

## HOW TO ACCOUNT FOR FLEXIBLE AQUATIC VEGETATION IN LARGE-SCALE MORPHODYNAMIC MODELS

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Worldwide, aquatic vegetation is important for the physical and ecological condition of coastal areas. Unfortunately, this vegetation (e.g. seagrasses) is also under pressure due to human activities. Protection and restoration are cumbersome, particularly because the complex relations between vegetation and its environment are not yet well understood. One of the key characteristics of aquatic vegetation is its flexibility, causing the plants position and drag to vary in time. The model presented in this paper, a combination of the detailed process-based hydrodynamic/plant motion model Dynveg and the large-scale morphological model Delft3D that deals with rigid vegetation, can be useful in studying some of these relations. By choosing the height and the drag coefficient of the rigid objects equal to that of the flexible plants under similar conditions, the flow pattern is analogous. The applicability of this modelling approach is demonstrated by comparing model results with flume experiments on the seagrass species *Zostera noltii*.

### INTRODUCTION

Aquatic vegetation like seagrass is an important component of a coastal system, not only from an engineering point of view but also from an ecological standpoint. Vegetation can form a physical protection of the coast by attenuating waves and currents and by stabilizing sediments (Fonseca and Cahalan 1992; Turker et al. 2006).

The presence of vegetation is also important for ecology: it improves water quality by using nutrients to produce oxygen and increases biodiversity by creating habitats for all kinds of other organisms. Moreover, the reduction of nutrient levels leads to fewer algae, which, combined with the stabilization of sediments contributes to clearer water that benefits photosynthesis and thus vegetation growth. All these benefits make seagrasses and other aquatic vegetation also economically very valuable (Costanza et al. 1997).

Unfortunately, seagrasses worldwide are under pressure of climate change and the accompanying sea level rise, eutrophication, pollution, coastal engineering works and fishery. Attempts are undertaken to protect or restore vegetation (e.g. van Katwijk (2000) for the Dutch Wadden Sea, and Zimmerman et al. (1995) for San Fransisco Bay), which requires understanding of complex interactions between hydrodynamics, water quality, plant development and morphodynamics.

Often these processes are studied in laboratory flumes (Gambi et al. 1990; Morris et al. 2008) or in the field (Orth et al. 1994) because models can be

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difficult to make due to the amount of parameters involved (e.g. Zharova et al. 2001). However, flumes have the disadvantage of their limited size, and in the field some environmental factors that trouble the image cannot be excluded. Therefore, models that combine these interactions between plants and their environment can be a very useful tool to improve the success of restoration attempts, dispersal of seeds and larvae, or to study the impact of engineering activities on plant populations.

In making a useful model, two processes are of major importance: the bending of plants, depending on flow and plant characteristics, and the stabilization of sediments due to reduced flow velocities. Instead of using empirical coefficients to represent these processes, modelling the processes themselves creates a much more widely applicable model. Some authors have attempted to incorporate flexible vegetation in a hydrodynamic model (Abdelrhman 2007), or rigid vegetation in a sediment transport model (López and García 1998), but the combination of morphodynamics and flexible vegetation is still lacking.

#### **MODELLING APPROACH**

The objective of this study is to develop a model that simulates flow and sediment transport in and around meadows of flexible aquatic vegetation. A reliable 1DV-model for flow through flexible vegetation already exists (Dijkstra et al. 2006), but this does not deal with spatial variations. Likewise, the well-known Delft3D model simulates morphological developments on larger scales well (Lesser et al. 2004), but it does not account for flexible vegetation. It does deal with rigid vegetation quite successfully though, according to Temmerman et al. (2005). Therefore, it seems rational to combine these two models instead of creating a new one from scratch.

#### **Modelling flexible vegetation at a small scale**

The 1DV-modelling of the interaction between hydrodynamics and flexible vegetation is not discussed in detail here, as it has been described in Dijkstra et al. (2006) already. In this model –called Dynveg-, vegetation is simulated as a single plant, which is made of a number of elements that exert forces on the water and on each other. Using simple engineering formulae for cantilever beams is not possible because of the large deformations. The drag- and friction forces exerted on the water depend on the velocity difference between the water and an element, and the orientation of the element, which determines the drag coefficient. The forces that the elements exert on each other lead to bending moments, which, in combination with buoyancy, inertia and the rigidity of the plant, determine the position of the plant.

