

The effect of sediment transport on eelgrass development – and vice versa

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ABSTRACT: By changing flow patterns and sediment transport, aquatic vegetation can affect the development of estuarine bed topography. Besides, since the sediment transport also determines the amount of light available for photosynthetic growth, the presence of vegetation can also affect its own development. This self-supporting interaction should be taken into account in long-term modelling studies. A process-based model offers the possibility to study this interaction and improve the predictability of eelgrass restoration attempts.

1 INTRODUCTION

Submerged aquatic vegetation is an important component in many estuarine and riverine systems. It provides shelter and food to many organisms, stabilises sediments and attenuates flow and waves, hence it affects its environment. The environment on its term determines the habitat for the vegetation: this is a very interactive process. Therefore it is neither sufficient to model just the effect of vegetation on the environment as morphologists tend to, nor to model just the effect of the environment on the vegetation, as ecologists often do.

An example of a situation in which this interaction might be crucial, is the disappearance of eelgrass (*Zostera marina*) from the Dutch Wadden Sea in the 1930's (van Katwijk 2000), and the number of restoration attempts in recent years: as long as there is no or little vegetation, there is no protection for the rest of the vegetation, and the water is more turbid. The abundance or absence of eelgrass are alternative stable states: there is little in between.

Light availability, which is determined by the depth and the water clarity, is a key factor in eelgrass development (Zimmerman et al. 1995, Vermaat et al. 1997, Best et al. 2001, Zharova et al. 2001). Hence, sediment transport not only affects morphodynamics, but, through the turbidity, also the vegetation growth. This combination makes that the light availability is not a simple sinusoidal function. The aim of this study is to model this interaction between flow, sediment transport and vegetation development, and to see how important it is in medium to long term modelling studies.

2 MODELLING APPROACH

A process-based modelling approach of vegetation development and morphodynamics seems the most promising tool that can be applied to gain a better understanding of how vegetation and morphology affect each other, without imposing interaction rules a priori. This tool has been used to study three scenarios:

- Vegetation development in a steady environment;
- Morphologic development with steady vegetation;
- A scenario in which both may change.

The morphodynamic model Delft3D (Lesser et al. 2004) of WL|Delft Hydraulics functions as a starting point for a model that incorporates both the development of seagrass and its effect on morphodynamics. In this model, the effect of vegetation on flow is incorporated according to (Uittenbogaard 2003). For this study, the morphodynamic model has been combined with a simple model that calculates the light attenuation by sediment and simulates the development of eelgrass. The following processes are especially relevant:

- Photosynthetic vegetation growth;
- Light attenuation due to suspended sediment;
- Flow attenuation by vegetation;
- Information exchange.

2.1 *Vegetation growth*

The eelgrass growth model simply calculates the increase of biomass per grid cell, based on primary

production –an approach that has often been used with success (e.g. (van Nes 2002)):

$$P = P_{\max} \frac{I}{I + H_I} \quad (1)$$

Where P is the gross photosynthesis rate (h^{-1} , actually $\text{mg O}_2 \text{ g DW}^{-1} \text{ h}^{-1}$), calculated as a function of the maximum photosynthesis rate P_{\max} , in situ light I and the light half-saturation constant H_I . Besides photosynthesis, the biomass (B) also changes as a result of mortality (M) and respiration (R):

$$\Delta B = B(P - R - M) \quad (2)$$

Values for P_{\max} (0.0047 h^{-1}) and R (0.0017 h^{-1}) are based on data of (Vermaat et al. 1997).

2.2 Turbidity

Light reduction by the water column can be modelled using the Lambert-Beer equation:

$$I_v = I_{surf} e^{-cL} \quad (3)$$

Where I_v is the irradiance available to vegetation, I_{surf} the irradiance at the water surface, and c is the light attenuation coefficient (m^{-1}). The value of c is calculated from a background value and a linear effect of the suspended sediment concentration (c_s ; mg l^{-1}) as:

$$c = 0.3 + 0.4c_s \quad (4)$$

Since the hydrodynamic model has a number of computational cells over the vertical, the reduction is calculated for each cell, based on the light coming in at the top and the cell height L . The light available for photosynthesis is finally calculated at a level equal to half the vegetation height.

