Simulation of Hydrodynamics and Transport of Fine Sediments in Vegetated Polders with a Controlled Reduced Tide: Pilot Project Lippenbroek

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Abstract: This paper presents results from ongoing multidisciplinary hydromorphological research on the pilot project Lippenbroek. Lippenbroek is a flood control area (FCA) with a controlled reduced tide (CRT). A Delft3D model has been developed to examine the sediment transport in the vegetated polder. Vegetation was modeled using the trachytope module of Baptist (2005). Optimal parameter settings have been selected and a good representation of the measured water levels and observed inundation pattern was obtained. The paper demonstrates the possibilities for the application of a robust modeling system to assess the morphological evolution of a FCA with CRT. In addition, a better comprehension of processes and parameters that determine sedimentation in a FCA has been obtained. The knowledge described in this paper will be important for the assessment of other, similar polders that will be converted to flood control areas with CRT. As the model takes into account the various relevant processes that determine sedimentation patterns in the FCA it is believed to assist future maintenance decisions.

Keywords: Actualized Sigma plan, flood control area, controlled reduced tide, Scheldt, combining safety with estuarine restoration, Delft3D, vegetation, Baptist, settling velocity, coagulation, mud, sedimentation

Introduction

Pilot project Lippenbroek

The Actualized Sigmaplan aims for satisfying safety and ecological needs along the Scheldt river in a sustainable way. Therefore different measures have been elaborated which combine safety with estuarine restoration, eg. dike strengthening together with more space for the river, flood control areas (FCA), and non-tidal wetlands. As a pilot project, the former Lippenbroek polder has been converted into a 10 ha flood control area (FCA, **Figure 1**) with a controlled reduced tide (CRT) installed (Cox et al, 2006; Maris et al, 2007). During storm surges that occur on average once a year, the FCA is filled via a lowered levee. In addition, a well designed sluice system allows limited semi-diurnal water exchange between the FCA and the estuary. Goal is to obtain inundation characteristics similar to natural tidal marshes (**Figure 1**).

In 2006 Lippenbroek started functioning as freshwater intertidal habitat. Two years of intensive monitoring on the pilot site demonstrate the potentials of this approach (Maris et al, 2008). Former cropland is evolving towards an estuarine ecosystem. The vegetation cover shows a succession from pioneer generalist to typical estuarine and wetland species, driven by the installed tidal variation. The same evolution, colonization by typical estuarine and wetland species, is also observed for zoo-benthos, fish and birds. In addition, a pronounced springtide/neap tide variation is realized and sedimentation-erosion patterns comparable to natural marshes are observed.

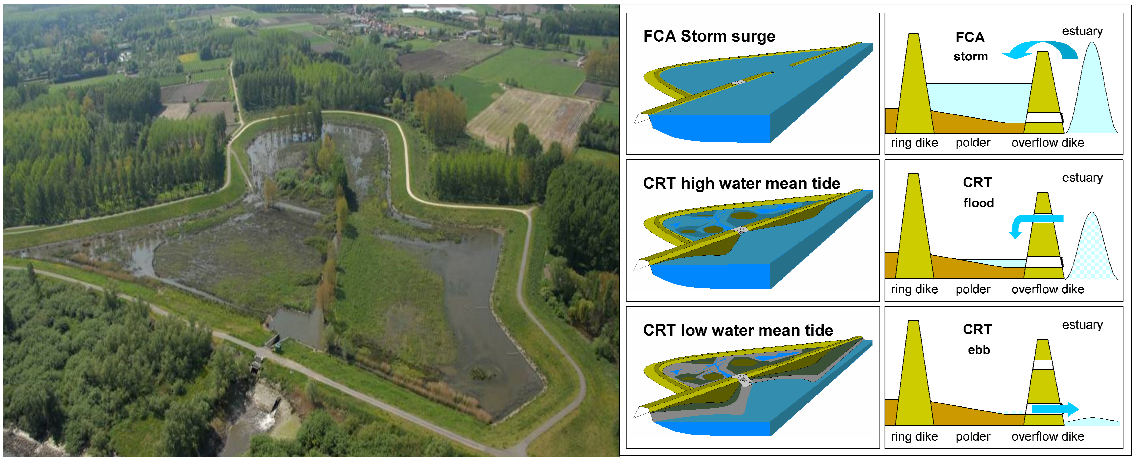

Figure 1: Left: Aerial photograph of the FCA converted Lippenbroek polder (May 2008). Right: Overview of the CRT-principle.

