Simulating the long-term development of levee–basin topography on tidal marshes

Stijn Temmerman\textsuperscript{a,\ast}, Gerard Govers\textsuperscript{a}, Patrick Meire\textsuperscript{b}, Stanislas Wartel\textsuperscript{c}

\textsuperscript{a}Laboratory for Experimental Geomorphology, Katholieke Universiteit Leuven, Redingenstraat 16, B-3000 Leuven, Belgium
\textsuperscript{b}Ecosystem Management Research Group, University of Antwerp, Universiteitsplein 1-c, B-2610 Antwerp, Belgium
\textsuperscript{c}Sedimentology Department, Royal Belgian Institute of Natural Sciences, Vautierstraat 29, B-1000 Brussels, Belgium

Received 1 August 2003; received in revised form 29 March 2004; accepted 30 March 2004
Available online 18 May 2004

Abstract

Although natural levees and lower basins are typical geomorphic features along tidal marsh creeks, long-term sedimentation and elevation changes in tidal marshes were traditionally studied using 0-dimensional point models without considering spatial variations. In this study, the long-term evolution of the surface elevation of tidal marsh levees and adjacent basins was studied by applying a 0-dimensional, time-stepping model (MARSED) using spatially differentiated model parameter values for levees and basins. Firstly, the model was calibrated using field data on short-term (\textless\ 1 year) spatio–temporal variations in sedimentation rates measured along four levee–basin transects within tidal marshes along the Scheldt estuary (SW Netherlands–Belgium). Secondly, the long-term (10–100 years) elevation change of the levees and basins was simulated, starting from a historically known marsh elevation. Predicted elevations were successfully validated against the present-day observed topography along each of the studied levee–basin transects. The model simulations show that the elevation difference between levees and basins tends to an equilibrium. Once levees grow 20 to 30 cm higher than the adjacent basins, the positive influence of the proximity of a tidal creek on the sedimentation rate on the levees is compensated by the negative influence on the sedimentation rate of the higher surface elevation on the levees. Once this sedimentological, geomorphic equilibrium condition is attained, both levees and basins accumulate at the same rate, which is in equilibrium with the rate of mean high water level (MHWL) rise. Finally, additional simulations show that the equilibrium elevation difference between levees and basins is mainly determined by the rate of mean sea-level rise and the incoming sediment concentration. A faster sea-level rise will result not only in a lower equilibrium elevation of the marsh surface relative to MHWL but also in a more pronounced elevation difference between levees and adjacent basins. On the other hand, higher incoming sediment concentrations will result in higher equilibrium elevations. Significantly larger elevation differences between levees and basins are only obtained for increased differences in incoming sediment concentrations between levees and basins. This study demonstrates that the long-term response of tidal marsh surfaces to different scenarios of changing sea-level and incoming sediment concentrations is not uniform in space.
but that spatial variability in tidal marsh morphodynamics is important and that natural levees and inner basins will react in different ways.

© 2004 Elsevier B.V. All rights reserved.

**Keywords:** Salt marsh; Tidal wetlands; Natural levee; Numerical modelling; Sediment accretion; Scheldt estuary

1. **Introduction**

The geomorphology of tidal marshes consists of a rather flat, vegetated surface dissected by a dendritic network of tidal creeks. The apparently flat surface of high, well-developed marshes is typified by a micro-relief of natural levees bordering the tidal creeks and lower inner marsh basins located at larger distances from the creeks. This differentiation between levees and basins gives rise to one of the most important geomorphic gradients, which determine hydrological, biogeochemical and ecological processes in tidal marshes (e.g., Covi and Kneib, 1995; Zedler et al., 1999; Bockelmann et al., 2002; Kostka et al., 2002).

Analogous to the formation of natural levees along alluvial river channels, it is assumed that levees in tidal marshes arise from the progressive settling of suspended sediments during overbank flooding. As the rising tide floods the marsh surface and flows through the marsh vegetation, flow velocities decrease and suspended sediments are settled out, starting from the creek margins into the inner marsh. Over the recent years, various field studies have shown that, at the timescale of individual inundation events, the amount of deposited sediment decreases with increasing distance from stream channels, both in alluvial floodplains (e.g., Walling et al., 1996; Middelkoop and Asselman, 1998) and in tidal marshes (e.g., French et al., 1995; Leonard et al., 1995; Reed et al., 1999; Temmerman et al., 2003a). This lateral sedimentation gradient is also reported by numerical modelling studies of advective and diffusive sediment transport along transects perpendicular to stream channels of alluvial rivers (James, 1985; Pizzuto, 1987) and perpendicular to tidal creeks in tidal marshes (Woolnough et al., 1995).

Traditionally, the long-term evolution of tidal marsh surfaces has been studied using point data (e.g., Cundy and Croudace, 1996; Roman et al., 1997) and 0-dimensional time-stepping models, simulating vertical marsh accumulation with time at one point in space (i.e., no horizontal spatial dimension but only a time dimension) (Krone, 1987; Allen, 1990, 1995, 1997; French and Spencer, 1993; Day et al., 1999; Van Wijnen and Bakker, 2001; Pont et al., 2002; Rybczyk and Cahoon, 2002; Temmerman et al., 2003b). These point approaches can be used to investigate the overall response of tidal marshes to changing factors, such as changing sea-level rise and changes in incoming sediment concentration (e.g., Allen, 1990; French and Spencer, 1993; Temmerman et al., 2003b), but they do not address the effect of spatial variations in sedimentation rates on the development of geomorphic gradients within marshes. As a consequence, our understanding of the long-term development of natural levees and of the factors controlling the height difference between levees and adjacent basins remains rudimentary.