Feedback to the hydrodynamic part of the model occurs through the additional production and dissipation of turbulence, which is calculated using a  $k-\epsilon$  turbulence model. Extra production of turbulence is related to the force exerted on the plants, whereas more dissipation comes from introducing an

effective time scale that depends on the spacing between the plants, i.e. the maximum eddy size. Both plant movement and hydrodynamics are solved fully implicitly, but the feedback between them is modelled explicitly.

The Dynveg model was tested against flume measurements on various plastic strips differing in flexibility and length, for flow velocities ranging from 2.0 to 40  $\text{cm s}^{-1}$ . Both the positions and the drag forces acting on the strips were predicted well. Hydrodynamic properties like the vertical distribution of the flow velocity, the amount of turbulence (TKE) and the eddy viscosity compared well with those from experiments by Nepf and Vivoni (2000), who used artificial vegetation similar to the seagrass *Zostera marina*.

#### Simplification: model flexible vegetation as rigid rods

Since the plant motion-algorithm of the Dynveg model described above is too computationally expensive to use for medium- or long-term (i.e. more one year), a simpler approach is necessary. Fortunately, as Figure 1 shows, the flow through rigid rods can be very similar to the flow through flexible vegetation, provided the correct deflected height ( $k_{veg}$ ) and equivalent drag coefficient ( $C_{Deq}$ ) are chosen. This is valid for a range of conditions that can occur in nature (depth  $h = 0.1\text{-}2$  m, depth averaged flow velocity  $U = 0.1\text{-}1$   $\text{ms}^{-1}$ , and number of plants  $np = 10\text{-}1000$   $\text{m}^2$ ).

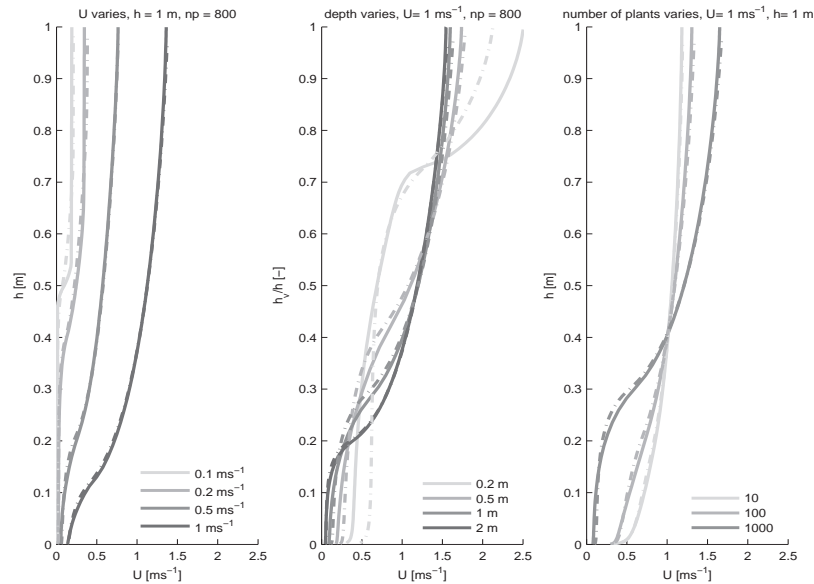


Figure 1 Comparison of flow velocity profiles for simulations with Dynveg (solid lines) and with rigid rods that have similar parameters (dash-dot lines) for various conditions.

Of course, this similarity alone does not solve the problem until there is an efficient way of determining the right values for  $k_{veg}$  and  $C_{Deq}$  for the actual flow conditions. When keeping in mind that the area of application of the final model is in estuaries, it could be assumed that water depth and depth averaged flow velocity vary relatively slowly, i.e. more likely at a scale of (tens of) minutes than seconds. Therefore, it is not necessary to calculate  $k_{veg}$  and  $C_{Deq}$  for every time step of the hydrodynamic model, which is in the order of seconds due to the necessary spatial resolution and the Courant condition.

#### **Deriving relations between hydrodynamics and plant properties**

The actual values of  $k_{veg}$  and  $C_{Deq}$  are determined by the hydrodynamic parameters water depth and flow velocity on one side, and by plant parameters like density, length, leaf area and bending stiffness on the other side. Ideally, an analytic expression would provide a relation between all these measurable parameters and the representative parameters  $k_{veg}$  and  $C_{Deq}$ . However, the range of plant shapes in combination with all possible hydrodynamic conditions creates such a large parameter space with non-linear behaviour, that it is impossible to find one formula that fits all conditions. Even with the help of Genetic Programming algorithms, which have been applied successfully by Baptist et al. (2007) in order to find simpler bed roughness coefficients for rigid vegetation, formulas fitted only a part of the spectrum.