Research objectives

It should be stressed that in order to obtain a well functioning freshwater intertidal habitat, settlement of sediment is a necessity and therefore wanted. However, too much sedimentation will give rise to safety issues (Peeters et al, 2009). Therefore hydromorphological monitoring combined with different modeling techniques aims to understand water flows and sediment transport within pilot project Lippenbroek, and in extension every other future FCA with CRT-functioning.

This study aims to determine by means of numerical modeling how much sediment is retained in the polder, what is the spatial distribution, and in particular how this process is influenced by the development of marsh vegetation. The study serves as a test-case and evaluates the possibilities for application of a robust numerical modeling system to assess the morphological evolution of flood control areas with CRT. In addition, a better comprehension of dominant processes and parameters that determine sedimentation in a FCA is aimed at.

Problem analysis

Description of dominant parameters and processes

To understand how the sedimentation and erosion processes take place in the polder it is important to know the significance of the various observed phenomena. The observed sedimentation is related to the influx of sediments through the inlet structure and to the local erosion of the main creek (Peeters et al, 2009). Internal factors like vegetation and topography influence where sediment will settle. Outside the creek the rise and fall of the water level is slow, and little turbulent flow can be expected. Also vegetation is known to decelerate the flow and to retain sediments. After the polder is flooded a stagnant water phase up to two hours allows the sediments to settle. The deposition may therefore be related to the sediment concentration at the start of the stagnant phase, the settling velocity of the sediments and the local water depth (Temmerman et al., 2003). Due to flocculation of smaller particles that have been transported into the polder, the receding (outgoing) flow may not be able to re-suspend these larger particles.

Hypotheses

How important are all these sedimentation processes in the Lippenbroek polder? The following hypothesizes have been put forward of which some will be discussed in this paper:

1. Vegetation plays a role in transportation, deposition and fixation of sediments. However, because of the small flow velocities in the polder the influence of vegetation on flow velocities and water levels in this particular case is negligible.
2. Local topography, translated into a certain water depth during the stagnant phase, can be correlated directly to the sedimentation in the polder. Following this assumption the presence in the polder of creeks and sub-creeks is of minor importance.

3. Coming from the stilling basin of the inlet all the large coagulated particles from the Scheldt river have been broken up into small particles with small settling velocities. Even though, once the flow becomes less turbulent, coagulation regroups the small particles into larger ones, the assessment of the sediment deposition should be based on these smaller particle sizes.
4. Local production of organic material and the expansion of root systems of common types of vegetation contribute to the increase of bed level. (Will not be addressed in this paper.)

Data analysis

Vegetation and mapping

Currently the vegetation in the polder is in a transition state from terrestrial ruderal vegetation and transient pioneers to typical tidal marsh vegetation (Jacobs et al., 2009). Vegetation has a determining effect on the development of geomorphological features that are typical for a tidal marsh, such as vegetated platforms with incised tidal creeks (Temmerman et al., 2003). Due to their coherence and close positioning of the stems vegetation causes a deceleration of the flow. In summer, leaf cover has to be taken into account, while in the winter clusters of dead stems, standing or lying, are dominant. As a result, the vegetation imposes friction on the flow, resulting in longer retention times of water around the vegetation, allowing for deposition of fine sediments to take place within the vegetated areas. Even though after the colonization phase the position of the main creeks will be more or less fixed, geomorphological adjustments (such as creek extension and platform flattening) will continue for many more years (probably on the order of decades).