This paper aims to provide insight to the long-term evolution of the surface elevation of tidal marsh levees and basins by applying a 0-dimensional, time-stepping model (MARSED) using spatially differentiated parameter values for levee and adjacent basin locations. Firstly, the model is calibrated using field data on short-term (biweekly) sedimentation rates measured at the levee and basin locations. Secondly, the ability of the model to predict the long-term (10–100 years) elevation change of levees and inner marsh basins is evaluated by comparing predicted elevations with the present-day observed elevations of the levee and basin locations. Finally, additional model simulations are carried out to determine the dominant factors that control the height difference between tidal marsh levees and basins and to simulate the long-term response of levees and basins to different scenarios of changing sea-level and incoming sediment concentrations.

2. **Study area**

The model was applied to four levee–basin transects within the tidal marshes of the Scheldt
estuary, situated in the southwest of the Netherlands and the northwest of Belgium (Fig. 1). The tidal regime in the Scheldt estuary is semidiurnal, meso- to macrotidal, with mean tidal range at the mouth ranging between 4.46 and 2.97 m during spring and neap tides, respectively. Farther upstream, these mean tidal ranges increase to 5.93 and 4.49 m at Schelle, and then decrease further inland to 2.24 and 1.84 m near Ghent (Claessens and Meyvis, 1994).

The suspended sediment concentration (SSC) in the upper part of the water column, which floods the tidal marshes, varies along the Scheldt estuary from 30–60 mg l\(^{-1}\) between the mouth and the Dutch–Belgian border, up to 100–200 mg l\(^{-1}\) between the border and Temse. Farther upstream, the SSC again decreases to 50–100 mg l\(^{-1}\) (Wartel, 1977; Van Eck et al., 1991; Van Damme et al., 2001). In addition, SSC in the Scheldt estuary typically varies over semidiurnal, spring–neap and seasonal timescales (Fettweis et al., 1998).

The tidal marshes, which border the stream channel of the Scheldt estuary, can be classified into salt, brackish and freshwater tidal marshes, according to the salinity gradient that exists along the estuary (Fig. 1). For this modelling study, field data were used from four levee–basin transects located within these three types of tidal marshes. All transects were established in high marshes with a well-developed levee–basin geomorphology, perpendicular to a similar first order marsh creek (with depth = 1.5–2 m and width = 5–8 m). One transect was established in the salt Paulina marsh, near the mouth of the estuary (Fig. 1), within typical halophytic vegetation of NW European high salt marshes (Fig. 2). A second transect was located within the brackish marsh vegetation of the Kruispolder marsh (Fig. 2), situated in the middle estuary (Fig. 1). Finally, in the freshwater Notelaar marsh, situated in the inner estuary (Fig. 1), two transects were established in two contrasting vegetation types that dominate the freshwater tidal marshes, *Phragmites australis* and *Salix* (Fig. 2). The vegetation, geomorphological and sedimentological characteristics of the four transects are presented in Fig. 2.
Fig. 2. Description of the four levee–basin transects used in this study: (A) the salt Paulina marsh, (B) the brackish Kruispolder marsh, (C) the freshwater Notelaar *Phragmites* marsh, (D) the freshwater Notelaar *Salix* marsh. For each transect, the following field data are presented (from bottom to top in each panel): (1) topographic cross-section with location and numbering of the measuring sites; (2) Whisker boxplots of biweekly sedimentation rates (in g m$^{-2}$) with indication of the number of measurements for each measuring site; (3) solid bars (mean) and error bars (standard deviation) of six measurements of sedimentation rates (in mm a$^{-1}$) above feldspar marker horizons; (4) dry bulk density (DBD; in g cm$^{-3}$), clay (< 2 μm), silt (2 – 63 μm) and sand (>63 μm) content (in %) of surface sediment; for DBD: solid bars indicate the mean and error bars the standard deviation of measurements on three replicate samples on each measuring site; (5) dominant plant species: Ely: *Elymus athericus*; Pucc: *Puccinellia maritima*; Atr: *Atriplex portulacoides*; Sci: *Scirpus maritimus*; Imp: *Impatiens glandulifera*; Phr: *P. australis*; Sal: *Salix* sp.
3. Methods

3.1. The numerical model

Temmerman et al. (2003b) proposed a 0-dimensional, time-stepping marsh sedimentation model (further called MARSED), in which the rate of elevation change $dE/dt$ (m a$^{-1}$) at a certain point of the marsh surface is simulated as:

$$dE/dt = dS_{\text{min}}/dt + dS_{\text{org}}/dt - dP/dt$$

(1)

where $dS_{\text{min}}/dt$ is the rate of mineral sediment deposition, $dS_{\text{org}}/dt$ the rate of organic sediment deposition, and $dP/dt$ is the rate of compaction of the deposited sediment, after dewatering, under younger sediment load. All terms are in m a$^{-1}$. As discussed in Temmerman et al. (2003b) and similar model studies of Allen (1990) and French (1993), $dS_{\text{org}}/dt$ can be considered as constant and $dP/dt$ as negligible in tidal marshes that are dominated by mineral sediment deposition. Therefore, $dP/dt$ is set here to zero.

The mineral sediment deposition term $dS_{\text{min}}/dt$ is further specified as:

$$dS_{\text{min}}/dt = \sum_{\text{year}} \int_{T} \frac{w_{s}C(t)dt}{\rho}$$

(2)

where $w_{s}$ is the settling velocity (in m s$^{-1}$), $C$ the depth-averaged concentration (in g l$^{-1}$ or kg m$^{-3}$) of the suspended sediment above the marsh surface, and $\rho$ the dry bulk density (in kg m$^{-3}$) of the deposited sediment, after dewatering over spring–neap and seasonal timescales. Eq. (2) is used to calculate the sedimentation rate $dS_{\text{min}}/dt$ over the total duration $T$ of a tidal inundation cycle and then over all inundation cycles during a year.

