and defuzzification

The use of different model concepts dictates that we need an approach to interpret the continuous values of the hydrodynamic model in the rules of the discrete cell-oriented ecological fuzzy model. Firstly a transformation of continuous values in quasi-discrete fuzzy sets is necessary for a consideration of the hydro- and morphodynamic variables in the fuzzy rule-based method. The system variables of the hydrodynamic numerical model will be in the form of "crisp" real numbers with definitive values, e.g. the absolute hydrodynamic velocity ($u = 1.2$ m/s). The process of transforming these crisp input variables into unsharp linguistic variables is called *fuzzification*. The input values are translated into linguistic state concepts (e.g. *low*, *medium*, *high*, *very high*), which are represented by fuzzy sets (Figure 6). Each of these linguistic terms $\tau_i$ has an associated degree of membership $\mu_U^i \in [0,1]$. This leads to an extension of the finite set of states $S = \{s_0, s_1, \ldots s_n\}$ in this way, so that each state $s_i$ gets a specific degree of membership. Thus, a modified set of states $\tilde{S} = \{(s_0, \mu_U^0(u)), (s_1, \mu_U^1(u)), \ldots, (s_n, \mu_U^n(u))\}$ can be obtained, where the pairs $(s_i, \mu_U^i(u))$ characterize the states of each cell $c_k$ and allow a processing of continuous simulation results in the cell-based fuzzy model.

Secondly the quasi-discrete state variables of the cell-based ecological model have to be converted into continuous parameters for processing in the hydro- and morphodynamic model. In particular, the task of generating continuous values from the discrete model without producing erroneous

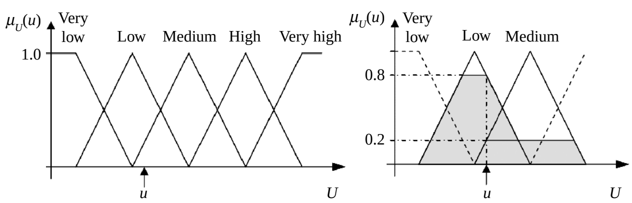



**Figure 6** | Fuzzification of hydrodynamic velocity into quasi-discrete linguistic terms.

discontinuities represents a particular challenge for a suitable coupling strategy.

As a result of the reasoning process of the cell-based model, we obtain a series of fuzzy sets $\mu_V^j(v)$ which describe the degree of membership for each linguistic state variable (e.g. *low*, *medium*, *high*). For a processing of these discrete ecological simulation results in the hydrodynamic numerical model, a transformation of this fuzzy information into sharp values $\bar{v}$ is necessary. This transformation from a fuzzy set to a crisp number is called the *defuzzification process*. It is not a unique operation, as different approaches are possible. The most important ones are the mean-of-maximum method (MOM) and the center-of-area method (COA):

$$\bar{v}_{\mathrm{MOM}} = \frac{\int_{V'} v\,\mathrm{d}v}{\int_{V'} \mathrm{d}v} \quad \text{with} \quad V' = \{v \mid \mu_V(v) = \max_v \mu_V(v)\}$$
$$\text{and} \quad \bar{v}_{\mathrm{COA}} = \frac{\int_V v\cdot\mu_V(v)\,\mathrm{d}v}{\int_V \mu_V(v)\,\mathrm{d}v} \tag{17}$$

where $\mu_V(v)$ is the resulting fuzzy set for the linguistic variable $V$, which can be obtained by aggregation of all corresponding fuzzy sets $\mu_V^j(v)$ for the linguistic terms. Figure 7 illustrates the possibilities to extract crisp values $v$ for each linguistic variable.

Now a continuous representation of the values of the ecological linguistic variable for each cell is realized.

## Spatial and geometric coupling

Through the use of fuzzyfication and defuzzyfication, it is sufficient to examine consistent and conservative interpolations methods. With the use of standard interpolation methods it is not guaranteed that state variables are transferred correctly from the cell-based to the finite element grid (see Figure 8). This could lead to discontinuities and inconsistent results during the coupling procedure. Therefore, extended conservative interpolation methods are used 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. So we've to compute a representative value for each cell $c_k$, that we can fuzzify. This can be obtained by a weighted integral formulation for each cell $c_k$:

$$\hat{u}(c_k) = \frac{1}{\mu^*(c_k)} \int_{c_k} u_{\mathrm{h}}(x)\,\mathrm{d}c_k \tag{18}$$

Again the quasi-discrete ecological values $\hat{u}(c_k)$ have to be transferred into continuous parameters for processing in the finite element model. This is based on the Voronoi decomposition of the domain $\Omega$ (see Figure 9). In this way, every node is influenced by the cells $c_i$ in the Voronoi