Twice a year, during spring and autumn, the University of Antwerpen makes vegetation maps of the Lippenbroek polder in order to evaluate the spatio-temporal evolution of vegetation composition. Based on dominant types of vegetation various areas are outlined. In each area the following parameters are mapped as percentage of the surveyed area: leaf coverage, litter (standing or lying), open ground and algae. In addition the average height of the vegetation and the micro relief of the bed are noted. Based on the mapping various types of vegetation have been selected that would have an impact on the flow during the various seasons. Three overall types have been distinguished which all have leaf cover in summer, while in the winter they have either only dead standing stems, or lying litter or have fully disappeared.

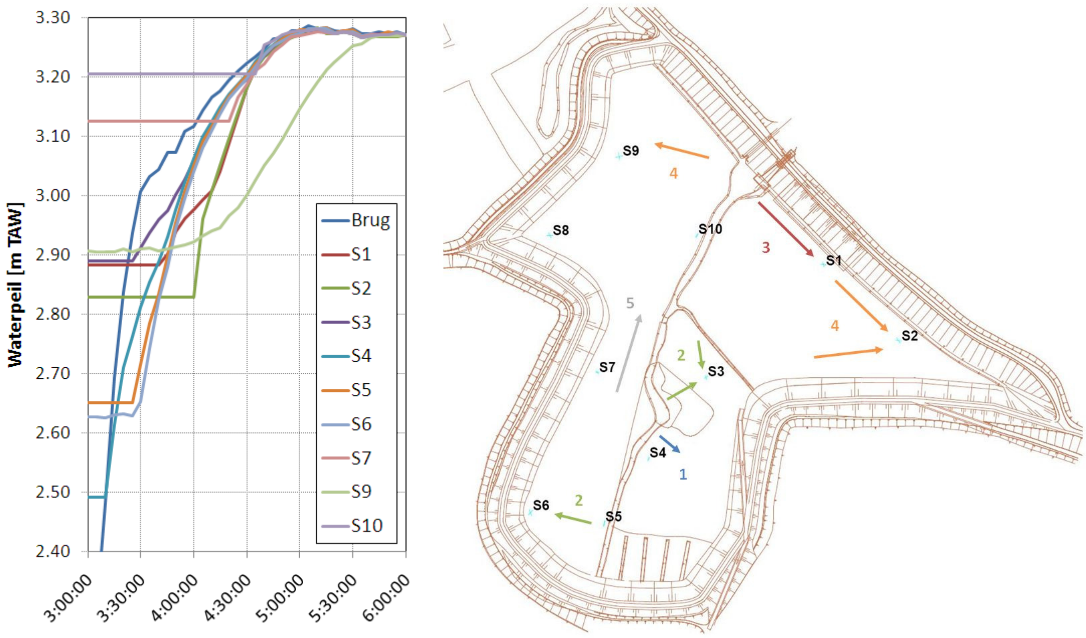

Figure 2: Left: Measured water levels at 10 different locations throughout the polder during inflow. Right: Location of measurement stations, arrows and numbers indicate the inundation sequence.

Discharges and water levels

When the tide in the Scheldt reaches the sill of the inlet sluice, water together with suspended sediments start to flow into the Lippenbroek polder. The inflow is one of the four distinguished phases during a tidal cycle in the polder (Maris et al., 2008 and Peeters et al., 2009). Measurements of water levels at ten different sites throughout the polder are presented in **Figure 2**; the locations of the probes are shown on the right panel. In the same figure also the inundation pattern obtained from the changes in water level is presented (IMDC, 2010).