The temporal variation in suspended sediment concentration $C(t)$ during a tidal inundation cycle is further modelled using the following mass balance equation:

$$\frac{d[h(t) - E]C(t)}{dt} = -w_{s}C(t) + C(0) \frac{dh}{dt}$$

(3)

This equation describes the change in suspended sediment mass during a tidal inundation cycle with a time-varying water surface elevation $h(t)$ above a unit area of marsh surface with elevation $E$ (first term), as the result of the vertical settling of suspended sediment (second term) and lateral flux of water with a suspended sediment concentration $C(0)$ (third term). Both $h(t)$ and $E$ are expressed in m relative to a fixed datum. $C(0)$ will have a specific value during flood tide (when $dh/dt>0$), while during ebb tide (when $dh/dt<0$) $C(0)$ is set to equal $C(t)$.

Temmerman et al. (2003b) empirically found that the incoming sediment concentration $C(0)$ during flood tide can be written as a positive linear function of inundation height at high tide:

$$C(0) = k[h(t_{\text{HW}}) - E]$$

(4)

where $k$ is an empirical constant and $h(t_{\text{HW}})$ is the water level at high tide (relative to the fixed datum).

Eq. (4) can be explained as follows: as the marsh is inundated by higher tides, the flooding water has a higher capacity to transport suspended sediments, so that $C(0)$ is higher. Temmerman et al. (2003b) showed that the incorporation of this relationship is crucial to obtain good model results.

The MARSED model was programmed in Matlab, solving Eqs. (2) and (3) in time steps of 300 s and Eq. (1) in time steps of 1 year.

3.2. Model calibration

Along the four levee–basin transects that were used in this modelling study, biweekly measurements of sedimentation rates were carried out during a 1-year period using plastic sediment traps, which were placed on the marsh surface and replaced every 2 weeks (at neap tide after each spring–neap cycle; see Temmerman et al., 2003a). For each transect, measurements were carried out on the natural levee, at a distance of 2 m from the creek edge, and in the adjacent basin, 20 and 40 m from the creek edge (Fig. 2). This dataset, which was originally published and analysed in Temmerman et al. (2003a), is used here for calibration of the model. For all model parameters, representative input values could be derived from the field data, except for the parameters $k$ and $w_{s}$, for which suitable values were obtained by model calibration (see below).

For the model parameter $[h(t_{\text{HW}}) - E]$ [Eq. (4)] data on inundation height were measured automatically...
with an ISCO flowmeter for every inundation cycle during the 1-year measuring period and at each measuring transect. The function \( h(t) \) [Eq. (3)], describing the temporal variation of the water level within one tidal inundation cycle, was modelled using the average tidal curve for the nearest tide-gauge station (Fig. 3a). For tidal inundation cycles with different inundation heights \( [h(t_{HW}) - E] \), \( h(t) \) was simulated by shifting up or down this average tidal curve.

The model parameters \( k \) [Eq. (4)], describing the relationship between incoming sediment concentration \( C(0) \) and inundation height at high tide \( [h(t_{HW}) - E] \), and the settling velocity \( w_s \) [Eqs. (2) and (3)] of the suspended sediment, were derived directly from suspended sediment concentration measurements at basin site 3 on the salt marsh and basin site 8 on the freshwater marsh (Temmerman et al., 2003a,b). For both locations, a value for \( k \) was determined empirically by linear regression between incoming suspended sediment concentrations \( C(0) \), measured above the marsh surface at the beginning of a large series of inundation events, and the inundation heights \( [h(t_{HW}) - E] \), measured during these events (Temmerman et al., 2003a). Because \( C(0) \) values were found to be significantly higher during the winter (October–March) than during the summer period (April–September) for a same inundation height (see Temmerman et al., 2003a), higher \( k \) values were determined for the winter than for the summer (Table 1). The settling velocity \( w_s \) was calculated from the decrease in suspended sediment concentrations during a large series of inundation events and was estimated to be \( 10^{-4} \text{ m s}^{-1} \) (Temmerman et al., 2003b).

However, for all levee and basin sites other than sites 3 and 8, no such detailed data on suspended sediment concentrations were available to determine empirical values for \( k \) and \( w_s \). Only biweekly sedimentation rates were measured. For each levee and basin site, \( k \) and \( w_s \) were calibrated using these datasets of biweekly sedimentation rates. For all basin sites, significantly higher sedimentation rates were measured during winter than summer; therefore, calibration was done separately for the winter and summer dataset. For the levee sites, no significant difference between winter and summer datasets was observed (Temmerman et al., 2003a), and therefore, one calibration dataset was used, containing all sedimentation rates measured during the 1-year period.

For each levee or basin dataset, sedimentation rates \( \text{in g m}^{-2} \) were calculated with the model for each biweekly spring–neap cycle by solving Eqs. (2), (3) and (4) in time steps of 300 s for each inundation event.