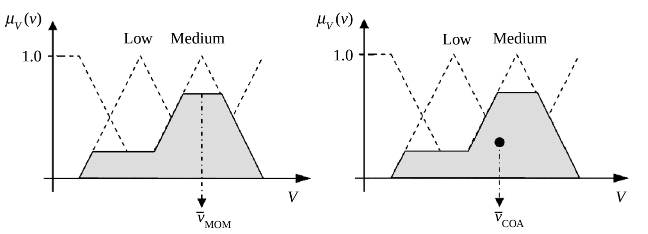
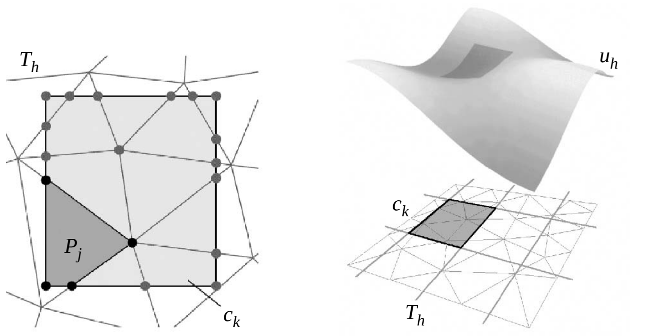



**Figure 7** | Defuzzification of linguistic ecological state variables into sharp numerical values by mean-of-maximum method (left) and center-of-area method (right). Q2




Q2 **Figure 8** | Coupling by integration of the FE approximation over each cell region $c_k$.

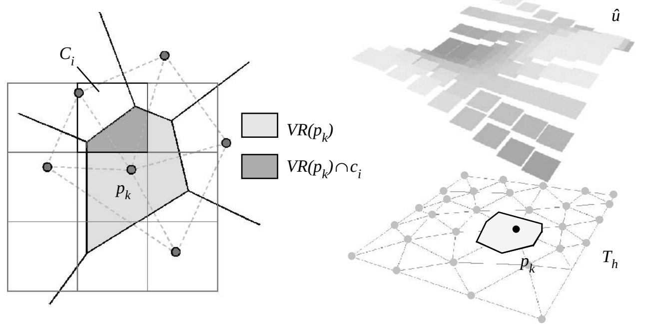



**Figure 9** | Consideration of all cells $c_i$ in the Voronoi region $VR(p_k)$ for geometric coupling.

region $VR(p_k)$:

$$u_k = \frac{1}{\mu^*(VR(p_k))} \int_{VR(p_k)} \hat{u}(x)\,\mathrm{d}VR(p_k) = \frac{\sum \mu^*(\mathrm{VR}(p_k) \cap c_i) \cdot \hat{u}(c_i)}{\sum \mu^*(\mathrm{VR}(p_k))} \quad (19)$$

With this approach, uniform conservative geometric coupling can be realized, which considers the structural differences of both models and guarantees a correct and consistent transfer of all system parameters.

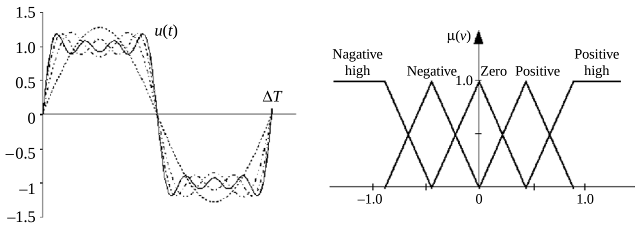
Through the analysis of hydro- and morphodynamic as well as ecological processes it can be recognized that these processes take place not only in spatial, but much more often in very different time scales (Mynett 2004). The up-scaling and down-scaling between different time scales in the process of model coupling is a significant challenge. For example, physical processes like currents or waves change comparatively fast in the water body; therefore a temporal resolution of seconds' proximity is used in the hydrodynamic model. Ecological processes, however, are indicated by considerably bigger time periods. For this reason a time step of a day up to a month are used in ecological models. How big the time step exactly is depends on the ecosystem.

As a part of the coupling process of the finite element model with the cell-based fuzzy model suitable membership degrees of the specification of the corresponding linguistic variables must be generated. The generation of such membership degrees, which will be processed in the rules of the ecological model, is a hard task to tackle. An integration of the continuous numerical system values over the characteristic period $\delta T$ and subsequent fuzzification generally leads to a consistent, but often a false, mapping. This is connected with the fact that by such an averaging the state variables are smoothed strongly or it can even come to an abolition of the model quantities. The example of a periodic scalar value $v(t)$ may well illustrate this phenomenon (see Figure 10).