First, during inflow, the water is transported along the main creek to the back of the polder. When the water level continues to rise, also the tidal flats are inundated. Once the tide in the river has dropped below the sill of the inlet sluice, the water in the polder becomes stagnant for about one to two hours (phase 2). When the tide falls below the water level in the polder, water starts to flow back to the Scheldt through the outlet sluice (phase 3), During the outflow the water in the polder follows a more or less opposite flow pattern as compared to the inflow phase. When the water level in the polder reaches the sill of the outlet sluice or when the tide has risen to the water level in the polder, outflow stops. Before the tide reaches the inlet again, there is leakage through the gated outlet sluice (Phase 4) .

Sediment characteristics

Due to its gradation sediment cannot be characterized by one grain size and according settling velocity. Furthermore, the settling velocity is not constant due to coagulation or flocculation processes, which are a function of local flow conditions, and due to hindered settling. Typical settling velocities range between 0.1 mm/s and 10 mm/s and between 0.001 and 0.1 mm/s for unflocculated material. Due to the turbulent inflow sediment flocs (build up from sand, clay and diatoms) coming from the Scheldt break up into small particles. Only after transportation into more tranquil areas of the polder coagulation will increase the floc size and hence the sediment settling velocity. From laboratory measurements it was found that it takes about 7 to 10 minutes for coagulation to take place. In situ this gives rise to the idea of higher sedimentation rates further into the polder than would be expected based only on the settling velocity of the coagulated particles. It is clear that the change in settling velocity influences the sediment distribution in the polder and should be taken into account when modeling.

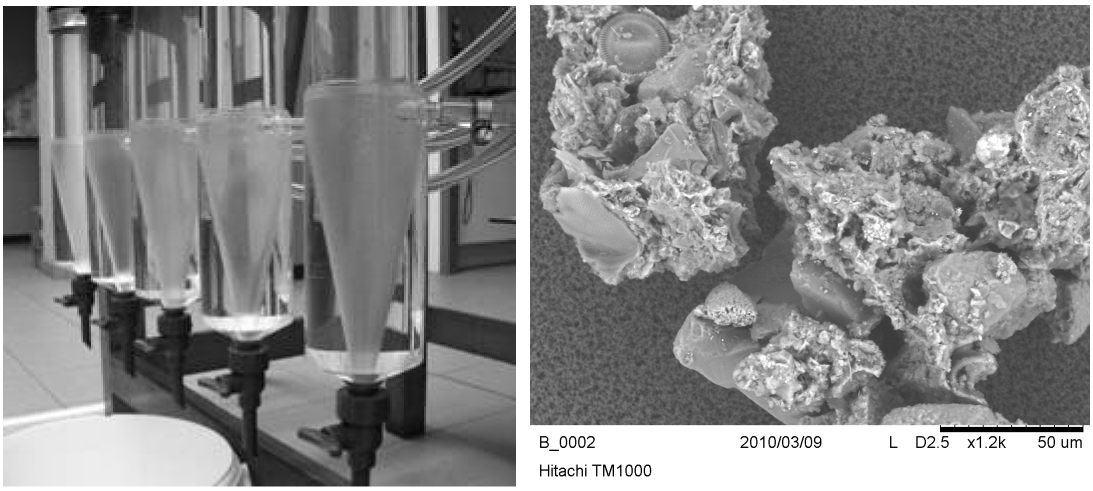

Figure 3: Left: Settling tube used to determine the settling velocity of the sediments. Right: SEM-picture of settled material consisting of coagulated sand and clay particles and diatom skeletons.

Grain size distributions of the inflowing sediment have been determined by Flanders Hydraulics Research (FHR) by means of a laser diffraction method using a Mastersizer 2000 (Malvern) based on ultrasonic (US) breaking. The US breaking leads to a shift towards the finer sediments. The distribution presents a predominant load of fine sediments of clay (4%) and fine silt (41%, silt smaller than 16 μm) and medium and coarse silt (37%). In addition, sediment deposition samples at various locations throughout the polder have been collected by the University of Antwerp. These samples have been analyzed by FHR to determine the settling velocity by means of a settling tube (**Figure 3**). Based on the length of the tube and the time elapsed since the start of the experiment the settling velocity of the sediments deposited during the preceded time interval is computed.