Fig. 3. (a) Mean tidal curves for the period 1981–1990, used as input for the model parameter \( h(t) \) (see text), at the tide-gauge station of Terneuzen (used for sites 1 to 3 at the Paulina marsh), Bath (used for sites 4 and 5 at the Kruspoiler marsh) and Temse (used for sites 6 to 11 at the Notelaar marsh). For the location of tide-gauge stations and marshes, see Fig. 1. (b) Observed (dots) and modelled (line) high water frequency distribution at Antwerp for the period 1981–1990 with indication of the regression equation and \( R^2 \) and \( p \)-values. All tidal data are after Claessens and Meyvis (1994).
event during the spring–neap cycle. Next, the total sedimentation rate was summed over all inundations that occurred during that spring–neap cycle. Sedimentation rates were calculated using \( k \) values ranging from 0.025 to 1.5 in steps of 0.025 and \( w_s \) values ranging from 1 to 10 \( \times 10^{-4} \) m s\(^{-1} \) in steps of \( 1 \times 10^{-4} \) m s\(^{-1} \). For each combination of \( k \) and \( w_s \), the calculated sedimentation rates were compared with the measured rates. The model efficiency coefficient (ME), as proposed by Nash and Sutcliffe (1970), was used as a measure of likelihood:

\[
ME = 1 - \frac{\sum (Y_{\text{obs}} - Y_{\text{pred}})^2}{\sum (Y_{\text{obs}} - Y_{\text{mean}})^2} \tag{5}
\]

where \( Y_{\text{obs}} \) is the observed sedimentation rate, \( Y_{\text{pred}} \) is the predicted sedimentation rate, and \( Y_{\text{mean}} \) is the mean of the observed sedimentation rate dataset. Values for ME range from \(-\infty\) to 1. The closer ME approximates 1, the better the model predicts individual sedimentation rates.

The calibrated values for \( k \) and \( w_s \) were compared with the values that were obtained independently from the suspended sediment concentration measurements at sites 3 and 8. In addition, the \( w_s \) values were compared with values calculated using Stokes’ formula:

\[
w_s = \frac{gd^2(\rho_s - \rho_w)}{18\mu} \tag{6}
\]

where \( g \) is the gravity acceleration (\( = 9.81 \) m s\(^{-2} \)), \( d \) is the median particle diameter of the surface sediment (m), \( \rho_s \) is the particle density (a value of 2650 kg m\(^{-3} \) is used), \( \rho_w \) is the density of the water (a value of 1000 kg m\(^{-3} \) is used), and \( \mu \) is the viscosity of the water (a value of 0.000891 N s m\(^{-2} \) at 298 K is used). Grain size analyses were carried out on surface sediments, which were sampled with metal rings (0.05 m in diameter and height), using the standard sieve–pipette method after pretreatment with \( \text{H}_2\text{O}_2 \), HCl and \( \text{Na}_2\text{C}_2\text{O}_4 \).

### 3.3. Model implementation

After calibration, the model was used to simulate the long-term vertical rise of the marsh surface at the selected levee and basin locations starting from a
historical marsh surface elevation $E(0)$ in a certain year $T(0)$. For sites 8 and 11 on the Notelaar marsh, historical marsh surface elevations were determined by dating of sediment cores, as presented in Temmerman et al. (2003b). Based on these field data, representative $E(0)$ and $T(0)$ values were chosen for sites 8 and 11 (see Table 2). For the adjacent levee locations along these two transects, no such detailed data on historical marsh surface elevations are available. For simplicity, the simulation is started from a planar marsh surface, taking the same $E(0)$ and $T(0)$ values along the whole transect (Table 2). This allows investigation of whether the simulation model can predict the formation of levees and basins starting from a planar marsh surface, and if the model is able to reproduce the present-day levee–basin topography. The present-day topography was surveyed along each transect relative to Belgian Ordnance Level (TAW) using an electronic total station (Sokkia SET5F; Fig. 2). For the transects on the Paulina and Kruispolder marsh, a similar methodology was used, starting the simulation from a planar marsh surface with an elevation $E(0)$ in year $T(0)$. For these marshes, historical data on $E(0)$ and $T(0)$ are available from old topographic surveys that were carried out by the Meetkundige Dienst of Rijkswaterstaat, with a vertical accuracy of 0.1 m. The $E(0)$ and $T(0)$ values, as well as the input values for all other model parameters that were used for the implementation and validation of the model, are listed in Table 2.

Simulated deposition rates were also compared with accumulation rates that were measured over the last 3 years (March 2000–March 2003) on each of the measuring sites using white feldspar marker horizons of 60 by 60 cm. The thickness of sediment deposits above these marker horizons was estimated by the mean and standard deviation of six measurements, carried out after 3 years above each marker horizon using a small corer.

As already mentioned in Section 3.2, the model parameter $h(t)$ was determined from field data, while $k$ and $w_s$ were derived by model calibration (Table 2). The mineral sedimentation rate $dS_{min}/dt$ can then be calculated for any tidal inundation cycle with a high water level $h(t_{11W})$, using Eqs. (2), (3) and (4). However, to calculate $dS_{min}/dt$ over a whole year, we further need to model the frequency with which high water levels $h(t_{11W})$ occur during every year of the simulation period. To do this, we used on the one hand the evolution of yearly mean high water level (MHWL), which was interpolated for each of the studied marsh sites based on the yearly MHWL recorded at the nearest up- and downstream tide-gauge stations: Vlissingen and Terneuzen for the Paulina marsh, Hansweert and Bath for the Kruispolder marsh and Schelle and Temse.

### Table 2
Summary of model parameter values used for model calibration and long-term model application for each of the levee and basin locations

<table>
<thead>
<tr>
<th>Location</th>
<th>Parameters long-term model application</th>
<th>Parameters model calibration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$h(t)$</td>
<td>$h(t_{11W}) - E$ (m TAW)</td>
</tr>
<tr>
<td>1</td>
<td>*</td>
<td>35.1</td>
</tr>
<tr>
<td>3</td>
<td>*</td>
<td>1.0</td>
</tr>
<tr>
<td>4</td>
<td>*</td>
<td>1.0</td>
</tr>
<tr>
<td>5</td>
<td>*</td>
<td>1.5</td>
</tr>
<tr>
<td>6</td>
<td>*</td>
<td>2.0</td>
</tr>
<tr>
<td>8</td>
<td>*</td>
<td>1.0</td>
</tr>
<tr>
<td>9</td>
<td>*</td>
<td>18.4</td>
</tr>
<tr>
<td>11</td>
<td>*</td>
<td>1.5</td>
</tr>
</tbody>
</table>

$dP/dt=0$ for every location.