Through analysis of the integrals and averaging over the time interval $\Delta T$ we obtain

$$\bar{v} = \frac{1}{\Delta T} \int_{t}^{t+\Delta T} v(\tau)\,\mathrm{d}\tau = 0 \quad (20)$$

A subsequent fuzzyfication of this integrated value returns a full membership only for the linguistic term "around zero". However, as can be seen, throughout the temporal course of the state variable $v(t)$, the value "around zero" is rarely taken comparatively to the whole integration interval (see Figure 11). Obviously the integrated values nullify each other, and it results in a false mapping of the function in the observed time interval. This error goes in the rule application of the cell-based fuzzy model. To resolve this problem an integration of the linguistic variables instead of the sharp continuous values is carried out. For this the corresponding degrees of membership of the linguistic variables will be integrated, and thereby the integration of linguistic variables is realized:




Q2

**Figure 10** | Continuous functions and linguistic terms.

$$\overline{\mu_{\mathcal{T}_i}} = \frac{1}{\Delta T} \int_{t}^{t+\Delta T} \overline{\mu_{\mathcal{T}_i}}(\nu(\tau))\,\mathrm{d}\tau \quad (21)$$

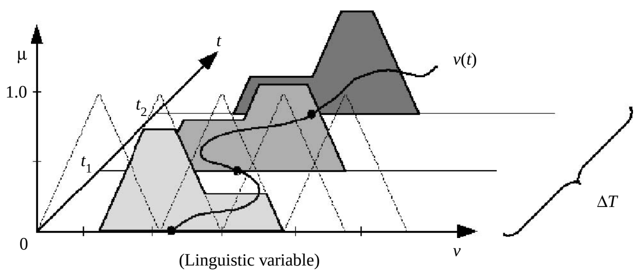
This equation represents an integration of the membership vector who's occupancy in the interval $[t, t + \Delta T]$ constantly changing, according to the fuzzification of $v$.

In this way, as opposed to the real-valued integration, a consistent temporal transmission can be realized. Figure 12 shows the results of both time integration schemes.

The mapping of the time course of linguistic variables in continuous system values may occur initially on the basis of classical defuzzification procedures:

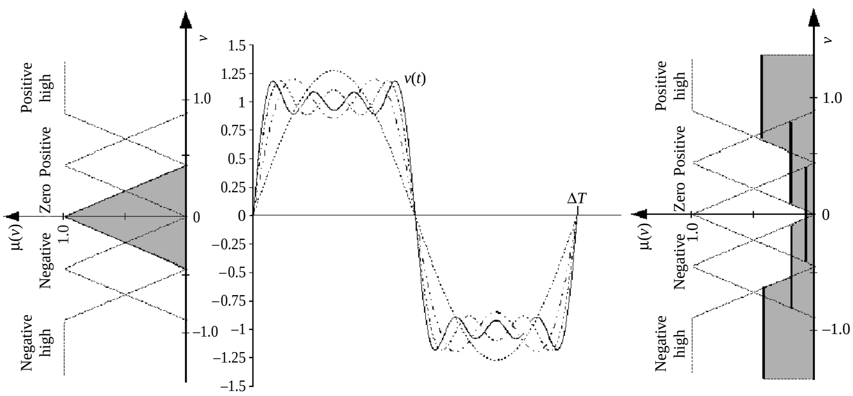
$$\bar{z}(\vec{x}, t) = \frac{1}{\Delta T} \int_{t}^{t+\Delta T} \mathrm{defuz}(z(\vec{x}, \tau))\,\mathrm{d}\tau \quad (22)$$

With the time and spatial transfer methods, the algorithmic basis for the consideration of the interaction




Q2

**Figure 11** | Integration of the linguistic variable.




Q2

**Figure 12** | Results of different fuzzy integration.

between ecological and physical model components is established.

## Physical–phenomenological coupling

Vegetation exerts strong effects on water motion (Fonseca *et al.* 1982; Verduin & Backhaus 2000) and sediment dynamics (Ward *et al.* 1984; Fonseca & Fisher 1986).

It has been generally agreed (Yen 2002) that vegetation has a great influence on hydro- and morphodynamic processes. The dense carpet of leaves is able to raise the flow resistance and change sediment transport behavior and deposition. There are a lot of investigations in the field of vegetation roughness in open channels (see Järvelä 2004). Based on first experiments and studies by Li & Shen (1973), the most popular theories are those of Lindner (1982), Pasche & Rouvé (1985), Mertens (1989) and Nuding (1991). The majority of research on vegetative flow resistance is based on theory and experiments with rigid cylindrical elements. However, seagrass is a very flexible material with a low flexural stiffness and is far from this simplification. Oplatka (1998) dealt with the flow resistance of flexible willows and could show that the friction factor varies greatly with the mean flow velocity due to bending of the vegetation (Figure 13).