Another way of establishing a relation between hydrodynamics, real plant characteristics and the two representative parameters is to make a species-specific look-up table using Dynveg: Plant properties like buoyancy and bending stiffness generally remain constant over time, which means the parameter space is more limited. In its simplest form, when also the plant length and spatial density are considered constant, such a table contains  $k_{veg}$  and  $C_{Deq}$  for a range of realistic depths and flow velocities. Within this range (typically  $h=0-2$  m,  $U=0-0.5$  ms<sup>-1</sup>, but larger values are possible) missing values are found by linear interpolation. An example is given in Figure 2, where interpolated values are bold and encircled. Straightforward linear interpolation is allowable despite the non-linear behaviour, on the condition that the values are close together, i.e. steps of 0.1 m for  $h$  and 0.05 ms<sup>-1</sup> for  $U$ .

As hydrodynamics and plant position affect each other, and because flow conditions in nature are always variable, it is not sufficient to look up  $k_{veg}$  and  $C_{Deq}$  just once. An iterative procedure, which is described in Figure 2, is necessary to reach a stable solution. First, a short run with Delft3D is made to have a first estimate of the flow velocity ( $U_{in}$ ; why  $U_{in}$  is used instead of  $U$  is discussed in the next paragraph) and water depth on the location of the vegetation. Based on these values, a Matlab-routine searches the representative  $k_{veg}$  and  $C_{Deq}$  in the lookup-table, in order to apply them to a new short Delft3D run in which the flow will be slightly different due to the different vegetation position. This continues a number of times until a stationary condition is reached or until the simulation ends.

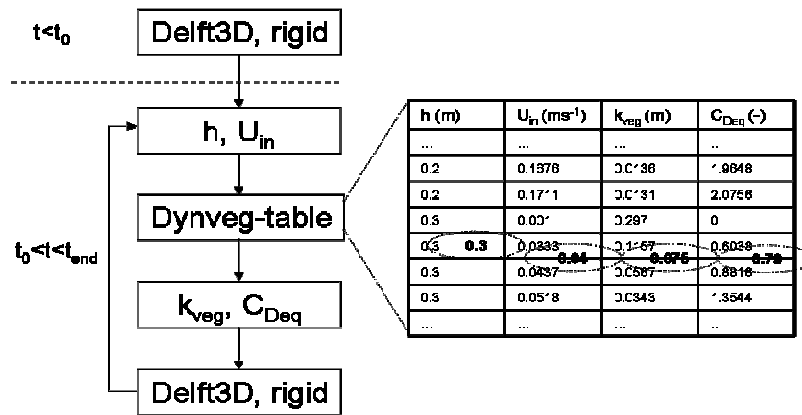


Figure 2 Schematisation of the calculation procedure for combined Delft3D (hydro/morphodynamics) - Dynveg (vegetation position) simulations.

#### Modelling in more dimensions

Looking at a vegetation field in nature or in a flume, one observes that the plants at the leading edge of the meadow bend further than those in the middle, where all plants assume more or less the same position. This is because the flow needs some space to adapt to the presence of the vegetation. How long this adaptation area is depends on flow- and plant characteristics. The consequence of this redistribution of flow over the vertical is that the depth averaged velocity  $U$  cannot be used as a determinant for the plant position: After all, due to conservation of mass  $U$  would be the same throughout a flume, leading to the same plant position everywhere.

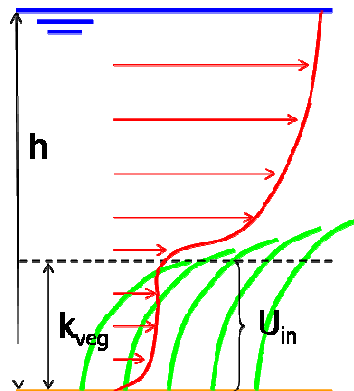


Figure 3 Calculation of  $U_{in}$  based on plant height and flow velocity profile.