*—$h(t)$: mean tidal curve at Terneuzen (for locations 1, 3), at Bath (locations 4, 5) and Temse (locations 6, 8, 9, 11) (see also Fig. 3a).

**—$h(t_{11W}) - E$: for model calibration: maximum inundation height measured for each inundation cycle using ISCO equipment; for model application: inundation heights modelled based on the evolution of yearly mean high water level (MHWL) at Paulina marsh (for locations 1, 2, 3), at Kruispolder marsh (locations 5, 6) and Notelaar marsh (locations 6 to 11), and based on the frequency distribution of high water levels around MHWL at Antwerp (see also Fig. 3b; data after Claessens and Meyvis, 1994).
for the Notelaar marsh (see Fig. 1 for locations). On the other hand, the frequency distribution of all high water levels occurring during a year was then modelled based on this yearly MHWL and on the yearly averaged frequency distribution of high water levels around MHWL at Antwerp, which is considered representative for the whole estuary. Fig. 3b shows how this frequency distribution is modelled using a regression model, based on tidal data from Claessens and Meyvis (1994).

The dry bulk density \( \rho \) [Eq. (2)] of the deposited sediment was estimated from three replicate surface sediment samples collected on each measuring site with metal rings (0.05 m in diameter and height). \( \rho \) was rather low in the basins (ca. 300–685 kg m\(^{-3}\)) and up to two times larger on the natural levees (ca. 600–1000 kg m\(^{-3}\); Fig. 2 and Table 2).

Finally, the deposition rate of organic matter \( dS_{\text{org}}/dt \) [in Eq. (1)] is estimated for each measuring location, based on organic matter content of the sediment and recent marsh accumulation rates measured above the marker horizons. The estimated \( dS_{\text{org}}/dt \) values, listed in Table 2, are very small compared to simulated values of \( dS_{\text{min}}/dt \) and will therefore have a negligible influence on the rate of marsh elevation change \( dE/dt \).

4. Results

4.1. Model calibration

The results of the model calibration are presented in Figs. 4 and 5 and Table 1. Fig. 4 shows the model efficiencies (ME) obtained by model simulations using different combinations for \( k \) and \( w_s \) for a typical levee and basin situation. For the parameter \( k \), the calibration curve shows a rather well-defined peak from which an optimal value for \( k \) can be derived. However, for the parameter \( w_s \), no clear peak in the calibration curve can be defined. For a same \( k \) value, different \( w_s \) values ranging from 1 to \( 10^{-4} \text{ m s}^{-1} \) only have a very small influence on ME. This indicates that the model results are not very sensitive to the input value for the settling velocity \( w_s \) of the suspended sediment.

For the basin site 8 at the Notelaar marsh, the average settling velocity \( w_s \) was estimated to be \( 10^{-4} \text{ m s}^{-1} \) based on field measurements (Temmerman et al., 2003b). When using this value for \( w_s \), model calibration results in a very well-defined optimal \( k \) value of 0.025 for the summer dataset and 0.275 for the winter dataset, or a whole-year average value of 0.150 (Fig. 4 and Table 1). These \( k \) values obtained from model calibration using the sedimentation rate dataset compare well with the \( k \) values that were obtained from independent direct field measurements of incoming sediment concentrations on site 8 (Temmerman et al., 2003a): based on regression analysis between the measured incoming sediment concentrations and inundation heights, a \( k \) value of 0.075 was derived for the summer, 0.194 for the winter and 0.1345 for the whole year (Table 1).

Initial model calibrations show that \( w_s \) is not a very sensitive model parameter, and that for all sites, good simulation results can be obtained using a wide range of \( w_s \) values (Fig. 4).
discussed in Discussion below. Thus, although the estimation of \( w_s \) would be a rough approximation, this will not have an important effect on the simulated sedimentation rates. Therefore, \( w_s \) was no longer determined by calibration but a fixed value for \( w_s \) was used and only the parameter \( k \) was calibrated.

For all basin sites, a \( w_s \) value of \( 1.10^{-4} \text{ m s}^{-1} \) was used in the model calibration because the median particle size of the surface sediment is for all basin sites very comparable to the median particle size at site 8, where a \( w_s \) value of \( 1.10^{-4} \text{ m s}^{-1} \) was empirically derived from the detailed sediment concentration measurements. The resulting optimal \( k \) values are listed in Table 1 (column 3). For site 3, the calibrated \( k \) values are in good agreement with the \( k \) values obtained independently from field measurements of incoming sediment concentrations (column 6). For all basin sites, high model efficiencies were found for the winter datasets (ranging from 0.67 to 0.89), while generally much lower ME values are obtained for the summer datasets (column 4). This is probably due to the very low sedimentation rates measured during the summer period, and consequently, the higher relative errors on the sedimentation rate measurements during the summer period. As can be expected, optimal \( k \) values are systematically lower for the summer datasets than for the winter datasets (column 3).

For the levee sites, the median grain size diameter of the surface sediments is generally coarser (Table 1 column 1). Calibration of \( k \), using \( w_s \) values estimated from these median particle sizes using Stokes law, results in optimal \( k \) values which are systematically higher for the levees than for the adjacent basins (column 3). This suggests that the incoming water contains much higher sediment concentrations on the levees than in the basins. The obtained model efficiency values are all very high for the levee sites (0.88 to 0.98; column 4).