Pasche & Deussfeld (2003) presented an approach for the 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. The total flow resistance $F_R$ of the seaweeds can be obtained as the sum of two force components $F_{D,\top}$ and $F_{S,\|}$, where $F_{D,\top}$ denotes the vertical drag force and $F_{S,\|}$ the friction force which acts on the surfaces of the leaves. Both forces result from the movement of the water around the seagrass and both depend on the actual hydrodynamic conditions:

$$\begin{aligned} F_R &= F_{D,\perp} + F_{S,\|} \\ &= \frac{1}{2}\rho \cdot u^2 \cdot C_D \cdot \mathrm{LAI} \cdot l_p b_p \cdot \sin\theta + \frac{1}{8}\rho \cdot u^2 \cdot \lambda_p \cdot \mathrm{LAI} \cdot l_p b_p \cdot \cos\theta \end{aligned} \quad (23)$$

where $\theta$ is the vegetation slope; $u$ is the depth-averaged flow velocity, LAI is the leaf area index; $\rho$ is the vegetation density; $C_D$ is the drag coefficient; $\lambda_p$ is the roughness parameter and $A_p = l_p b_p$ is the the area of the seagrass leaves. According to Kouwen & Unny (1973), there is a

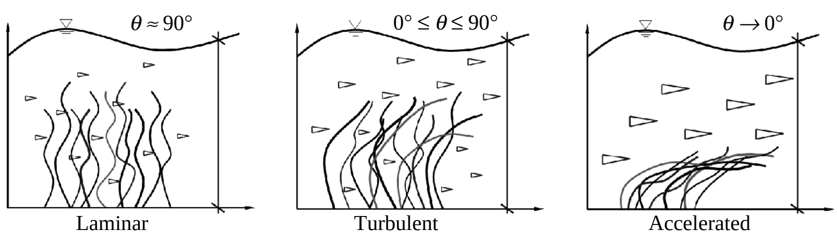



**Figure 13** | Dependence of the vegetation slope on different flow velocities.

correlation between vegetation slope $\theta$, depth-averaged flow velocity $u$, vegetation density $\rho$, leaf area index LAI and the relative vegetation height $l_p/h$:

$$\theta = f\left(u, \rho_p, \mathrm{LAI}, \frac{l_p}{h}\right). \tag{24}$$

At present, there are not enough studies and measurements to quantify the dependences between geometric parameters of the seagrass plants and the hydraulic drag and friction coefficients (see Pasche & Deussfeld 2003).

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 $k_{St}$:

$$\begin{aligned} k_{St} &= \rho_p \lambda_1 + (1 - \rho_p)\lambda_2 \\ \lambda_1 &= A\cos(k\theta) + B \quad \text{with} \quad A = \frac{k^{=}_{St,g} - k^{\perp}_{St,g}}{2}, \\ B &= \frac{k^{=}_{St,g} + k^{\perp}_{St,g}}{2} \qquad k = 3.0 \\ \lambda_2 &= k_{St,b} \end{aligned} \tag{25}$$

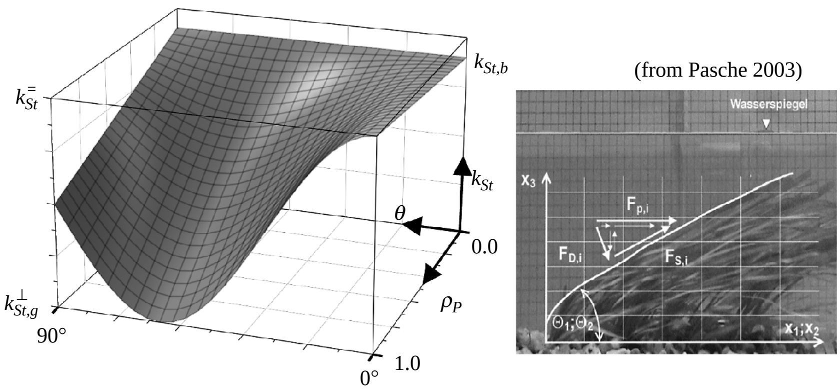
where $\rho_p$ is the density of the seagrass plants; $k^{\perp}_{St,g}$ is the equivalent friction coefficient for upright seagrass elements; $k^{=}_{St,g}$ is the equivalent friction coefficient for bended seagrass and $k_{St,b}$ is the bottom friction factor. The influence of the vegetation slope $\theta$ and the density of the vegetation layer $\rho_p$ on the equivalent Strickler friction coefficient $k_{St}$ are illustrated in Figure 14.

The existence of a vegetation layer has also significant influences on the sediment dynamics and morphological developments in coastal zones. As mentioned before, there is a strong reduction of the flow velocities, especially in the plant layer which decreases critical bottom shear stresses $\tau_B$. Moreover, the vegetation layer acts as sediment catchment since the dense carpet of leaves cause fine-grained suspended particles to settle out and they are then stabilized by the root and rhizome systems of the seagrass plants (Ginsburg & Lowenstam 1958; Heiss *et al.* 2000). Thus, it is an important challenge to integrate these processes in the morphodynamic model. Morphodynamic changes result from transport of bed-load at the bottom and suspended load in the water body. There are several possible approaches which can be found in the literature (Malcherek 2003). In the model presented here, the formula of van Rijn (1984) is used for bed-load transport, and for the determination of the suspended sediment concentration the approach of Rossinsky & Debolsky (1980) is implemented. The consideration of ecological components like seagrass plants leads to the adaptation of sedimentological parameters $d_{50}$ (median grain size) and $\tau_c$ (critical sheer stress).

