ELSEVIER

Marine Geology 212 (2004) 1–19

MARINE GEOLOGY
INTERNATIONAL JOURNAL OF MARINE GEOLOGY, GEOCHEMISTRY AND GEOPHYSICS

www.elsevier.com/locate/margeo

Modelling estuarine variations in tidal marsh sedimentation: response to changing sea level and suspended sediment concentrations

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Received 12 February 2004; received in revised form 3 August 2004; accepted 1 October 2004

Abstract

This study presents the validation of a zero-dimensional time-stepping physically based model (MARSED) to simulate the varying rates of long-term (10–100 years) tidal marsh accumulation within an estuary. First, field data on long-term tidal marsh accumulation were collected for 25 marsh sites scattered along the Scheldt estuary (NW Europe), based on old topographic data and radiometric and paleoenvironmental dating of sediment cores. The field data showed that estuarine marshes accumulate at highly varying rates depending on (1) the age of the marsh, (2) estuarine variations in mean high water-level (MHWL) rise, and (3) variations in suspended sediment concentrations (SSCs). As a general mechanism, young low marsh surfaces accumulate quickly and asymptotically up to an equilibrium level around MHWL. After this, high old marshes accumulate much slower at rates that are comparable to local MHWL rise. Furthermore, marsh accumulation rates are higher in the inner part than in the outer part of the estuary. This difference can be attributed to the faster MHWL rise and higher SSC values in the inner estuary. Second, the MARSED model was validated against the field data. The model was able to simulate the observed variations in marsh accumulation rates with good accuracy. Furthermore, the model allows to quantify the combined effect of sea-level change and SSC on variations in accumulation rates: they showed that tidal marshes can maintain their equilibrium elevation around MHWL, only if incoming SSC is high enough. Finally, the model allows to predict marsh accumulation rates in response to changing environmental conditions. Simulations for the next 100 years suggest that the tidal marshes in the Scheldt estuary will be able to keep up with the rising MHWL, unless MHWL rise would increase and SSC would decrease importantly.

Keywords: salt marshes; sediment accretion; morphodynamics; sea-level rise; environmental change; Schelde estuary

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0025-3227/$ - see front matter
doi:10.1016/j.margeo.2004.10.021

1. Introduction

Situated at the edge between land and sea, tidal marsh ecosystems are very sensitive to environmental changes, such as sea level rise (e.g., Adam, 2002). The balance between sediment accumulation in tidal marshes and sea level rise ultimately determines whether tidal marshes will survive or will be increasingly flooded and degrade to bare tidal flats or open water. Many studies have been dedicated to the quantification of long-term ($10–10^2$ years) sediment accumulation rates in comparison with local rates of sea-level rise (e.g., Cundy and Croudace, 1996; Dijkema et al., 1990; Orson et al., 1998; Reed, 1995; Roman et al., 1997; Stevenson et al., 1986; Van Wijnen and Bakker, 2001). A wide range of accumulation rates were reported, varying from less than 1 to several tens of mm a^{-1}, resulting in survival in some marsh systems and submergence in others. However, explanations for these varying accumulation rates and different responses to rising sea level are often unclear.

Recently, an increasing number of numerical modelling studies appeared, which aimed to identify and simulate the main processes of marsh elevation change in response to changing sea level (Allen, 1990, 1995, 1997; Callaway et al., 1996; Chmura et al., 1992; Day et al., 1999; French, 1993; Krone, 1987; Morris et al., 2002; Pont et al., 2002; Rybczyk and Cahoon, 2002; Rybczyk et al., 1998; Temmerman et al., 2003a; Van Wijnen and Bakker, 2001). However, as stated by Allen (2000), these models are at a rather rudimentary stage of development. They are all zero-dimensional models, simulating vertical marsh accumulation with time at one point in space. The change in marsh surface elevation is described as the result of above- and belowground processes. Aboveground processes are the deposition of mineral inorganic sediment and of organic matter, while belowground processes include sediment compaction under younger sediment load, root biomass production, and decomposition of organic matter and deep subsidence (Callaway et al., 1996).

The existing models can be grouped into two approaches. A first group of models is empirically based. In these models, mineral sediment deposition is modelled either as a constant time-independent term (Chmura et al., 1992) or as an empirical negative linear function of marsh elevation relative to mean sea level (Callaway et al., 1996; Day et al., 1999; Morris et al., 2002; Pont et al., 2002; Rybczyk and Cahoon, 2002; Rybczyk et al., 1998). The latter is equivalent to the modelling of sediment deposition as a positive linear function of inundation frequency (Van Wijnen and Bakker, 2001). The relationship between sediment deposition and elevation/inundation frequency is then calibrated using field data on sediment deposition rates. As a consequence, empirical model approaches are not suitable to simulate the impact of changes in suspended sediment characteristics, such as changes in the sediment concentration in the water that floods the tidal marshes.

A second group of models is based on physical process descriptions of the settling of suspended sediments from the water column on the time scale of individual tidal inundation cycles (Krone, 1987; Allen, 1990; French, 1993; Temmerman et al., 2003a). These physically based models incorporate the effect of long-term changes in tidal inundation regime, e.g., as a consequence of sea-level rise, and changes in suspended sediment characteristics.

Although the above-mentioned models were used to predict marsh response to future scenarios of sea-level rise, they were only validated to a very limited degree against field data on long-term accumulation rates. Validations are restricted to marsh sites where detailed field data were collected (e.g., Temmerman et al., 2003a). It is not known to what extent zero-dimensional models can be applied for larger areas and for other marsh sites for which no detailed input data are available.