Therefore, the more specific velocity inside the canopy  $U_{in}$  (see Figure 3), which is a measure for the amount of momentum acting the plants actually, is used instead of  $U$ . The introduction of  $U_{in}$  however, also introduces instability to the model, as it is integrated over the deflected vegetation height  $k_{veg}$ : When  $k_{veg}$  increases,  $U_{in}$  decreases, making  $k_{veg}$  decrease, leading to an increase of  $U_{in}$ , and so on, resulting in a flapping plant.

Similar-looking oscillations also occur in nature, probably due to coherent eddies penetrating into a meadow. This phenomenon, called ‘monami’ has been described by various authors (e.g. Ghisalberti and Nepf (2002) and Grizzle et al. (1996)), but there is no real consensus about the exact mechanism. Furthermore, because Delft3D is not able to resolve vertical eddies on this scale and morphodynamic calculations over multiple tidal periods require a stable flow field, such oscillations are unwanted.

Therefore, spatial and temporal stabilisation methods are used. Time-averaging occurs before spatial averaging. Both  $k_{veg}$  and  $U_{in}$  are averaged over time, but according to different schemes:

$$U_{in}^t = \theta U_{in}^t + (1 - \theta) U_{in}^{t-1} \quad (1)$$

$$k_{veg}^t = \frac{1}{2} (k_{veg}^t + k_{veg}^{t-1}) \quad (2)$$

With  $\theta$  between 0 and 1. For spatial integration, both parameters are averaged over three cells (upstream, the cell of interest  $i$  and downstream):

$$U_{in}^i = \frac{1}{4} U_{in}^{i-1} + \frac{1}{2} U_{in}^i + \frac{1}{4} U_{in}^{i+1} \quad (3)$$

$$k_{veg}^i = \frac{1}{4} k_{veg}^{i-1} + \frac{1}{2} k_{veg}^i + \frac{1}{4} k_{veg}^{i+1} \quad (4)$$

The procedures for  $C_{Deq}$  are exactly the same as those for  $k_{veg}$ , but  $C_{Deq}$  is only averaged over time. To speed up calculations, plants with similar  $k_{veg}$  and  $C_{Deq}$  values have been put into ‘classes’ with discrete values representative for the whole class; instead of running calculations for possibly thousands of different plants, the model only has to deal with several classes. This seems permissible, as the plants in the middle of a meadow will have a similar position anyway.

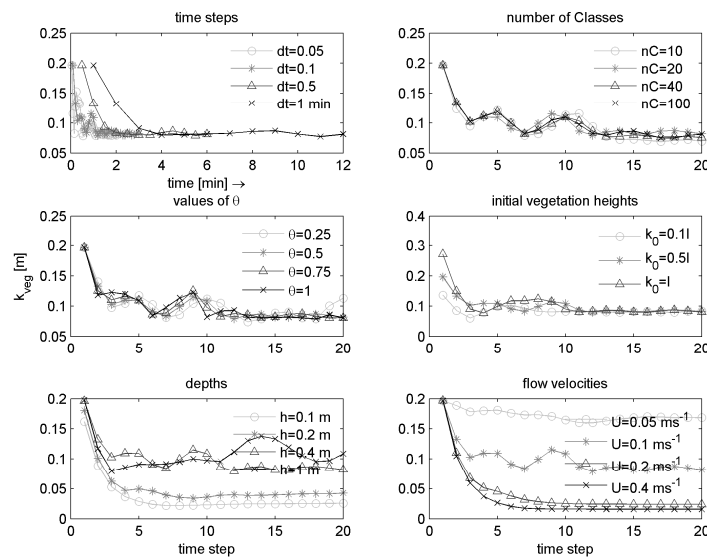
All these integration procedures mean that there will be a lot of damping, and that the simulation is not suitable for quickly varying flow or very sharp gradients. In tidal areas, the temporal variation is very small compared to the time scale of the simulation, hence no problems are expected. Strong spatial gradients however, like they occur at the edges of vegetation meadows, may not be represented well if larger grid cells are used.

## MODEL TESTING

### Verification of numerics and sensitivity

To see the sensitivity for different numerical and hydraulic parameters, a number of runs have been made with a standard set of parameters. These

resemble normal conditions in a long straight flume ( $h= 0.4$  m,  $U= 0.1$  ms<sup>-1</sup>), using a 6 m long meadow of *Zostera marina*-like vegetation. *Z. marina* is 30 cm tall, 5 mm wide and 0.35 mm thick, with a density ( $\rho_v$ ) of 950 kgm<sup>-3</sup>, elasticity ( $E$ ) of 10 MPa and 1000 individuals per m<sup>2</sup>. Standard settings of the numerical parameters are: 20 classes,  $\theta= 0.5$  and the initial position of the vegetation is half the leaf length. Standard simulation time is two minutes; with an information exchange time step  $dt$  of 0.1 min (6 s, i.e. 20 iterations). The horizontal grid cell size is 10 cm; the vertical grid consists of 40 layers with a thickness that is related to the water depth. The results are shown in Figures 4 and 5.