## OBJECT-ORIENTED FRAMEWORK

A reusable and extendable software design allows for 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 five packages *Finite Element Model*, *Cell-based Model*, *Geometrical Model*,




Q2

**Figure 14** | Dynamic equivalent roughness parameters $k_{st}$ reproduce the flexible behaviour of seagrass plants as additional resistance in hydrodynamic–numerical models.

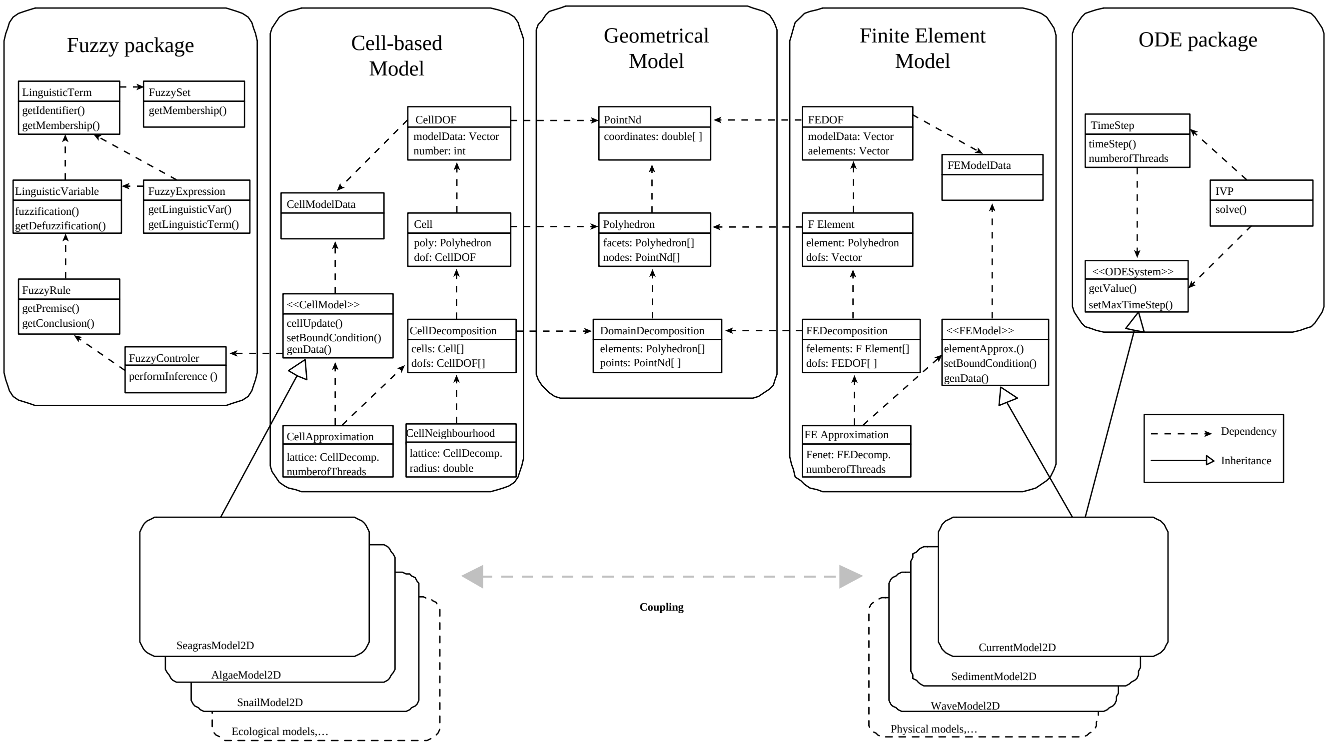



**Figure 15** | UML class diagram of the object-oriented eco-hydraulic framework.

*Fuzzy* and *ODE* packages. Each package consists of several modules and classes (see Figure 15). The package *FEM* contains classes and interfaces such as *FEDOF*, *FElement*, *FEModelData*, *FEModel*, *FEDecomposition* and *FEApproximation*. The implementation of the *ODE* package allows the application of ordinary differential equations. It contains an interface *ODESystem* and classes *TimeStep* and *IVP* (initial value problem). The linking to physical problem definitions takes place by means of the implementation of the interfaces *FEModel* and *ODESystem* and the allocation of the model data to the class *FEDOF*. The design of the FEM and ODE packages provide methods and algorithmic implementations for the approximation and solution of time-dependent partial differential equations. This contains domain integration and approximations as well as different time integration schemes (Euler, Runge-Kutta, etc.).