### 4.2. Model validation

The MARSED model was applied to simulate the long-term vertical rise of the marsh surface along each of the levee–basin transects during the last decades using the input parameter values listed in Table 2. Because sedimentation rates were calculated on a yearly basis in this long-term simulation, a single \( k \) value was used, which was calculated for the basin sites as the average of the winter and summer \( k \) values obtained by calibration (Tables 1 and 2).

Fig. 5 shows that the present-day observed levee–basin topography is very well predicted by the model for each of the four studied transects. Although we supposed a planar marsh surface for each transect at the beginning of the simulation period, the model correctly predicts that after 10–50 years natural levees are formed, which raise up to an elevation of 0.2 to 0.3 m above the adjacent inner marsh basins. Once this elevation difference is attained, the levees and basins accrete at a similar rate, in equilibrium with the rate of mean high water level rise (Fig. 5). Thus, the model simulations show that the originally flat marsh surface evolves within a period of only a few decades to a sedimentological, geomorphological equilibrium condition with levees, next to tidal creeks, which are 0.2 to 0.3 m higher than the inner marshes some 20 to 40 m away from the tidal creeks. This is in agreement with field observations (Fig. 5): even for transect 6–7–8, which was established on a young marsh surface that originated around 1950 from a bare mud flat, the present-day morphology is characterised by a well-developed levee–basin morphology.

Starting from a flat marsh surface, the model simulates that the incoming sediment concentration \( C(0) \) is higher on the levees than in the inner basins, as \( k \) values are much higher for levee sites (Table 2). As a consequence, the predicted sedimentation rates \( dS_{\text{min}}/dt \) and rates of elevation change \( dE/dt \) are higher on the levees than in the basins (Fig. 5). This is in agreement with the widely reported finding that sedimentation rates in tidal marshes decrease with increasing distance from tidal creeks, as a result of progressive sediment trapping (e.g., French et al., 1995; Leonard et al., 1995; Reed et al., 1999; Temmerman et al., 2003a). However, after a period of time, the levees become higher than the basins so that the frequency and height of tidal inundations become considerably lower on the levees than in the basins. Because the incoming sediment concentration \( C(0) \) is related to inundation height [see Eq. (4)], the \( C(0) \) values that are simulated on the levees will decrease, which results in reduced rates of sedimentation and elevation change (Fig. 5). Thus, the positive influence of the proximity of the tidal creek on the sedimentation rate on the levee is progressively compensated by
Fig. 5. Comparison of observed (in dots) and predicted (in thick lines) long-term change of marsh surface elevation (in m TAW) with time (graphs at the top of each panel) and change in sedimentation rate (in kg m\(^{-2}\) a\(^{-1}\)) with time (graphs at the foot of each panel) on the levees (thick solid lines) and in the adjacent basins (thick broken lines) for each of the four studied transects: (A) Paulina marsh, (B) Kruispolder marsh, (C) Notelaar \textit{Phragmites} marsh, (D) Notelaar \textit{Salix} marsh. In the graphs at the top of each panel, the evolution of local mean high water level (MHWL) is plotted in thin solid lines.
the negative influence of the higher surface elevation on the sedimentation rate. Both effects will compensate each other once an equilibrium in the elevation difference between levees and adjacent basins is attained. From that moment, both levees and basins will accumulate at a similar rate. This mechanism would only work if inner marsh basins are submerged also by relatively low tides that do not overtop the higher natural levees. This is indeed typical for tidal marshes, where small shallow creeks that break through the natural levees, bordering the larger creeks, penetrate into the inner basins and supply water and suspended sediments even during relatively low tides that do not or only slightly overtop the higher levees.

The model simulations suggest that, for all studied transects, the geomorphic equilibrium condition, with levees that are 0.2 to 0.3 m higher than the basins, is met at present. However, the present-day short-term sedimentation rates (in g m⁻²/spring–neap cycle) that were measured along these transects are still up to two times larger on the levees than in the basins (Fig. 2). This is due to the difference in dry bulk density of the deposited sediments, which is up to two times larger on the levees than in the basins (Fig. 2). On its turn, this difference in bulk density can be explained by the higher sand content of the deposited sediments on the levees (Fig. 2), and the better drainage and consolidation of the surface sediments during low tides on the levees because of the proximity of a tidal creek, while on the contrary, basins are rather enclosed and farther away from creeks, through which subsurface drainage and consolidation is much less. As a consequence, the volumetric accumulation rates (in m a⁻¹), which were measured over a 3-year period above the feldspar marker horizons, are comparable on the levees and in the basins (Fig. 2). This is in agreement with the model simulations, which show that present-day simulated sedimentation rates dSₘᵦᵢₙ/dt (in kg m⁻² a⁻¹) are indeed up to two times larger for levee than for basin sites, while the present-day simulated rates of elevation change dE/dt are comparable for levees and basins (Fig. 5).

4.3. Factors influencing the long-term evolution of levees and basins

Model simulations of the vertical rise of a marsh surface, starting from different surface elevations E(0), show that a marsh surface always tend to an equilibrium level E(eq) relative to the mean high water level (MHWL), which is only marginally affected by the assumed initial marsh elevation E(0) (Fig. 6). Below, we will further investigate how the different model parameters influence the precise elevation of this equilibrium level E(eq), the time T(eq) (in years) necessary to reach E(eq) and especially the difference in equilibrium level ΔE(eq) between levees and adjacent basins. In our simulations, the following criterion is used to define that an equilibrium elevation E(eq) is reached in the year T(eq), which is the first year since the beginning of the simulation period for which:

\[(E - \text{MHWL})_{T(eq)} - (E - \text{MHWL})_{T(eq-1)} < 0.0002 \text{ m a}^{-1}\]  \hspace{1cm} (7)

where \((E - \text{MHWL})_{T(eq)}\) is the difference between the marsh surface elevation E and MHWL in the year T(eq), and \((E - \text{MHWL})_{T(eq-1)}\) the difference between E and MHWL in the previous year T(eq - 1).