As a result of the movement of the earth, the irradiance at the water surface varies during the day and during the year, according to:

$$I_{surf} = I_0 \sin \varphi \quad (5)$$

$$\sin \varphi = \cos \alpha \cos \delta \cos \lambda + \sin \delta \sin \lambda$$

With I_0 the solar constant ($1367 \text{ J m}^{-2} \text{ s}^{-1}$), φ the solar elevation that is determined by: α , the hour angle at the current time (i.e. 24 hour cycle), δ , the solar declination (i.e. one year cycle) and λ , the latitude (52°). To account for reflection at the water surface, atmospheric scatter and the limited part of the spectrum suitable for photosynthesis, the Photosynthetically Active Radiation (PAR) is considered to be 45% of the total irradiation.

2.3 Vegetation drag

The influence of the presence of vegetation on flow is incorporated through a k - ϵ turbulence model from (Uittenbogaard 2003). In this model, the vegetation

is seen as a number of drag-generating rods. The properties of the vegetation that need to be specified are: C_D , the drag coefficient; d , the diameter; l , the height; and n , the number of stems per m^2 . Since the vegetation growth model only calculates changes in biomass, this biomass has to be translated into more specific vegetation properties. The shape of an eel-grass plant can be considered more or less constant during the year, only the length of the leaves and the number of stems change considerably (van der Heijde, pers. comm.). Therefore, $C_D = 1.5$ and $d = 5 \text{ mm}$, and l and n are calculated from the biomass following the following scheme: The initial number of stems is 1500, with a length of 30 cm. First, the length of the stems increases to a maximum of 50 cm, and when biomass increases further, the number of stems will grow. A decrease in biomass will first cut back the number of stems, and subsequently the stem length.

2.4 Interaction

To simulate the interaction with the environment, a fictitious $130 \times 200 \text{ m}$ and 1.5 m deep shallow area is created. The grid has 10 layers over the vertical and the horizontal grid size is 10 m. At one side, an area of three by five cells ($= 30 \times 50 \text{ m}$) is filled with plants, allowing the water to flow around or over the vegetation, and spatial differences in plant development. The size of the sediment is set at 0.065 mm (very fine sand), and the Van Rijn (1993) transport formula is used. The driving force is an M_2 -tide with an amplitude of 0.5 m and flow velocities of 0.5 m/s.

In order not to neglect any possibly relevant changes, the exchange of information between the morphological model and the biomass development model should occur often, without slowing down the calculations too much. Figure 1 shows that one hour is the largest time step at which results still converge.

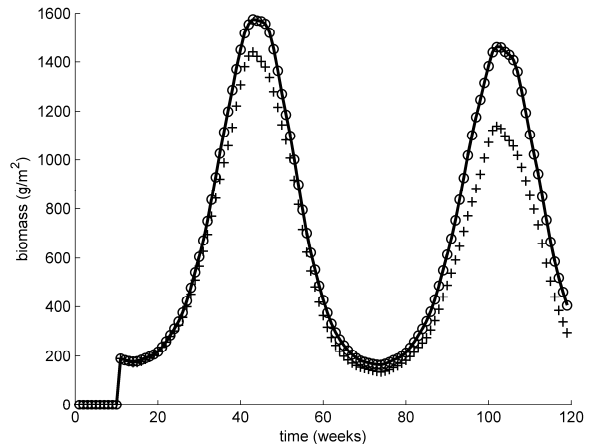


Figure 1. Biomass development for different time steps, based on a varying water depth due to a combination of M_2 and S_2 tides. Circles are $dt = 0.5 \text{ h}$, continuous line 1 h and crosses 2 h.

Therefore, the hydrodynamic data are sampled every hour for a period of 24 hours, after which the vegetation properties are updated and fed back to the morphodynamic model.

3 RESULTS

3.1 Vegetation development in a steady environment

To see how important the environment can be for vegetation development, a first run has been made with a two-dimensional version of the model. Here, vegetation could grow, and the presence of plants affected the flow and sediment concentration, but the bed level was kept constant. Two runs have been made: one with the horizontal and vertical tide in phase, and one out of phase. Figure 2 shows how the flow and sediment transport are reduced in the vegetated area (i.e. between 90 and 120 m), while Figure 3 shows the light availability and how the vegetation developed in 150 days.