An analogue structure can be found for the *Cell-based Model* package, where classes *CellDOF*, *CellModelData*, *CellModel*, *CellDecomposition*, *CellNeighbourhoodRelation* and *CellApproximation* are realized to facilitate the generation of ecological models. The major difference between cell-based and finite element models is in the fuzzy rule-based description instead of mathematical equations. Therefore, the main purpose of the *Fuzzy* package is to provide the classes *FuzzySet*, *LinguisticTerm*, *LinguisticVariable*, *FuzzyExpression*, *FuzzyRule* and *FuzzyControler*. These classes include methods and constructs to handle uncertain knowledge, rule-based formulation and fuzzy reasoning. The design of the *Cell-based Model* and *Fuzzy* package allows the creation of ecological models by implementation of the interface *CellModel* and the use of the fuzzy modeling approach.

The classes for the description of geometry, such as, for example, *PointNd*, *Polyhedron* and *DomainDecomposition*, belong to the package *Geometry* and are commonly used by all kinds of models.

In particular, the *FEModel*, *Fuzzy* and *ODE* packages use a common mathematical package, which contains abstract classes and methods for integration and differentiation of scalar- and vector-valued functions.

The object-oriented approach allows the creation of reusable, extensible and reliable model components for eco-hydraulic simulation in coastal engineering.

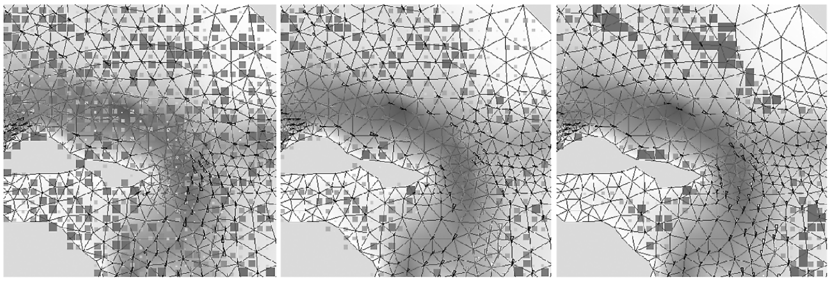


Figure 16 | Result of the coupled eco-hydraulic simulation, where only seagrass variables are shown.

## SIMULATION RESULTS

Case studies on seagrass prediction in the North Sea around the Island of Sylt show the main effects and possible influences on a changed hydro- and morphodynamic process. 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 16).

Due to the evolution and existence of the natural cover, changes of the hydrodynamic conditions occurred. The left side of Figure 17 shows the distribution of seaweeds after a simulation period of 2 years. The consideration of the vegetation layer as a source of additional roughness can be modeled by adaptation of friction coefficients in the hydrodynamic–numerical model (Equation (25)). The right-hand side of Figure 17 presents differences of the maximum velocities compared to the simulation without consideration of ecological model components. The existence of vegetation leads to a change of the effective hydrodynamic cross sections in the tidal basins. Biological processes and seagrass meadows can be found, especially on the tidal flats. This causes the reduction of the maximum hydrodynamic velocities in the shallow areas, while the velocities in the tidal channels are increased. These first simulations show general influences of ecological components on the hydrodynamic model and vice versa.

Changed hydrodynamic conditions influence sediment transport processes and morphodynamic developments in the intertidal basins. Due to the reduced velocities in the tidal flats, more sedimentation is expected. However, the results of the morphodynamic simulation (Figure 18) do not show sedimentation phenomena in these regions. Changes of morphological developments concentrate on areas of the deeper tidal channels at the northern and southern end of Sylt. The increased maximum hydrodynamic velocities in the tidal channels cause morphological deepening. The higher suspended load concentration is deposited at the sand banks at the northern and southern end of Sylt.

In addition to the expected local effects of biological processes and seagrass vegetation the results of the numerical ecological, hydro- and morphodynamic simulations show influences on remote areas, which have to be studied and analyzed.

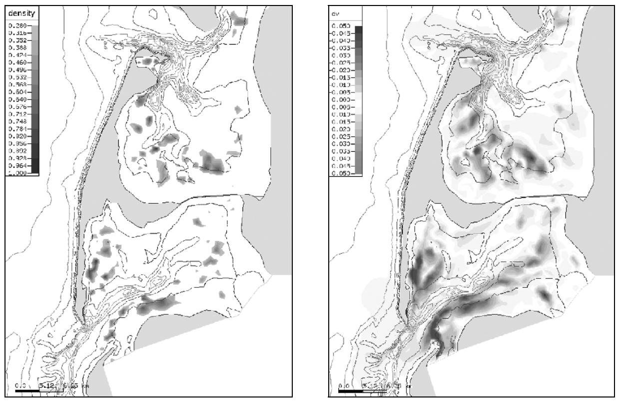


Figure 17 | Distribution of seagrass vegetation (left) and velocity differences (right) due to the existence and consideration of seaweeds.