This study presents the validation of a zero-dimensional physically based model to simulate the varying rates of tidal marsh accumulation within an estuary in response to changes in sea-level rise and suspended sediment concentrations (SSCs). As such a model requires detailed input data on sediment characteristics, some simplifying assumptions were made to obtain the necessary input data. First, data on long-term tidal marsh accumulation were collected for a large number of marsh sites along the Scheldt estuary (NW Europe). These data were interpreted in relation to the highly variable rates of mean high water-level rise and suspended sediment concentrations that are present in the Scheldt estuary. Next, model simulations were carried out and were validated against the field data. Finally, the impacts of potential changes in future mean high water-level rise and changes in suspended sediment concentrations on tidal marsh accumulation were evaluated using the simulation model.

2. Study area

The Scheldt estuary (e.g., Baeyens et al., 1998; Meire et al., 1992) is situated in the southwest of the Netherlands and the northwest of Belgium (Fig. 1). The Dutch and Belgian parts of the estuary are called the Western Scheldt and Sea Scheldt, respectively. The Scheldt estuary is characterised by large gradients in environmental conditions, which are expected to have their impact on tidal marsh accumulation rates.

First, the semidiurnal tidal regime strongly varies along the estuary. During spring and neap tides, respectively, the mean tidal range increases from 4.46 and 2.97 m at the mouth of the estuary up to 5.93 and 4.49 m at 91 km from the mouth. Farther inland, these

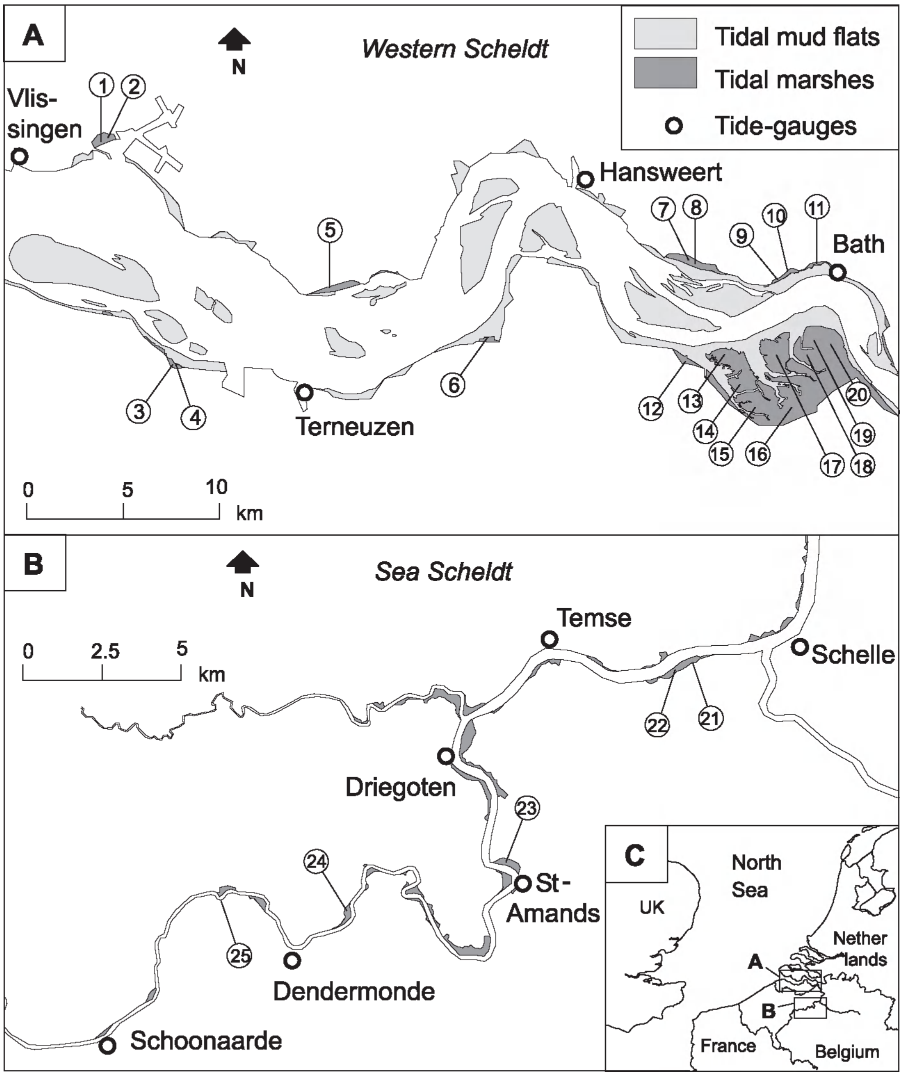

Fig. 1. Map of the study area: (A) the Western Scheldt, (B) the Sea Scheldt, (C) location within NW Europe. The studied marsh sites (see Table 1) are indicated with numbers.

values again decrease to 2.24 and 1.84 m at 160 km form the mouth, where tidal action is stopped by sluices. In accordance with this variation in tidal range, the mean high-water level (MHWL) increases from 4.35 m TAW (i.e., Belgian ordnance level, which is about 2.3 m below local mean sea level) at the mouth to 5.53 m TAW at 103 km and then decreases again to 5.00 m TAW at the inland border of the estuary (Claessens and Meyvis, 1994). Furthermore, the MHWL has risen during the past century at rates that strongly vary from 3 mm a^{-1} at the mouth up to 15 mm a^{-1} in the inner estuary.

Second, the suspended sediment concentration (SSC) in the Scheldt estuary varies strongly in time and space. The time-averaged SSC (1996–2001) in the upper part of the water column (which floods the tidal marshes) varies from 30 to 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 slightly decreases to 50–100 mg l^{-1} (Van Damme et al., 2001).