**Figure 4** Development of the vegetation height in the middle of the field ( $x= 9$  m) in time.

The development in time in Figure 4 shows that the time step does not influence the final result, but only how fast this result is reached. Small communication time steps ( $dt= 0.05$  and  $0.1$  s) reach a stationary situation within 2 minutes in the model, but this requires a lot of time-consuming communication between Matlab and Delft3D. Larger time steps reach equilibrium after about 4 iterations, but require more calculation time for hydrodynamics. So, for longer calculations larger communication time steps are useful. The other three numerical settings, like the number of classes, the values of  $\theta$  and the initial vegetation height do not matter for the final result, nor do they determine how rapidly the simulation converges.

The graphs of the physical parameters basically show what can be expected: In shallower water, the vegetation will bend more because there is less space for

flow rerouting, i.e. more water is forced through the meadow. Similarly, when flow velocities are low, plants are more upright. In deeper water ( $h=1$  m) there is more room for the plants to move, which they do. This movement also may have to do with the larger thickness of the computational layers at this larger depth: If a plant moves from one layer to the other,  $U_{in}$  (and therewith  $k_{veg}$ ) changes more when the layers are thick.

When looking at the spatial pattern at the end of the simulation (Figure 5), the stronger plant bending at the leading edge of the meadow is clear, as well as a more or less constant height downstream. The slightly stronger bending downstream can be attributed to the flow ‘bouncing back’ from the rerouting at the beginning. Also, the fact that all solutions are very similar for the four numerical parameters, except for the not-to-be-used  $\theta=0.25$ , gives confidence.

For the physical parameters the picture also looks good, with the exception of  $h=1$  m due to reasons mentioned before. However, the larger the depth the less important the exact position of the vegetation is, as the difference in  $k_{veg}$  is only a small percentage of the water column. At high flow velocities or shallow depths, the vegetation assumes the same position all along the meadow. This may be natural, but it also may be because these conditions are on the limit of the model’s capabilities.

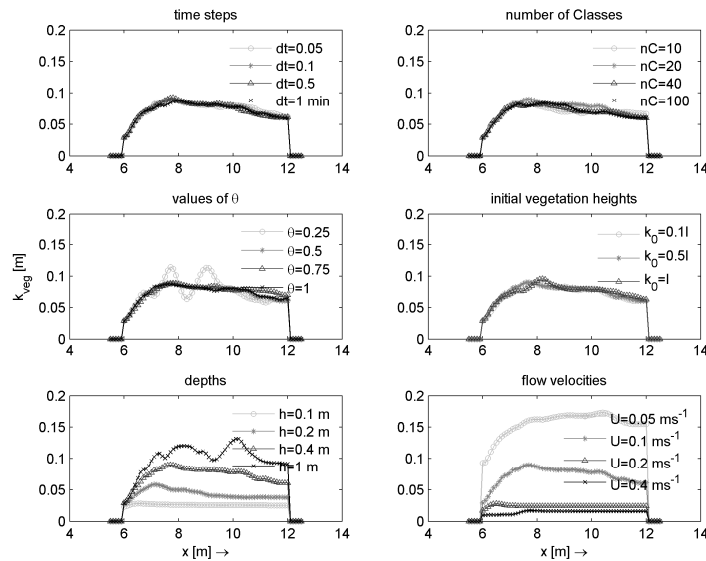


Figure 5 Vegetation height after the last time step (flow is from left to right).



### Validation with flume data

Using Dynveg, another lookup-table has been made to compare model results with experiments performed on flow through *Zostera noltii* plants used by Morris et al. (2008). These plants have a length of 8 cm, a width of 1.2 mm, a thickness of 0.15 mm and a density of 39620 leaves  $m^{-2}$ . Elasticity and buoyancy are considered similar to *Z. marina*. The flume in which the experiments have been performed is a 60 cm wide 40 cm deep racetrack flume, where the flow velocity is controlled by a drive belt. The test section with the plants is located at the end of the straight non-drive side.