On the one hand, E(eq) is strongly dependent on the rate of MHWL rise (Fig. 7): the higher the rate of MHWL rise, the lower E(eq) will be but also the faster this equilibrium elevation will be reached. On the other hand, E(eq) is strongly dependent on the rate of MHWL rise (Fig. 7): the higher the rate of MHWL rise, the lower E(eq) will be but also the faster this equilibrium elevation will be reached.
hand, the incoming sediment concentration \(C(0)\) also has a considerable influence. This is simulated by using different values for the model parameter \(k\) in Eq. (4), describing the relationship between incoming sediment concentration \(C(0)\) and inundation height at high tide \([h(t_{HW}) - E]\). Model simulations using higher \(k\) values result in higher equilibrium elevations \(E_{eq}\) and show that this equilibrium elevation is obtained faster (Fig. 7). The influence of the settling velocity \(w_s\) and dry bulk density \(\rho\) is rather low compared to the influence of MHWL rise and \(k\). Changing the input value for \(w_s\) or \(\rho\) by a factor 2 or 3 causes a change in \(E_{eq}\) of only a few centimetres.

Thus, MHWL rise and incoming sediment concentration are the dominant parameters influencing the equilibrium elevation of marshes. However, changes in these parameters result in changes in equilibrium elevation that are different for levees and basins. Fig. 8a shows that the difference in equilibrium elevation \(\Delta E_{eq}\) between a levee and an adjacent basin increases with an increasing rate of MHWL rise. A rising MHWL will result in more frequent marsh inundations with higher inundation heights, and therefore in higher incoming sediment concentrations \(C(0)\) [see Eq. (4)] and higher sedimentation rates \(dS_{min}/dt\) [Eq. (2)]. However, because \(k\) values are higher for levees than for basins, the difference in \(C(0)\) and \(dS_{min}/dt\) between levees and basins will increase as the height of marsh inundations increases. As a result, \(\Delta E_{eq}\) increases when MHWL rises faster. Under a scenario of descending MHWL, the elevation difference between levees and basins decreases after a period of time (Fig. 8a).

The incoming sediment concentration will also have an effect on the difference in equilibrium elevation \(\Delta E_{eq}\) between levees and adjacent basins. On the one hand, higher incoming sediment concentrations, which are simulated by multiplying the parameter \(k\) with the same factor for both the levee and basin (Fig. 8b), result in a much faster achievement of an equilibrium in \(\Delta E_{eq}\) between levees and basins. However, changing the input \(k\) values for the levee and basin by a factor 2 results in a lowering of \(\Delta E_{eq}\) of only a few centimetres (Fig. 8b). On the other hand, if the ratio \(k_{levee}/k_{basin}\) (the \(k\) value used for the levee and for the basin, respectively) increases, the difference in equilibrium elevation \(\Delta E_{eq}\) between levees and basins increases considerably.

5. Discussion

Despite the fact that the geomorphology of high old marsh surfaces is characterised by levees and
basins connected to the dendritic network of tidal marsh creeks, detailed studies about the formation and long-term evolution of this levee–basin geomorphology are very sparse. It is assumed that levees are the long-term result of the decrease in sedimentation rates with increasing distance from tidal creeks, as observed over short-term time-intervals (e.g., French and Spencer, 1993; Leonard et al., 1995; Reed et al., 1999; Temmerman et al., 2003a). However, if this were the only mechanism, levees would continuously grow higher above the adjacent basins.

This modelling study showed that levees will not grow higher than a certain equilibrium elevation relative to mean high water level. If levees were to grow higher, a second mechanism that controls marsh accumulation would begin to dominate: sedimentation rates would decrease with increasing marsh elevation because of decreasing inundation frequencies and heights (e.g., Stoddart et al., 1989; French and Spencer, 1993; Cahoon and Reed, 1995; Temmerman et al., 2003a), and therefore, after some time, the higher levees will receive less sediment than the lower inner basins. These two mechanisms (the influence of distance to creeks and the influence of surface elevation) are just in balance when an equilibrium in the elevation difference between levees and basins is reached. The model simulations suggest that from then on both levees and basins accumulate at the same rate.

For the studied marshes in the Scheldt estuary, the equilibrium condition is reached once the levees accumulated up to 0.2–0.3 m above the adjacent basins. Maximum elevation differences between levees and adjacent basins, reported from other tidal marshes in the world, are generally also in the order of 0.3–0.4 m (e.g., Redfield, 1972; Christiansen et al., 2000), suggesting that the existence of an equilibrium condition between levees and basins, and the model structure presented here to simulate this equilibrium