Third, a full salinity gradient from salt to fresh water exists along the Scheldt estuary. As a consequence, a distinction can be made between salt, brackish, and freshwater tidal marshes. The vegetation structure on these marsh types is highly different, ranging from low plant species (0.2–0.8 m in height) on the salt and brackish marshes (e.g., *Spartina anglica*, *Puccinellia maritima*, *Halimione portulacoides*, *Aster tripolium*, *Scirpus maritimus*) up to vegetation canopies of 3 m and higher on the freshwater tidal marshes (e.g., *Phragmites australis*, *Impatiens glandulifera*, *Salix* sp.; Van den Bergh et al., 2001).

3. Methods

3.1. Field data on long-term tidal marsh accumulation

Field data were collected for 25 marsh sites scattered along the Scheldt estuary using a combination of three methods (see Fig. 1 and Table 1 for an overview).

3.1.1. Analysis of old and recent topographic data

For the tidal marshes in the Western Scheldt, elevation data are available from old and recent topographic surveys, which were carried out by the Dutch Rijkswaterstaat Meetkundige Dienst in 1931 (Table 1, sites 3–20), 1955 (sites 3–11), 1961 (sites 12–20), 1968 (sites 3–6), 1992 (sites 12–20), and 2001 (sites 3–20). Old surveys were carried out using conventional surveying methods (theodolite) resulting in elevation data points with a mean density of around 1 point/7500 m^2. Elevations were mapped to the nearest 0.10 m relative to Dutch ordnance level (m NAP, which is 2.33 m lower than elevations in m TAW, the Belgian ordnance level). Recent elevation data (2001) are available from airborne laser altimetry (minimum density of 1 point/16 m^2, guaranteed minimal vertical accuracy of 0.20 m; Van Heerd and Van't Zand, 1999). These old and recent elevation data were processed to digital elevation models (DEMs) with a resolution of 20×20 m (e.g., Fig. 2). From these DEMs, the average elevation value of the

Table 1

Marsh sites (see Fig. 1) and methods used to determine historic marsh elevations and accumulation rates: topo—analysis of old and recent topographic data; ^{137}Cs—radiometric dating of sediment cores; paleo—paleoenvironmental dating of sediment cores

Number	Marsh site	Age	Method
1	Sloehaven	Old	^{137}Cs[a]
2	Sloehaven	Young	^{137}Cs[a]
3	Paulina	Old	Topo
4	Paulina	Young	Paleo ^{137}Cs[b]
5	Zuidgors	Young	Topo ^{137}Cs[a] ^{137}Cs[a]
6	Hellegat	Old	Topo
7	Waarde	Old	Topo
8	Waarde	Young	Topo paleo ^{137}Cs[c]
9	Bath west	Old	Topo
10	Bath mid	Young	Topo
11	Bath east	Old	Topo
12	Kruispolder	Young	Topo
13	Konijnenschor	Young	Topo ^{137}Cs[c]
14	Grauwse Plaat	Old	Topo
15	Heuvel	Old	Topo
16	Weideschor	Old	Topo
17	Marlemontse Plaat	Young	Topo
18	Rotte Putten	Young	Topo
19	Blauwe Plaat	Young	Topo
20	Noord	Old	Topo
21	Notelaar	Old	Paleo
22	Notelaar	Young	Paleo ^{137}Cs[b]
23	Mariekerke	Young	Paleo
24	Grembergen	Old	^{137}Cs[b]
25	Appels	Young	Paleo

[a] After Dyer et al. (2002).
[b] Own ^{137}Cs analysis.
[c] After Zwolsman et al. (1993).

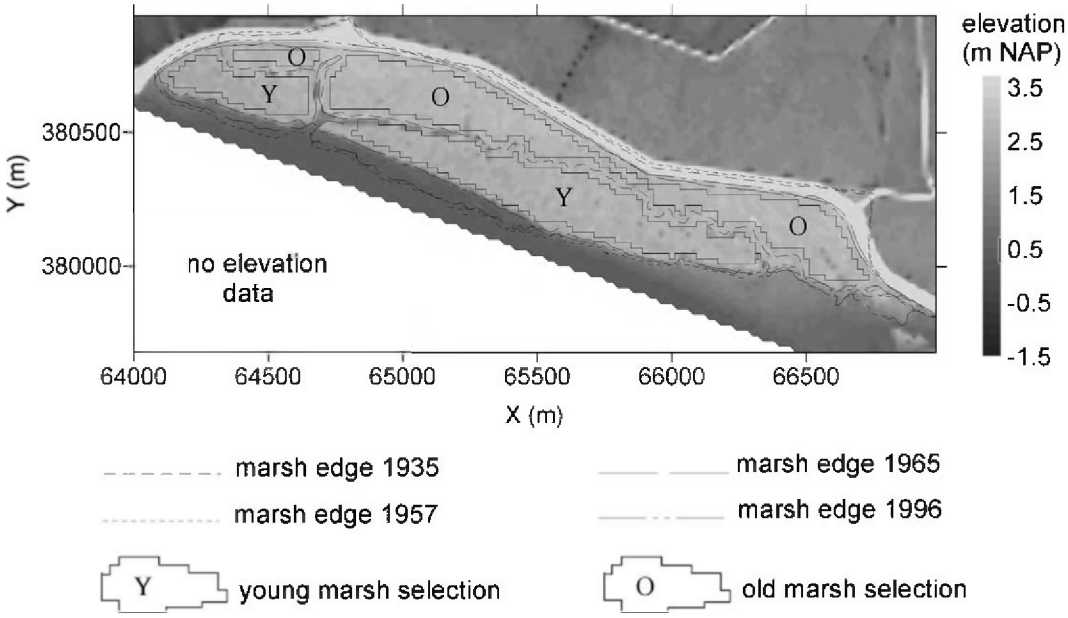

Fig. 2. Example of how young and old marsh polygons (sites 7 and 8) were calculated by overlay procedures in a GIS. In the background is the Digital Elevation Model (DEM) for 2001, in white lines the marsh edge polygons determined from aerial photographs (based on Van der Pluijm and De Jong, 1998).