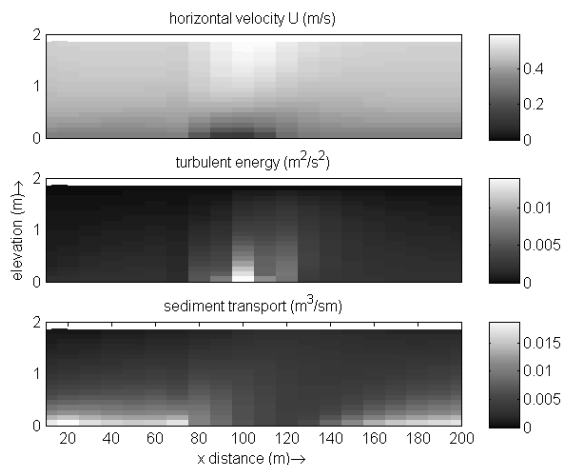


Figure 2. Flow properties affected by the presence of vegetation (high flow velocity coincides with high water level).

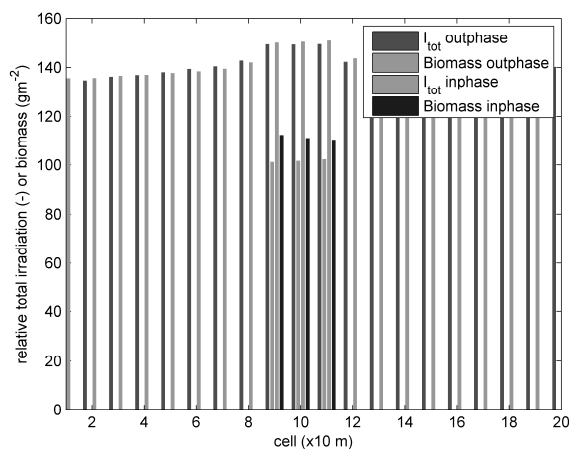


Figure 3. A comparison of the amount of light reaching the bed and biomass development for different tidal phases.

The total received irradiance is 6% higher in vegetated areas than on bare sand. Further, the amount of biomass in the ‘in phase’ situation is 9% higher than in the ‘out of phase’ situation, whereas the total received irradiance is only 0.7% higher. Hence, it seems to be better when bad circumstances (deep water and high sediment concentration) coincide and are followed by a good period, then when they occur in succession. This also means that aquatic vegetation development is strongly non-linear and that the value of total received irradiation cannot simply be used to predict vegetation growth: the combination of solar declination, horizontal and vertical tide is really necessary.

A later three-dimensional version, where the vegetation had no effect on neither flow nor sediment transport, showed that there was no spatial variation in plant development. Also, because the sediment concentration above the vegetation was not reduced, plants developed slower than in the scenarios where plants did have an effect on the environment.

3.2 Morphodynamic development with steady vegetation

When compared to the fully dynamic scenario, this scenario should show how important it is to incorporate the development of vegetation into morphodynamic models. A year of morphodynamic development has been simulated while keeping the vegetation properties constant at $l = 0.45$ m and $n = 2500$ m². Figure 4 shows that the flow is attenuated and rerouted around the vegetation, leading to sediment deposition in front of, inside and behind the vegetated area, but erosion next to it (Fig. 5).

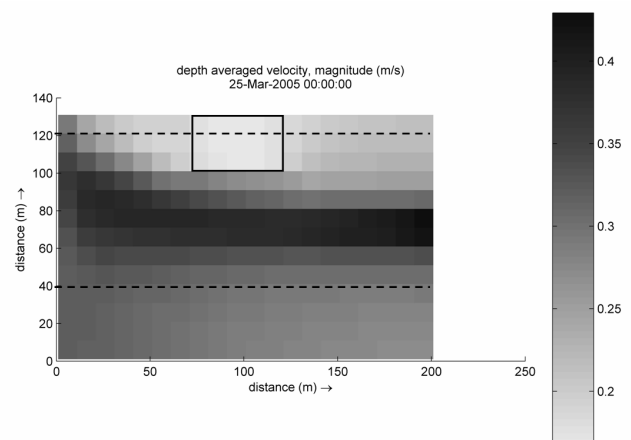


Figure 4. Depth averaged flow velocity; flow from left to right. The rectangle indicates the positions of the vegetation; the dashed lines are the cross-sections in Figs. 6 and 7.