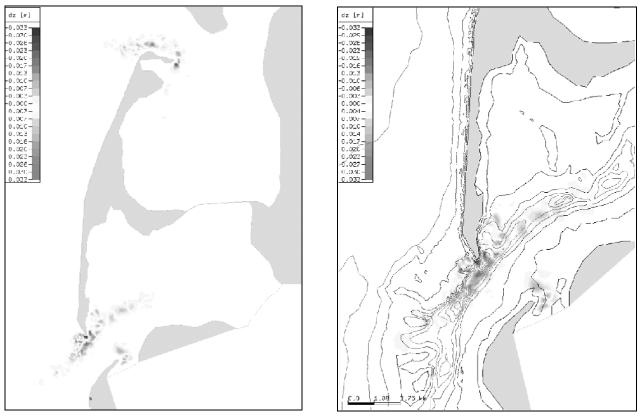


Figure 18 | Morphological influences of seagrass vegetation after the simulation period.

## CONCLUSIONS AND PERSPECTIVES

This 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 numerical 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 derived by biologists and ecologists and to describe the dynamics of ecosystems adequately. Special transfer and coupling strategies based on conservative interpolation are presented which allow for the coupling of these fundamentally 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. Dependent 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 to achieve refinements of interesting regions in the ecological model. Open questions are the adaptation of sedimentological parameters for adequate physical coupling between vegetation and morphodynamic processes as well as long term simulation with regard to different temporal scales of the physical and ecological processes.

## ACKNOWLEDGEMENTS

The authors would like to thank the German Research Foundation (Deutsche Forschungsgemeinschaft, DFG) for financial support of this research project.

## REFERENCES

Abbott, M. B. & Minns, A. W. 1998 *Computational Hydraulics*, 2nd edition. Ashgate. Aldershot, UK.

Chen, Q. 2004 *Cellular Automata and Artificial Intelligence in Ecohydraulics Modelling*. Taylor & Francis, London.

Chen, Q., Morales-Chaves, Y., Li, H. & Mynett, A. E. 2006 Hydroinformatics techniques in eco-environmental modelling and management. *J. Hydroinf.* **8** (4), 297–316. Q1

Chen, Q., Mynett, A. E. & Minns, A. W. 2002 Coupling of scales in finite stat cellular automata with applications to ecohydraulic modeling. In *Proc. Fifth International Conference on Hydro-informatics, Cardiff*, pp. 500–506. IWA Publishing, London. Q1

Cox, R., Wallace, S. & Thomson, R. 2003 Wave damping by seagrass meadows. In *Proc. 6th International COPEDEC Conference, Colombo, Sri Lanka.* Lanka Hydraulic Institute, Colombo, Sri Lanka, Paper No 115.

Fonseca, M. S. & Fisher, J. S. 1986 A comparison of canopy friction and sediment movement between four species of seagrass with reference to their ecology and restoration. *Mar. Ecol. Prog. Ser.* **29**, 15–22.

Fonseca, M. S., Fisher, J. S., Zieman, J. C. & Thayer, G. W. 1982 Influence of the seagrass, Zostera marina L., on current flow. *Est. Coast. Shelf Sci.* **15**, 351–364.

Ginsburg, R. N. & Lowenstam, H. A. 1958 The influence of marine bottom communities on the depositional environments of sediments. *J. Geol.* **66**, 159–169.

Heiss, W. M., Smith, A. M. & Probert, P. K. 2000 Influence of the small intertidal seagrss Zostera novazelandica on linear water flow and sediment texture. *New Zeal. J. Mar. Freshw. Res.* **34**, 695–717.

Hogeweg, P. 1988 Cellular automata as a paradigm for ecological modelling. *Appl. Math. Comput.* **27**, 81–100.

Horikawa, K. 1988 *Nearshore Dynamics and Coastal Processes*. University of Tokyo Press. Tokyo.

Hughes, T. J. R., Franca, L. P. & Hulbert, G. M. 1989 A new finite element formulation for fluid dynamics: VIII. The Galerkin/least-squares method for advective-diffusive equations. *Comput. Meth. Appl. Mech. Eng.* **73**, 173–189.

Imberger, J. & Mynett, A. E. 2006 Special issue on eco–environmental hydroinformatics. *J. Hydroinf.* **8** (4), 235–333.

Järvelä, J. 2004 *Flow Resistance in Environmental Channels: Focus on Vegetation.* Dissertation, Helsinki University of Technology, Helsinki.

Kolmogorov, A. N. & Fomin, S. V. 1975 *Reelle Funktionen und Funktionalanalysis*. Deutscher Verlag der Wissenschaften, Berlin.

Kouwen, N. & Unny, T. E. 1973 Flexible roughness in open channels. *J. Hydraul. Div. ASCE* **99** (5), 713–728.

Li, R. M. & Shen, H. W. 1973 Effect of tall vegetations on flow and sediment. *J. Hydraul. Div. ASCE* **99** (5), 793–814.