![Fig. 8. Model simulations showing the elevation difference $\Delta E$ between a levee and adjacent basin as a function of time $T$. The thick curves in each of the three graphs represent model results that are representative for the Paulina marsh, for which $h(t) =$ mean tidal curve at Terneuzen; mean high water level (MHWL) rise $= 4 \text{ mm a}^{-1}$; $k = 0.2$ for the levee and $k = 0.0575$ for the basin; $w_{\text{in}} = 0.0005 \text{ m s}^{-1}$ for the levee and $w_{\text{in}} = 0.0001 \text{ m s}^{-1}$ for the basin; $\rho = 1000 \text{ kg m}^{-3}$ for the levee and $\rho = 650 \text{ kg m}^{-3}$ for the basin; $dS_{\text{org}}/dt = 0.2 \text{ mm a}^{-1}$ for the levee and $dS_{\text{org}}/dt = 0.4 \text{ mm a}^{-1}$ for the basin. For all other simulations, the same parameter values were used, except for MHWL rise and $k$. Graph (a) shows how $\Delta E$ is influenced by different scenarios of MHWL change, while graphs (b) and (c) show the influence of different incoming sediment concentrations. The latter is simulated in graph (b) by multiplying the $k$ values mentioned above with a factor 0.5, 1, 2 and 4 for both the levee and basin and in graph (c) using different values for the ratio between $k$ on the levee and $k$ in the basin ($k_{\text{levee}}/k_{\text{basin}}$).]
condition generally apply to tidal marshes. Our model simulations indicate that larger height differences between levees and basins would require higher rates of sea-level rise (or MHWL rise) and/or higher ratios between incoming sediment concentrations (or $k$ values) on levees and in basins (Fig. 8).

In accordance with our data, several field studies indicated that incoming (initial) sediment concentrations are higher above levees than above basins during tidal inundation (e.g., Christiansen et al., 2000; Leonard et al., 1995; Leonard and Luther, 1995; Leonard et al., 2002). This can be explained as a consequence of overbank sedimentation, by which suspended sediment is progressively settled out during the transport partway of the water starting from the tidal creeks over the levees into the basins. On the other hand, the sediment grain size is also coarser on the levees than in the basins (Table 1). This can be explained by the same process of overbank sedimentation, by which the coarsest sediment is first deposited on the levees and finer sediments remain to be deposited in the basins.

It can now be questioned whether the higher sedimentation rates on the levees than in the basins are due to (1) the higher suspended sediment concentrations on the levees or (2) the coarser grain size, and thus higher settling velocities on the levees. The relative importance of both factors is demonstrated by the model. A small change in the model input for incoming sediment concentrations has a big influence on the simulated sedimentation rates, while changing the settling velocity by a factor 10 has almost no influence on the simulated sedimentation rates (Fig. 4). This can be explained as follows: both on the levees and in the basins, almost all of the suspended sediment has enough time to settle out from the water column. This is for example demonstrated in Temmerman et al. (2003a), where field measurements showed that suspended sediment concentrations decrease during a tidal inundation cycle to only a small fraction ($<10\%$) of the incoming sediment concentration. As a consequence, the sediment accumulation rate is most strongly determined by the incoming sediment concentration, rather than by the settling velocity of the suspended sediment. However, we note that the reason why sediment concentrations are higher above the levees than above the basins is probably related to grain size: the coarsest suspended sediment is first deposited on the levees so that less sediment (only the finer fractions) remains in suspension and reaches the basins. In this sense, we may say that sediment grain size does play a role in the formation of levees and basins.

In former numerical modelling studies, the long-term response of tidal marshes to different scenarios of sea-level rise and/or incoming sediment concentrations were studied based on a 0-dimensional time-stepping point approach, without considering spatial variations within marshes (e.g., Krone, 1987; Allen, 1990; French, 1993; Van Wijnen and Bakker, 2001; Rybczyk and Cahooon, 2002; Temmerman et al., 2003a,b). However, this model study demonstrates that the response of marsh surfaces cannot be considered to be uniform in space, but that, at short distances, levees and basins will react in a different way. The incorporation of this spatial variability in sediment accretion within tidal marshes will be of great importance when evaluating changes in tidal marsh dynamics, including vegetation patterns and other ecological processes, in response to changing sea-level and incoming sediment concentrations. In this regard, it is important to extend 0-dimensional approaches to two-dimensional (2D) spatially distributed models that are able to simulate the long-term evolution of 2D marsh topographies under changing sea-level and incoming sediment concentrations.

### 6. Conclusions

1. A 0-dimensional, time-stepping model (MARSED) was successfully calibrated and validated to simulate the long-term elevation changes of levees and adjacent basins sites in the Scheldt estuary.

2. The model results show that the elevation difference between levees and basins tend to a geomorphic equilibrium. For the studied marshes in the Scheldt estuary, this equilibrium is obtained within 10–50 years when the elevation difference between levees and adjacent basins is $0.2–0.3$ m. The model suggests that, from then on, the levees and basins rise at a similar rate, in equilibrium with the rate of mean high water level (MHWL) rise.
Model simulations demonstrate that the equilibrium in elevation difference between levees and basins is dependent on the rate of MHWL rise and on incoming sediment concentration. A faster MHWL rise results in more pronounced elevation differences between levees and basins. Higher incoming sediment concentrations, when simulated by multiplying them by a factor 2 to 4, both for levees and basins, have a negligible effect on the equilibrium in elevation difference between levees and basins. Significantly larger elevation differences between levees and basins are only obtained when larger differences in incoming sediment concentrations between levees and basins are used. This study demonstrates that the long-term response of tidal marsh surfaces to different scenarios of changing sea-level and incoming sediment concentrations is not uniform in space, but that natural levees and inner basins will react in different ways.

Acknowledgements

This research is funded by the Institute for the Promotion of Innovation by Science and Technology in Flanders (IWT) whose support is gratefully acknowledged. We also thank our colleagues, especially G. Verstraeten and J. Meersmans, who assisted collecting the necessary field data. Finally, we are grateful to the referees, Dr. B.O. Bauer and Dr. A.J. Plater, for their constructive comments on the manuscript.

References