DEM pixels was calculated for marsh surfaces with the same accumulation history. The standard deviation was calculated as a measure of the error on the average marsh surface elevation.

The following procedure was used to define marsh surfaces with the same accumulation history. Based on aerial photograph series of different ages, changes in marsh surface area since 1935 were mapped in detail (Huijs, 1995; Van der Pluijm and De Jong, 1998). From the digitised marsh edge polygons, old and young marsh surfaces were selected. Old marsh surfaces were defined as marshes that were already present on the oldest photographs of 1935 as marshes covered by dense vegetation and characterised by well-developed networks of tidal creeks. Young marshes were not yet present on the photos of 1935 and appeared on later photos as initially less dense, concentric patches of vegetation and without a well-developed creek system. Since their first appearance on the aerial photos, several of these old and young marshes decreased in surface area on later photos, either due to lateral erosion at the marsh edge or due to dike construction (Huijs, 1995; Van der Pluijm and De Jong, 1998). The old and young marsh surfaces that are still present today were selected from the digitised marsh edge polygons by overlay techniques in a GIS (see Fig. 2). The largest enclosed polygon was computed using a buffer of 20 m from the enclosing marsh edges. This buffer was used to exclude erroneous elevation data that can be present near marsh edges as a result of the spatial interpolation process during DEM generation. The mean and standard deviation of the surface elevations within the largest enclosed polygon were calculated. An algorithm was written so that these analyses could be performed in a uniform and automated way for all marsh sites in the Western Scheldt.

3.1.2. Radiometric dating of sediment cores

Radiometric dating of sediment cores, based on the determination of ^{210}Pb and ^{137}Cs activity profiles, is a widely used technique to estimate accumulation rates in tidal marshes on the time scale of the last 10–100 years (e.g., Armentano and Woodwell, 1975; Cundy and Croudace, 1996; DeLaune et al., 1978; Roman et al., 1997). For the Scheldt estuary, accumulation rates were determined with this technique for five marsh sites by Zwolsman et al. (1993) and Dyer et al. (2002)

(Table 1, sites 1, 2, 5, 8, and 13). In addition, we determined ^{137}Cs activity profiles for three other sites (Table 1, sites 4, 22, and 24).

^{137}Cs is an artificial radionuclide that was first released into the atmosphere by nuclear testing from the 1950s. After atmospheric fallout, ^{137}Cs is buried in sedimentary environments like tidal marshes. In sediment cores, usually a peak in ^{137}Cs activity can be recognised dating from 1963–1964, after which large-scale atmospheric nuclear testing stopped. In Europe, a second peak can be identified corresponding to the Chernobyl accident in 1986 (Walling and Quine, 1992).

At each of the three sites, sediment cores were sampled using a "Beeker-sampler", a piston corer (diameter=5.7 cm) with an inflatable valve at the bottom, so that disturbance, compaction, and loss of sediment during boring were minimized. The elevation of the boring locations was surveyed relative to local benchmarks in m NAP or m TAW. The cores were cut into slices of 2 cm, for which the dry bulk density was determined by 48 h of drying at 105 °C. For a series of subsamples, one half of the sample was analysed for ^{137}Cs activity, using a germanium detector connected to a multichannel analyser (Canberra Series 35 PLUS). On the other half of these subsamples, grain size analyses were carried out using the standard sieve–pipette method after pretreatment with H_2O_2, HCl, and $Na_2C_2O_4$. The accuracy with which the radiometric peaks can be detected is only dependent on the vertical resolution (i.e., 0.02 m) used for the analysis (Walling and Quine, 1992).

3.1.3. Paleoenvironmental dating of sediment cores

As shown in Temmerman et al. (2003a), marked vegetation cover changes in tidal marshes can be used to determine historic marsh surface elevations: these vegetation cover changes can be dated using aerial photographs of different age and can be recognised in sediment cores as changes in plant debris preserved at different depths. In addition to the data we reported in Temmerman et al. (2003a; Table 1, sites 21 and 22), we applied this method to four young marsh sites (Table 1, sites 4, 8, 23, and 25).

First, the time of marsh formation, at which the initially bare tidal flat was colonized by marsh plants, was determined from aerial photos. The error on this date was estimated by the time interval between successive photos before and after marsh formation. Second, at each site, three replicate sediment cores were collected using a Beeker-sampler. The cores were cut into 2-cm slices, for which the presence or absence of plant debris was determined. The marsh elevation at the time of marsh formation could be determined as the contact level between marsh sediments, rich in plant debris, and the underlying tidal flat sediments, which contain no plant material at all. The error on the determined marsh elevation was estimated by taking the average and standard deviation of the three replicate cores.

3.2. Modelling long-term tidal marsh accumulation

3.2.1. Model description

Temmerman et al. (2003a) proposed a zero-dimensional time-stepping marsh sedimentation model (MARSED), which is a further development of the physically based model approaches of Krone (1987), Allen (1990), and French (1993). The model equations are summarised below. For a full description and model sensitivity analysis, we refer to Temmerman et al. (2003a) and Temmerman et al. (2004).

The rate of marsh elevation change dE/dt (m a^{-1}) is calculated as

$$dE/dt = dS_{\min}/dt + dS_{\text{org}}/dt - dP/dt \tag{1}$$

where $dS_{\min}/dt$ is the rate of mineral sediment deposition, dS_{org}/dt the rate of organic sediment deposition, and dP/dt the rate of compaction of the deposited sediment under younger sediment load. All terms are in m a^{-1}.