Lindner, K. 1982 *Der Strömungswiderstand von Pflanzenbeständen.* Mitteilungen, Leichtweiss-Institut für Wasserbau, TU Braunschweig, Heft **75**

Malcherek, A. 2003 *Morphodynamik der Küstengewässer. Fixed link BAW-Hamburg.* Available at: http://www.baw.de/vip/abteilungen/wbk/Methoden/hnm/nummeth/morphodynamik.pdf

Marsili-Libelli, S. & Giusti, E. 2005 Modelling the submerged vegetation in the Orbetello lagoon with fuzzy cellular automata. In *Proc. 16th IFAC World Congress, Prague, Czech Republic.* Elsevier, Amsterdam.

Mertens, W. 1989 Zur Frage hydraulischer Berechnungen naturnaher Fließgewässer. *Wasserwirtschaft* **79** (4), 170–179.

Milbradt, P. 2002*a* A stabilized finite element method for systems of instationary advection dominated equations in multi-dimensional domains. In *Proc. 5th World Congress on Computational Mechanics (WCCM V), Vienna, Austria* (ed. H. A. Mang, F. G. Rammerstorfer & J. Eberhardsteiner). Vienna University of Technology, Austria, July 7–12, 2002.

Milbradt, P. 2002*b* Holistic modeling of morphodynamic processes with stabilized finite elements. In *Proc. 5th International Conference on Hydroinformatics, Cardiff, UK*, **vol. 1**, pp. 232–238. IWA Publishing, London.

Mynett, A. E. 2002 Environmental Hydroinformatics: the way ahead. Keynote address. In *Proc. 5th International Conference on Hydroinformatic, Cardiff, UK*, pp. 31–36. IWA Publishing, London.

Mynett, A. E. 2004 Hydroinformatic tools for ecohydraulics modelling. In *Proc. 6th International Conference on Hydroinformatics*, pp. 3–12. World Scientific Publishing Company, Singapore.

Nepf, H. 1999 Drag, turbulence and diffusivity in flow through emergent vegetation. *Water Resour. Res.* **35** (2), 479–489.

Nuding, A. 1991 Fliesswiderstandverhalten in Gerinnen mit Ufergebüsch. *Wasserbau-Mitteilungen,* no. 35, TH-Darmstadt, Germany.

Oplatka, M. 1998 Stabilität von Weidenverbauungen an Flussufern. *Mitteilungen der Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie,* no. 156, ETH Zürich.

Pasche, E. & Deussfeld, N. 2003 Hydro- und Morphodynamik in Seegraswiesen. *HANSA Int. Maritime J.* **5**, 67–73.

Pasche, E. & Rouvé, G. 1985 Overbank flow with vegetatively roughened flood plains. *J. Hydraul. Eng.* **111** (9), 1262–1278.

van Rijn, L. C. 1984 Part I: Bed load transport. *J. Hydraul. Eng.* **110** (10), 1431–1456.

Rossinsky, K. I. & Debolsky, V. K. 1980 *Riverine Load*. Nauka, Moscow.

Ruan, D. & Kerre, E. E. 1993 Fuzzy implication operators and generalized fuzzy method of cases. *Fuzzy Sets Syst.* **54**, 23–37.

Salski, A. & Sperlbaum, C. 1991 Fuzzy logic approach to modelling in ecosystem research. In *Uncertainty in Knowledge Bases. LNCS 521* (ed. B. Bouchon-Meunier, R. R. Yager & R. R. Zadeh), pp. 520–527. Springer-Verlag, Berlin.

Schanz, A. 2003 *Impact of Hydrodynamics on Intertidal Seagrass Beds in the Northern Wadden Sea.* Dissertation, University of Bremen.

Schonert, T. 2007 *Zur Kopplung finiter Element Approximationen und zellbasierter Fuzzy-Modelle*. Sharker Verlag. Aachen. Q1

Schonert, T. & Milbradt, P. 2005 Hydro- and morphodynamic simulation considering ecological model components on asynchronous parallel cellular automata. In *International Conference on Computing in Civil Engineering* (eds L. Soibelman & F. Peña-Mora). Cancun, Mexico.

Verduin, J. J. & Backhaus, J. O. 2000 Dynamics of plant-flow interactions for the seagrass Amphibolis antarctica: field observations and model simulations. *Est. Coast. Shelf Sci.* **50**, 185–204.

Ward, L. G., Kemp, W. M. & Boynton, W. R. 1984 The influence of waves and seagrass communities on suspended particulates in an estuarine embayment. *Mar. Geol.* **59**, 85–103.

Yen, B. C. 2002 Open channel flow resistance. *J. Hydraul. Eng.* **128** (1), 20–39.

Zadeh, L. A. 1965 Fuzzy sets. *Inf. Control* **8**, 338–353.

# Author Queries

*JOB NUMBER:* D_06_00029

*JOURNAL:* JHYDRO

**Q1** References Chen *et al.* (2002), Chen *et al.* (2006) and Schonert (2007) are provided in the list but not cited in the text. Please supply citation details or delete the reference from the reference list.

**Q2** Figures 3, 8, 9, 10, 11, 12, 14, 16, 17 and 18 are of poor quality. Please provide better quality figures.