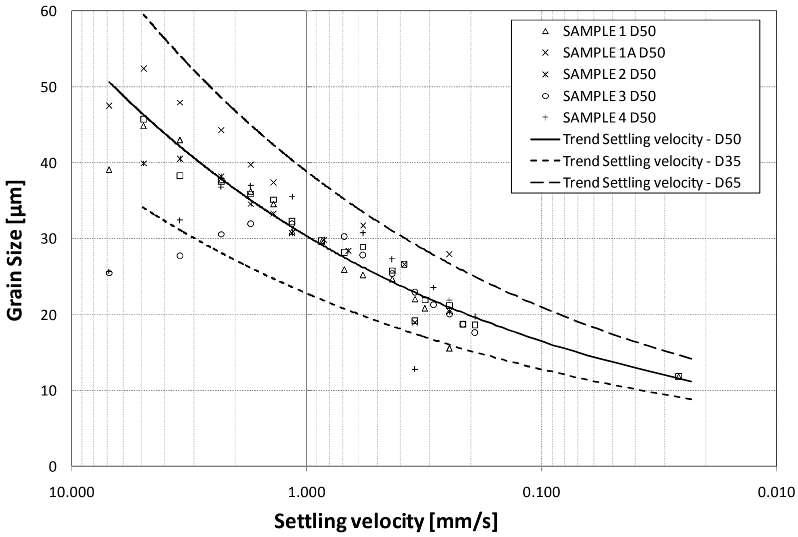

Figure 4: Relationship of measured settling velocities and measured grain sizes for different sediment samples from Lippenbroek. As coagulation takes place during the first 7 to 10 minutes spurious settling velocities have been computed for the higher settling velocities.

Using laser diffraction (US breaking) the grain size distribution of the deposited material in function of the settling velocity (per time interval) has been determined (**Figure 4**). Via the median grain diameter the settling velocity can be linked to the grain size distribution at the inlet structure. Note that in both experiments the actual floc size is unknown. As only a small percentage of sediments smaller than 16 µm ($w_s < 0.05$ mm/s) will deposit within the timeframe of stagnant water in the polder, only medium to coarse silt has been included in the sediment transport model. Three sediment classes have been selected, having median diameters of 20, 30 and 50 µm and settling velocities of 0.2, 1.0 and 6.5 mm/s.

Methodology

Delft3D modeling software

A numerical hydrodynamic and sediment transport model has been set-up of the Lippenbroek polder using the Delft3D software. Delft3D-FLOW is a multi-dimensional (2D or 3D) hydrodynamic and sediment transport simulation program which calculates non-steady flow and transport phenomena that result from tidal and meteorological forcing on a curvilinear, boundary fitted grid (Deltares, 2008). A depth averaged approach has been applied because 1) the vertical structure of the vegetation was neglected in this stage of the study, 2) as the flow velocity on the flats is usually very small, the 3D structure of the flow is not a critical variable, and 3) a reduction of computation time could be obtained.

Trachytope model

In the Delft3D model the influence of vegetation is incorporated using a sub-grid vegetation-flow interaction model. A more schematized, depth average approach has been applied based on Baptist (2005). Following this approach, a strict separation has been made between the effect of the vegetation on the bed roughness (equation 1) and the flow resistance (equation 2) in order to avoid that the presence of vegetation would increase both the bed shear stresses and the sediment transport rates, rather than reduce them. Therefore, an additional term is added to the momentum equation equal to $-\frac{1}{2}\lambda u^2$, in which λ represents the flow resistance of the vegetation. The equations for bed roughness and flow resistance read:

$$C = C_b + \frac{\sqrt{g}}{\kappa}\ln\left(\frac{h}{h_v}\right)\sqrt{1 + \frac{C_D n h_v C_b^2}{2g}} \qquad (1)$$