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

$$dS_{\min}/dt = \int_{\text{year}} \int_T \frac{w_s C(t) dt}{\rho} \tag{2}$$

where w_s is the settling velocity (m s^{-1}), C the depth-averaged suspended sediment concentration (kg m^{-3}), and ρ the dry bulk density (kg m^{-3}) of the deposited sediment. The right term in Eq. (2) is integrated over the total duration T of a tidal inundation cycle and subsequently 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:

$$\frac{\mathrm{d}[h(t) - E]C(t)}{\mathrm{d}t} = -w_s C(t) + C(0)\frac{\mathrm{d}h}{\mathrm{d}t} \quad (3)$$

where h and E are the water surface and marsh surface elevation (m TAW), and $C(0)$ is the incoming suspended sediment concentration (kg m^{-3}) in the water that floods the marsh surface. During flood tide (when dh/dt>0):

$$C(0) = k[h(t_{\mathrm{HW}}) - E] \quad (4)$$

while during ebb tide (when dh/dt<0), $C(0)$ is set to equal $C(t)$.The fundamental difference between MARSED and the models of Krone (1987), Allen (1990), and French (1993) is that MARSED takes into account the variation of incoming sediment concentration $C(0)$ as a positive linear function of inundation height $[h(t_{\mathrm{HW}}) - E]$ above the marsh surface. 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.

The collection of input data needed for this study is described below. As a consequence of limited site accessibility, field data on all model variables could be determined for only 13 of the 25 marsh sites (see Table 2).

3.2.2. Input data on tidal inundation

The tidal regime is incorporated in the model on two time scales. First, the temporal variation of the water level $h(t)$ during one semidiurnal tidal cycle is modelled based on the average tidal curve recorded in the nearest tide-gauge station (Claessens and Meyvis, 1994; see Fig. 1 and Table 2). To simulate semidiurnal cycles with different high water levels $h(t_{\mathrm{HW}})$, this tidal curve $h(t)$ is shifted up or down. This approach is acceptable because only the top of the tidal curve floods the marsh surface.

Second, the frequency distribution of high water levels $h(t_{\mathrm{HW}})$ is simulated for every year, using data on (1) the local evolution of yearly mean high water level (MHWL) and (2) the yearly averaged frequency distribution of high water levels around this MHWL. Both data are well documented for the Scheldt estuary, thanks to a dense network of ca. 20 tide-gauge stations, operated since the end of the 19th Century (Claessens and Meyvis, 1994; see Fig. 1 and Table 2).

3.2.3. Input data on suspended sediment concentration and settling velocity

The relationship between incoming sediment concentration $C(0)$ and high water level $h(t_{\mathrm{HW}})$ is specified by the k factor in Eq. (4). For the Notelaar and Paulina marshes (sites 3, 4, 21, and 22), a value for k was determined by linear regression between

Table 2
Summary of input values for all model variables for 13 marsh sites (see locations on Fig. 1)

Site number	$T(0)$ (yr)	$E(0)$ (m TAW)	Tidal data[a]	k	w_s (10^{-4} m s^{-1})	ρ (kg m^{-3})	dP/dt (mm a^{-1})	dS_{org}/dt (mm a^{-1})
1	1963	4.24	A/B	0.0451	0.7	397	2.12	0.64
2	1963	3.99	A/B	0.0451	1.1	448	3.11	0.79
3	1931	4.25	A/B	0.0585	1.0	260	3.09	0.41
4	1982	3.45	A/B	0.0585	1.7	500	22.13	0.94
5	1931	3.81	B	0.0614	3.4	685	3.65	0.55
6	1931	4.38	B/C	0.0552	1.2	478	3.65	0.64
8	1931	4.05	C/D	0.0606	1.1	560	0.00	2.19
12	1931	3.84	C/D	0.0606	1.5	492	0.00	0.83
21	1958	5.20	E/F	0.1345	1.0	350	0.00	0.90
22	1947	4.38	E/F	0.1345	1.0	350	0.00	0.90
23	1968	4.87	G	0.1958	1.3	434	9.62	1.55
24	1963	4.90	G/H	0.1610	1.0	389	1.57	0.69
25	1982	4.87	H/I	0.1555	3.6	610	4.01	1.79

[a] Tidal data [on the mean tidal curve $h(t)$ and the evolution of yearly mean high water level $h(t_{\mathrm{HW}})$] were obtained by linear interpolation of tidal data recorded at the nearest upstream and downstream tide-gauge stations: A—Vlissingen; B—Terneuzen; C—Hansweert; D—Bath; E—Schelle; F—Temse; G—St. Amands; H—Dendermonde; I—Schoonaarde (see Fig. 1 for locations; tidal data after Claessens and Meyvis, 1994).

incoming sediment concentrations, measured above the marsh surface at the beginning of a large series of marsh inundations, and the high water level, measured during these inundations (Temmerman et al., 2003b). However, such detailed field data are not available for all other marsh sites that are considered in this study. Therefore, the following method is proposed to estimate a value for k.

We used existing data on time-averaged suspended sediment concentrations (SSC) that are available from surface water samples, which were collected every month from January 1996 to January 2002 at 29 locations in the main stream channel of the Scheldt estuary (Van Damme et al., 2001). The sampling locations were sampled at different stages of the tidal cycle. This makes it difficult to compare the SSC between the sampling locations, because temporal variations in SSC during a tidal cycle are considerable (e.g., Fettweis et al., 1998). However, the data set of Van Damme et al. (2001) is the only one that covers the whole length of the estuary and at least allows calculation of a time-averaged SSC value for each sampling location in the data set (Fig. 3). Considering the length of the sampling period and the fact that there was no systematic relationship between the sampling location and the moment of sampling, it may be assumed that the variations in SSC were averaged out.