To keep things simple, an 18 m long rectangular flume is used in the numerical simulation, where the vegetation starts at  $x=6$  m. The grid cells are 10 cm long in flow direction, 60 cm (= the width of the flume) in  $y$ -direction and 1 cm thick (40 cells in a depth of 40 cm). The flow is driven by a depth averaged velocity boundary upstream ( $U=0.2$   $ms^{-1}$ ), and a water level boundary downstream. The time step in the Delft3D simulation is 0.001 min (0.06 s). After 100 Delft3D time steps (6 s), the vegetation position is updated using Matlab and a new run starts until the end of the simulation at 3 min (30 iterations). The results of the simulation, compared to the measured vegetation height, can be seen in Figure 6.

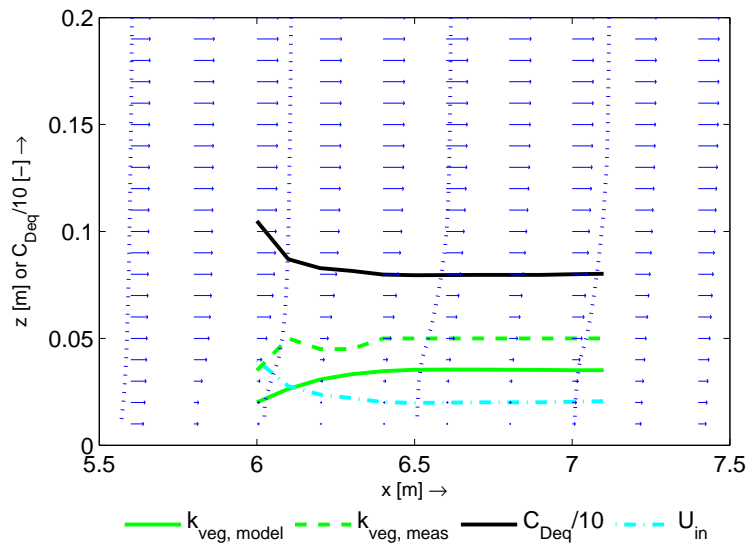


Figure 6 Longitudinal cross-section of the flume as used by Morris et al. (2008), with hydrodynamic and plant properties predicted by the model compared to measurements. Arrows and dotted lines indicate flow velocity profiles.

Comparing the predicted  $k_{veg}$  to that of the measurements, it is clear that the predicted  $k_{veg}$  is a bit too low, but that the length of the leading edge (where the vegetation height is not constant) is very similar. The difference may have several causes, both numerical and physical: The thickness of a computational layer is 1 cm, so  $k_{veg}$  is only one layer off. The more likely physical explanations are that the buoyancy and elasticity of the plants, which keep it upright, are underestimated, or that the bed roughness in the model is set too small, allowing for higher flow velocities close to the bed than in reality.

#### **DISCUSSION AND CONCLUSIONS**

A sensitivity test for various numerical and physical parameter settings, and a comparison with flume measurements have shown that the model works pretty well in various conditions. Very deep or extremely shallow water, and very strong or very weak flow are at the limits of its applicability, but still it seems to perform quite well in those areas too. Furthermore, now one is aware of that, some specific improvements can –and will- be made. Overall, it can be said that this approach has proven to be sensible.

The model in its current form could be used by ecologists to study the effect of hydrodynamic conditions and plant parameters (meadow size and density, plant size, density and stiffness) on the length of the leading edge, the rate of exchange of substances, and how far behind a meadow the flow is still affected. Such studies not only benefit the knowledge about plant growth conditions and survival, but also about the transport of seeds and larvae.

Of course, to make the model really applicable to real-world studies, it should be extended to all three dimensions. As Delft3D already is a 3D model, the only change necessary is in the Matlab-routine that calculated the right vegetation height and drag coefficient. As these parameters depend on the flow strength and not the flow direction, the necessary adaptations are relatively easy to make.

Despite that the model has been developed with the aim of studying sediment transport, this has not been treated in this paper. The first reason for this omission being that in a process-based model the transport of sediment is determined by hydrodynamics. Hence, when the hydrodynamics are simulated better, sediment transport will be simulated better automatically. Simulation data not shown here indeed seem to do so, at least qualitatively. The second reason is that validation data is lacking. This will be improved in further work, with a comparison with field data.

#### **ACKNOWLEDGEMENTS**

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