$$\lambda = C_D n \frac{h_v}{h}\frac{C_b^2}{C^2} \qquad (2)$$

where C is the representative roughness for vegetation and bed according to Chézy, λ is the flow resistance of the vegetation, n is the vegetation density (number of stems per square meter times stem diameter), C_D is the drag coefficient of the vegetation, h is the water depth, h_v is the vegetation height, and C_b is the alluvial bed roughness according to Chézy. In case of non-submerged conditions the two equations are independent of each other and reduce to:

$$C = C_b \tag{3}$$

$$\lambda = C_D n \tag{4}$$

The values of vegetation parameters used in the model are based on the mapping of the Lippenbroek polder by the University of Antwerpen. Since leaf cover cannot be neglected, a conversion was made from the standard mapping parameters of the University of Antwerpen to the parameters required for the model. Equations (1) and (2) show that only the product of vegetation density n and vegetation drag coefficient C_D needs to be considered and not the components separately.

Sensitivity analysis

A sensitivity analysis has been performed to determine which input data, schematization, or numerical aspects are likely to improve the results of the hydrodynamic model of the polder (IMDC, 2010). The various variables were varied between reasonable values and six parameters describing the hydraulic behavior were derived to evaluate the models performances (**Figure 5**). Using these parameters the model results were compared with the measurements at the different locations in the polder presented in **Figure 2**. The bias and standard deviation of the differences between model result and measurement were analyzed. From the analysis the optimal parameter settings for the model have been selected and a good representation of the measurements was obtained (for example **Figure 6** has been added).

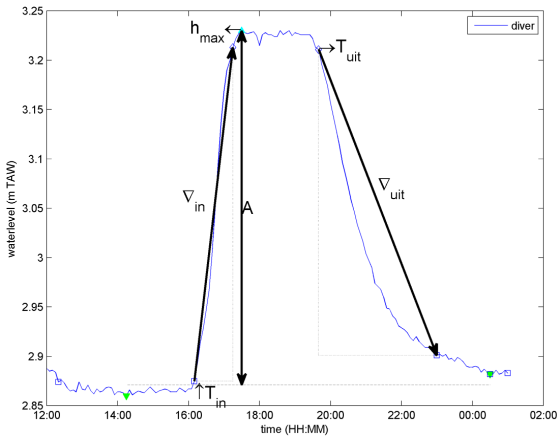

Figure 5: Definition of evaluation parameters: h_{max}: maximum water level, A: amplitude, T_{in}: start inundation, T_{uit}: start outflow, ∇_{in} : gradient inundation, ∇_{uit} : gradient outflow.

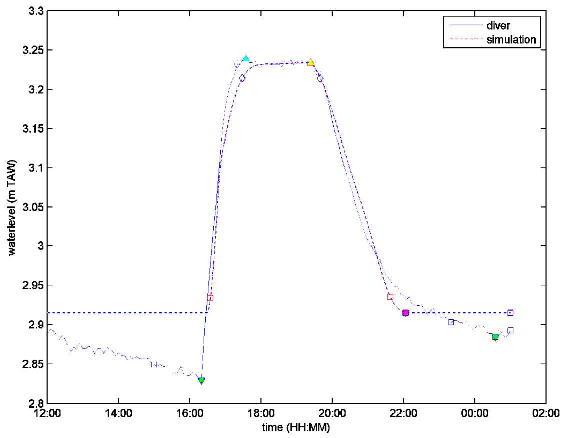

Figure 6: Comparison of model results (red) using the optimal parameter settings, with measurements (blue) at a the northeastern tidal flat (S2).

From the sensitivity analysis, it was concluded that the vegetation parameters and alluvial bottom roughness have little to no influence on the hydrodynamics. Some effect could be found on the flood propagation front (represented by the gradient in **Figure 5**) and in lesser extent during the outflow. As could be expected a decrease in density of vegetation results in a faster inundation. However, as the effect is small it was concluded that the vegetation parameters can be easily modified to improve the representation of the water velocities (and thus the sediment transport) without affecting the water levels.