At the Paulina marsh (sites 3 and 4), the average SSC in the adjacent stream channel is rather low (0.033 g l^{-1}), while at the Notelaar marsh (sites 21 and 22), this is much higher (0.109 g l^{-1}). This is in accordance with the SSC measurements carried out on both marsh sites, which showed that incoming SSC values at the Notelaar marsh range from 0.01 to 0.32 g l^{-1} and at the Paulina marsh from 0.01 to 0.11 g l^{-1} (Temmerman et al., 2003b). The yearly averaged k factor, determined from these incoming SSC measurements, is also higher for the Notelaar marsh (k=0.1345) than for the Paulina marsh (k=0.0585). The ratio between average SSC in the stream channel and k determined on the marsh is comparable for both marshes (0.81 for the Notelaar and 0.56 for the Paulina marsh). Based on a mean ratio of 0.69, the k factor was then estimated for every marsh site as:

$$k = 0.69 \text{ SSC} \tag{5}$$

where SSC is the average SSC (in g l^{-1}) in the stream channel. Thus, using this procedure, we assume that

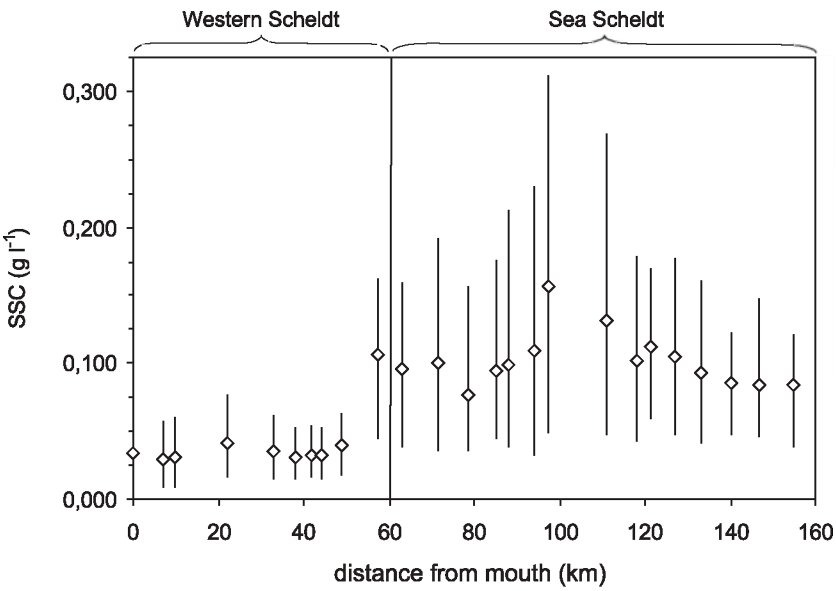

Fig. 3. Time-averaged longitudinal variation in suspended sediment concentration (SSC) along the Scheldt estuary, calculated from monthly monitoring data for 1996–2001 (data of Van Damme et al., 2001). Error bars represent the 10th and 90th percentiles of all SSC measurements at a station.

for a given inundation height, the incoming sediment concentration on the marsh is proportional to the average sediment concentration in the stream channel of the Scheldt.

Apart from the concentration, the settling velocity w_s of the incoming suspended sediment needs to be specified as input for the model. Field data on in situ settling velocities are difficult to obtain. However, in Temmerman et al. (2004), we showed that the model predictions are not very sensitive to variations in w_s: changing w_s by a factor 2 resulted in a change in predicted marsh elevation of only a few centimetres. Therefore, as in Temmerman et al. (2004), we made a rough approximate estimation of w_s based on the median particle diameter of surface sediments and Stokes' formula for settling velocities of spherical particles. On each of the 13 marsh sites in Table 2, four replicate samples of surface sediments were taken at a basin location using metal rings (0.05 m in diameter and height), and these samples were analysed using the standard sieve–pipette method after pretreatment with H_2O_2, HCl and $Na_2C_2O_4$.

3.2.4. Compaction and organic matter deposition

The same surface sediment samples were used to determine the dry bulk density ρ of the deposited sediment (Table 2). In addition, sediment cores were taken on each marsh site, using the Beeker-sampler, as explained above. These cores were cut into 2-m slices for which the dry bulk density and the organic matter content were determined (the latter by loss on ignition). For a number of subsamples, a grain size analysis was performed.

The depth profiles of dry bulk density were used as a measure of sediment compaction under younger sediment load. For a number of marsh sites, the density does not vary significantly with depth (e.g., Fig. 4B). For these sites, the compaction rate dP/dt was set to zero (Table 2). For the other marsh sites, a linear increase in dry bulk density with depth was observed (e.g., Fig. 4A). Because the grain size distribution in the sediment cores does not change significantly with depth, the increase in dry bulk density with depth can be attributed to compaction due to burying and ageing of the sediments. For these sediment cores, the compaction rate was estimated as follows.

The thickness P (in m) after compaction of a sediment layer with an initial thickness P_0 at deposition is

$$P = P_0 \frac{\rho_0}{\rho} \tag{6}$$

where ρ_0 and ρ are, respectively, the initial and final dry bulk densities (in g cm^{-3}) of that sediment layer. The compaction rate $\Delta P/\Delta t$ (in m a^{-1}) can be written as

$$\frac{\Delta P}{\Delta t} = \frac{P\left(1 - \frac{\rho}{\rho_0}\right)}{\Delta t} \tag{7}$$

Based on Eq. (7), the average compaction rate for the sediment column of thickness P (in m), deposited over the time period Δt (in years), was calculated using for ρ_0 the dry bulk density determined from the surface sediment samples (see above) and for ρ the average dry bulk density of the compacted sediment column with thickness P. Data on P and Δt were provided by the determination of historic marsh surface elevations as described above. Using this approach, we assume that the compaction rate is constant in time, which simplifies model calculations: this assumption is reasonable for vertically uniform marsh deposits with relatively low organic matter content and considering the relatively short time period over which marsh accumulation is simulated here (<70 years). However, it is clear that for vertically more heterogeneous and more organic rich marsh sediments and longer time periods, the compaction rate cannot remain constant, and a different formulation should be used.