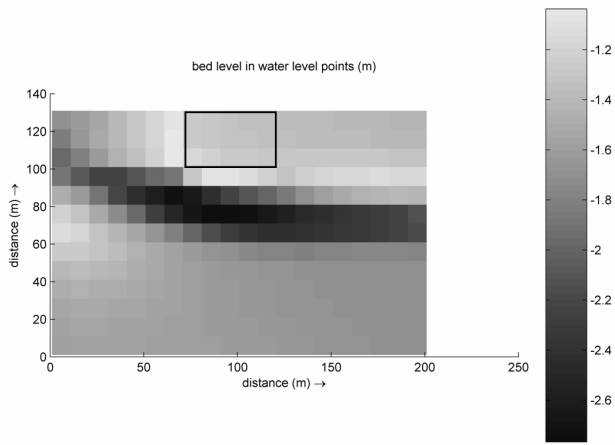


Figure 5. Bed level after one year of morphologic development with steady vegetation. Original bed level was -1.5 m.

3.3 Dynamic vegetation and morphology

In this one-year simulation, both the bed level and the vegetation vary in time, and have an effect on each other. The vegetation height l may vary between 0.3 and 0.5 m, and the number of stems per m^2 n between 1500 and 3500.

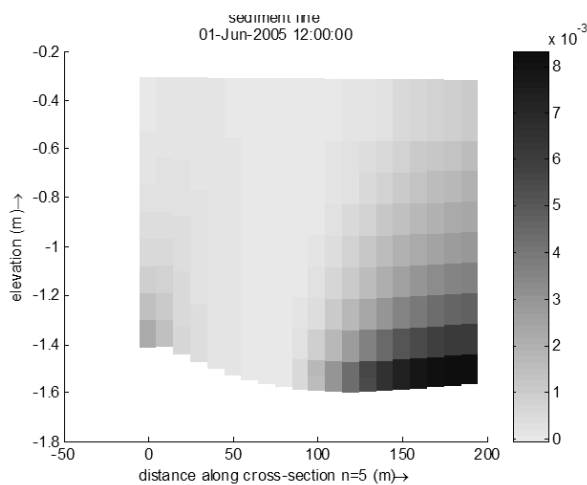
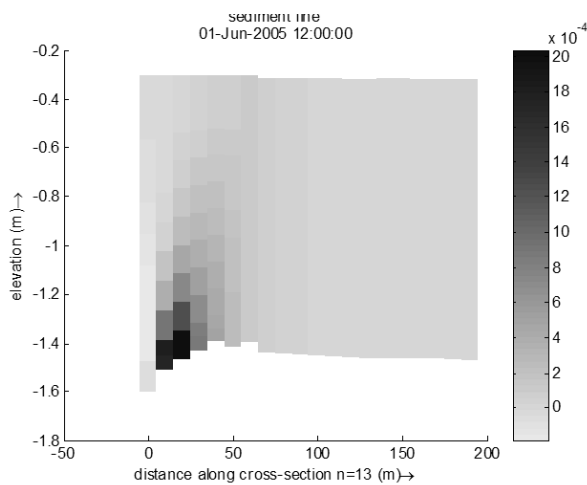


Figure 6. Cross-sections showing bed level change and sediment concentrations (g/l) after three months. The upper cross section, which is partly vegetated, can be found at 120 m in Figure 4; the lower at 40 m.

Figure 6 shows the sediment transport in a vegetated and a bare cross-section. The sediment concentration in the bare area is clearly higher. These pictures also show that, after some time, the rerouting of flow is not only the result of the presence of vegetation, but also caused by the adaptation of the bed.

The patterns of flow and bed level change are very similar to those produced by the simulation with static vegetation, but the values differ somewhat. The difference in bed level in the two cross-sections after one year can be seen in Figure 7. In this case, the effect of static vegetation on its environment is a bit larger than that of dynamic vegetation. Probably this is due to the fact that the amount of static vegetation is quite close to the upper limits of the dynamic vegetation.