Results and Discussion

A first set of simulations was carried out in order to compare various sediment characteristics, to analyze sedimentation patterns in the polder and to determine the effect of vegetation on sediment transport. **Figure 7** shows that a smaller settling velocity results in a wider distribution of sediments over the polder. Apparently the large particles do not reach the back of the polder where significant sedimentation is observed. This sedimentation here can only be explained by the presence of particles that have not flocculated and hence with much smaller settling velocities. Therefore in order to model the sediment distribution correctly, the settling velocities before flocculation need to be used.

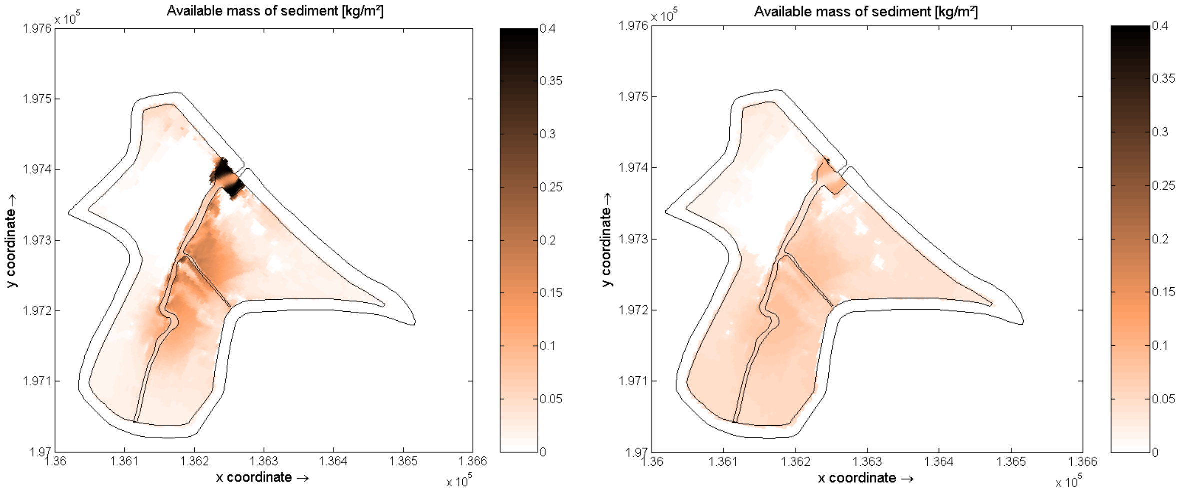

Figure 7: Model results of settled sediment mass [kg/m²]. Left: A settling velocity of 0.5 mm/s is used. Right: A settling velocity of 0.1 mm/s is used. Sediments with lower settling velocities can spread more uniformly throughout the polder and are less influenced by vegetation.

Furthermore, following the results in **Figure 7**, it can be concluded that the vegetation affects sedimentation, especially of sediments with large(r) settling velocities that settle predominantly in areas were vegetation was implemented in the model. This has been visualized by filtering the effect of the local water depth (or elevation) on sedimentation. In **Figure 8** the normalized sediment deposition have been divided by the normalized maximum water depth (at the start of the stagnant phase). Assuming the sedimentation is correlated directly to the (maximum) water depth, this comparison allows to evaluate which areas accumulate more sediment than should be expected based on the local water depth alone, and which areas accumulate less.

Figure 8a shows that the northeastern tidal flat with the highest vegetation cover has accumulated much more sediment than should be expected based on the local water depth. **Figure 8b** indicate that in case of a smaller settling velocity, vegetation has a much smaller influence and more sediments reach the end of the polder. Simulations without vegetation to isolate the effect of the settling velocity from the vegetation were not yet available at the time of submission of this paper. However, on a preliminary basis, it is concluded that the presence of vegetation is of minor importance as compared to particle size (settling velocity) and proximity to the creek in order to explain observed sedimentation patterns.