Finally, the deposition rate of organic matter dS_{org}/dt is estimated for each marsh site, based on the average organic matter content measured in the sediment cores and based on the long-term accumulation rates determined for each site (Table 2).

3.2.5. Simulating the impact of environmental change in past and future

Additional model runs were carried out to simulate the impact of past and future rates of mean high water-level (MHWL) rise and SSC on tidal marsh accumulation along the Scheldt estuary. First, tidal marsh accumulation during the past century was simulated under the scenario of lower SSC values than actually

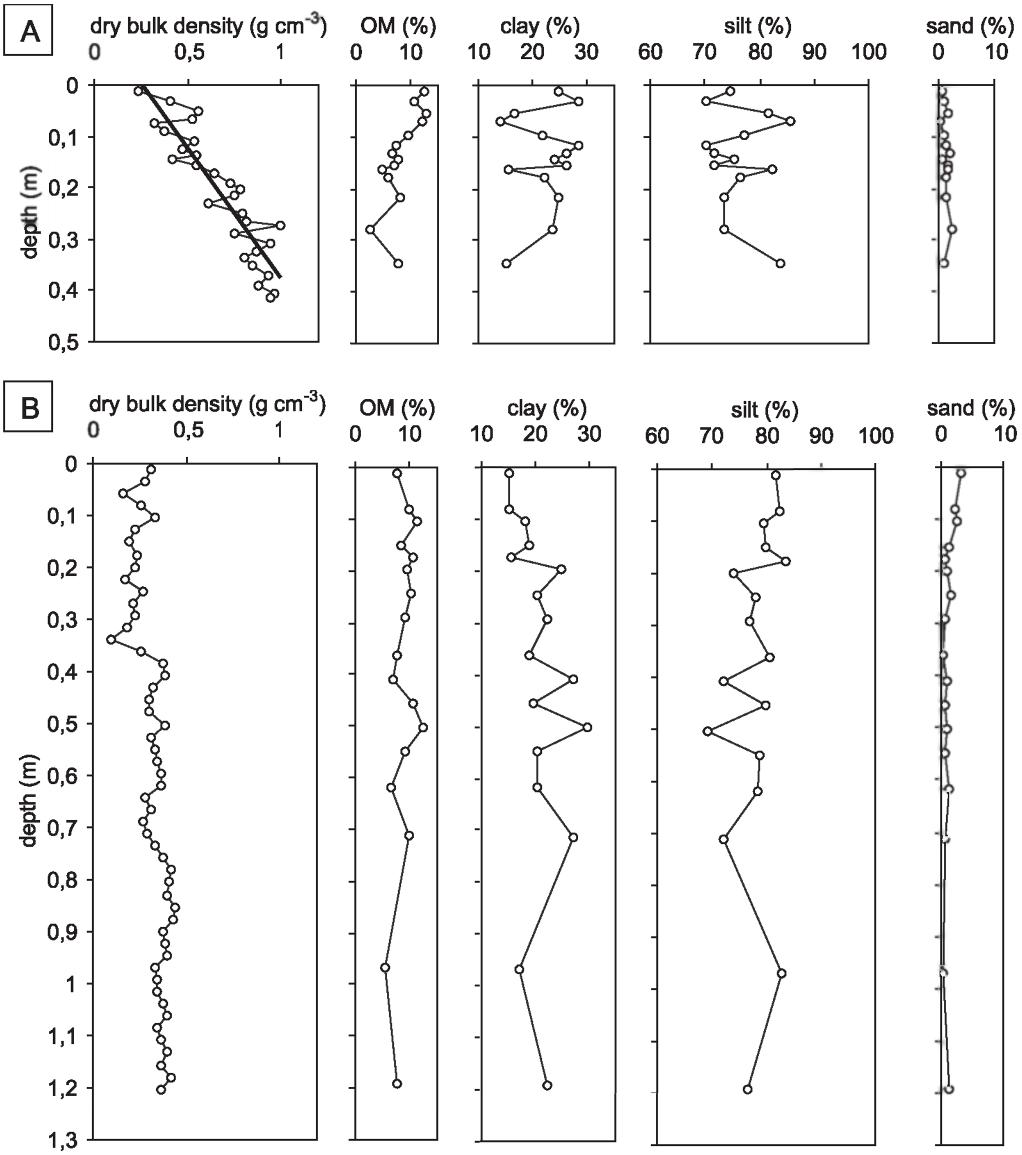

Fig. 4. Two examples of depth profiles of dry bulk density, organic matter content (OM), clay (<2 μm), silt (2–63 μm), and sand (>63 μm) content determined from sediment cores sampled at (A) site 3 and (B) site 22.

observed in the Scheldt estuary (by use of lower k values in Eq. (4)) to demonstrate the importance of incoming SSC for tidal marsh accumulation. Second, future scenarios were simulated starting from the present-day observed marsh elevations and simulating marsh accumulation for the next 100 years under two scenarios of MHWL rise: (1) by extrapolating the 'current' rate of MHWL rise (observed at every marsh site during the last 70 years); (2) using this current rate of MHWL rise multiplied by a factor 1.5. For both MHWL rise scenarios, three model runs were carried out to simulate the impact of changes in SSC: (1) using the present-day k values in Eq. (4) (i.e., no change in SSC); (2) using these k values multiplied by a factor 0.5 (decrease in SSC); and (3) using these k values multiplied by a factor 2 (increase of SSC).

4. Results

4.1. Field data on long-term tidal marsh accumulation

Based on the three methods described above, 95 time-elevation points could be determined covering the past 70 years for 25 marsh sites scattered along the Scheldt estuary. Fig. 5 presents a selected overview of historical marsh elevations that were determined for three points in time, including 64 time-elevation points.