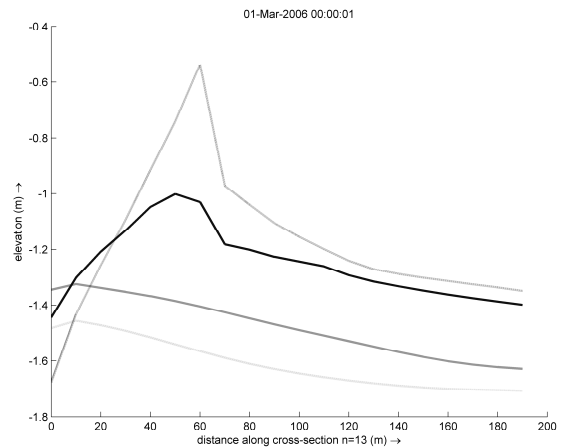


Figure 7. Bed level profiles after one year. Continuous lines are for dynamic vegetation; dashed lines for the static situation. The upper lines are at $y = 120$ m; the lower at $y = 40$ m.

4 DISCUSSION

Some basic principles governing vegetation development and morphological change are brought together in this study, giving an idea about how important modelling interaction can be. The current set of results is too limited to draw any conclusions about how important interaction between vegetation and morphology is in any arbitrary case, but they clearly show that in this case considerable interaction occurs.

A next step would be to find out more about the importance of interaction at different plant growth rates and morphological timescales. Another step is to find out more about how well the model describes sediment transport in and around vegetation, since this has not been tested thoroughly. Furthermore, the vegetation in the model is modelled as rigid rods, whereas eelgrass is a very flexible macrophyte. This also will have consequences for its effect on flow and sediment transport. According to the data of (Temmerman et al. 2005) the rod model works quite well for predicting sediment depositions patterns in

stiffer salt marsh vegetation. Also, a comparison with the measurements from (Gacia and Duarte 2001) could clarify this.

Of course, process-based modelling also has its drawbacks. Due to the variability in water level and sediment concentration resulting from the tide, and the continuous movement of the earth, the light availability strongly changes within hours. This hourly scale does not match with the much faster hydrodynamics (minutes), or with the much slower morphodynamics (days or more, depending on the spatial scale). The difference between these physical time scales is such that one can calculate one process, assuming the other constant for some time. However, although vegetation develops as slowly as morphology, this 'trick' cannot be applied to vegetation growth due to its dependence on the 24 hours day/night rhythm that does not coincide with the semi-diurnal (12.4 hours) rhythm. The seasonal change of the solar declination causes a similar difference in time scales, resulting in rather long calculations.

According to the data of (Vermaat et al. 1997), the photosynthesis-related parameters P_{max} and R are determined with about 4-8 % uncertainty. Moreover, (Zimmerman et al. 1995) showed that these values may vary with the season. These uncertainties, combined with the non-linear feedback from the morphological model, may lead to large errors in simulations over long periods. However, adding processes to Equation 1, like e.g. nutrient uptake, will make the model more stable as the sensitivity to the photosynthesis parameters will be relatively less. Nevertheless, like with every process-based model, good input data are absolutely necessary.

Partly to keep things simple, but also partly due to limited knowledge, three other probably important processes are left out for the moment: colonization of bare sediment by vegetation, vegetation retreat, and resuspension of sediment by waves. Likely, the influence of each of these processes on the results is just as important as the interaction caused by the sediment transport reduction in vegetation. Furthermore, the weather can have a decisive influence on what happens in reality.

5 CONCLUSIONS

The effect of the presence of vegetation on morphological development and the effect of changing sediment concentrations on vegetation development are very clear, and non-linear. Therefore, a process-based model offers a good possibility to study this interaction between eelgrass or other macrophytes and their environment. This can not only be used to study the needs and success of restoration attempts, but also to get an idea of how the environment will

change if vegetation fields of considerable size may be present again.

However, the number of represented processes is limited, and such a combined model may easily run out of control if the parameters are not exactly right. Furthermore, it is a very computationally intensive tool, and for many applications simpler approaches may work as well.

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