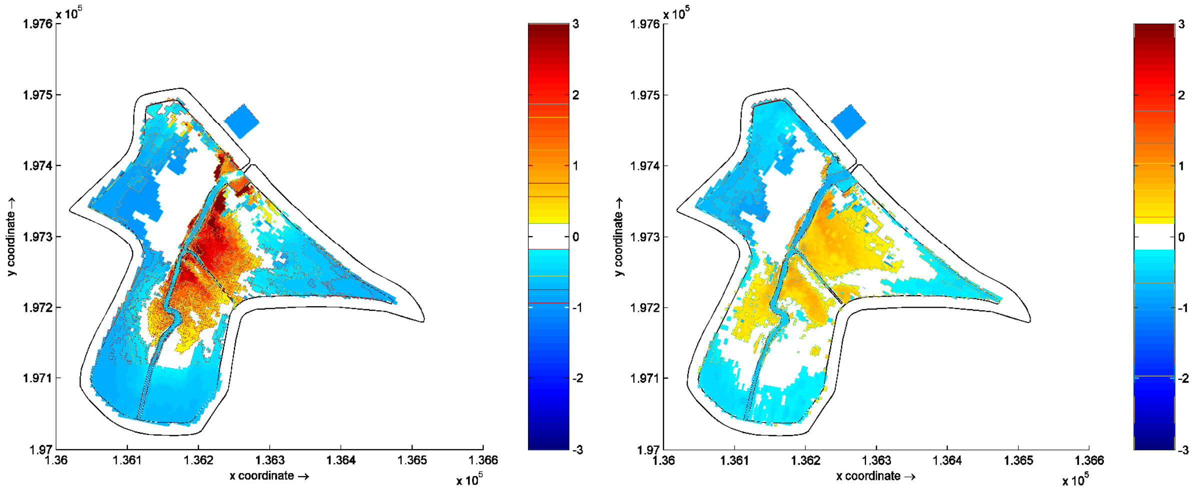

Figure 8: Normalized deposition over normalized maximum water depth. Left: A settling velocity of 0.5 mm/s is used. Right: A settling velocity of 0.1 mm/s is used. Red indicates more sedimentation than can be expected for the local water depth, blue means less sedimentation than can be expected.

Conclusion

A numerical Delft3D model has been developed to examine the sediment transport in the vegetated polder. Vegetation was modeled using the trachytope module based on Baptist (2005). Optimal model parameter settings have been selected and a good representation of the measured water levels and observed inundation pattern was obtained. Sediment samples have been analyzed and characteristics have been determined. From the first set of simulations three important parameters have been indicated that determine sedimentation patterns: proximity to the main creek, vegetation and the particle settling velocity.

As the flow velocities on the tidal flats are generally small, the influence of vegetation on the hydrodynamics is limited. The model showed the importance of finding a good representation of the settling velocity and indicated the effect of vegetation on the settlement of the larger particle sizes. As these larger particles represent a smaller fraction, vegetation as such has a limited effect on the overall sedimentation pattern. Since the settling velocity of the predominantly small particles is small, deposition of these particles largely occurs during the stagnant water phase and is therefore correlated to the local water depth. Sediment analysis indicates that during transportation into the polder due to coagulation of the particles the settling velocity increases. Measurements indicate higher sedimentation rates further up into the polder than would be expected based only on the settling velocity of the coagulated particles alone. Reproduction of the significant sedimentation observed at the back of the polder with the model is therefore only possible if smaller particle sizes and according settling velocities are applied.

The results presented in this paper demonstrate the possibilities for the application of a robust numerical modeling system to assess the morphological evolution of flood control areas with CRT. In addition, a better comprehension of processes and parameters that determine sedimentation in a FCA has been obtained. The knowledge described in this paper will be important for the assessment of other, similar polders that will be converted to flood control areas with CRT. As the model takes into account the various relevant processes that determine sedimentation patterns in the FCA it is believed to assist future maintenance decisions.

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