Before interpreting the data, the accuracy of the data needs special attention. The standard deviations

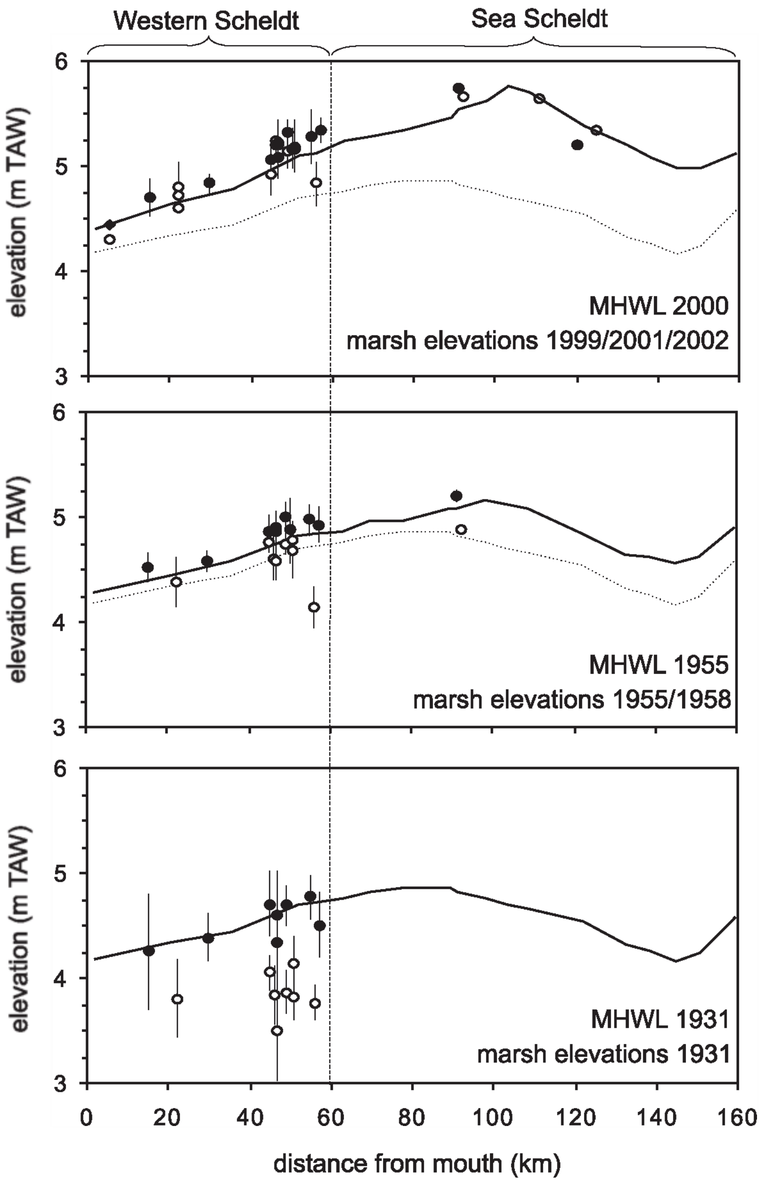

Fig. 5. Observed marsh elevations (mean values in symbols and standard deviations in error bars) and mean high water level (MHWL; in thick, black line) as a function of distance from the mouth of the Scheldt estuary for three points in time. Old marsh surfaces in black symbols, young marsh surfaces in white symbols. The thin, dashed line in the upper two panels represents the MHWL in 1931.

on the mean elevations, which were calculated based on old and recent topographic data, were highest for the 1931 data (0.16 to 0.55 m; Fig. 5). For the data of 1955/61 and 2001, standard deviations were rather low (0.09 to 0.31 m). This may be attributed partially to the lower quality of the oldest data of 1931 and partially to the fact that young low marshes were more numerous in 1931. On young low marshes, the spatial variability in elevation is generally higher than on old high marshes.

The results of the radiometric dating of sediment cores are presented in Fig. 6. Peaks in the ^{137}Cs profiles were attributed to the ^{137}Cs fallout maxima of 1963 and 1986. For sites 4 and 22, a good agreement was found between the radiometric dating and paleoenvironmental dating, based on the preservation of plant debris in the cores. The standard deviations on the marsh elevations that were determined by paleoenvironmental dating are all very low (<0.06 m). For sites 4, 5, 8, 13, and 22, a combination of two or three of the above-described methods was used. Fig. 7 illustrates that for these sites, a fair correspondence between the different methods was obtained, which confirms the reliability of the methods.

In the Western Scheldt, an important phase of young marsh formation occurred between 1931 and 1944. These young marshes originated by the establishment of marsh plants on bare tidal flats at an elevation of 1.10 to 0.55 m below local mean high water level (MHWL) at that time (Fig. 5). Between 1931 and 1955, the young marshes accumulated at rates of 1.58 to 3.22 cm a^{-1}, which is very fast compared to the MHWL rise of 0.32 to 0.58 cm a^{-1} in the Western Scheldt (Fig. 8). As a result, the young marshes attained an elevation around local MHWL by 1955. During the subsequent period of 1955–2002, they accumulated at lower rates of 0.43 to 1.84 cm a^{-1}. In contrast to the young marshes, the elevation of old marshes is at any time very close to MHWL (Fig. 5). They all accumulated at rates that are slightly in excess of the rate of MHWL rise (Fig. 8). This difference between young and old marsh accumulation is further illustrated in Fig. 7. It is generally observed in the Scheldt estuary that young marshes initially accumulate very quickly until they attain a quasi-equilibrium level, which is around MHWL. From then on, they actually can be considered as old marsh surfaces, which tend to maintain their equilibrium

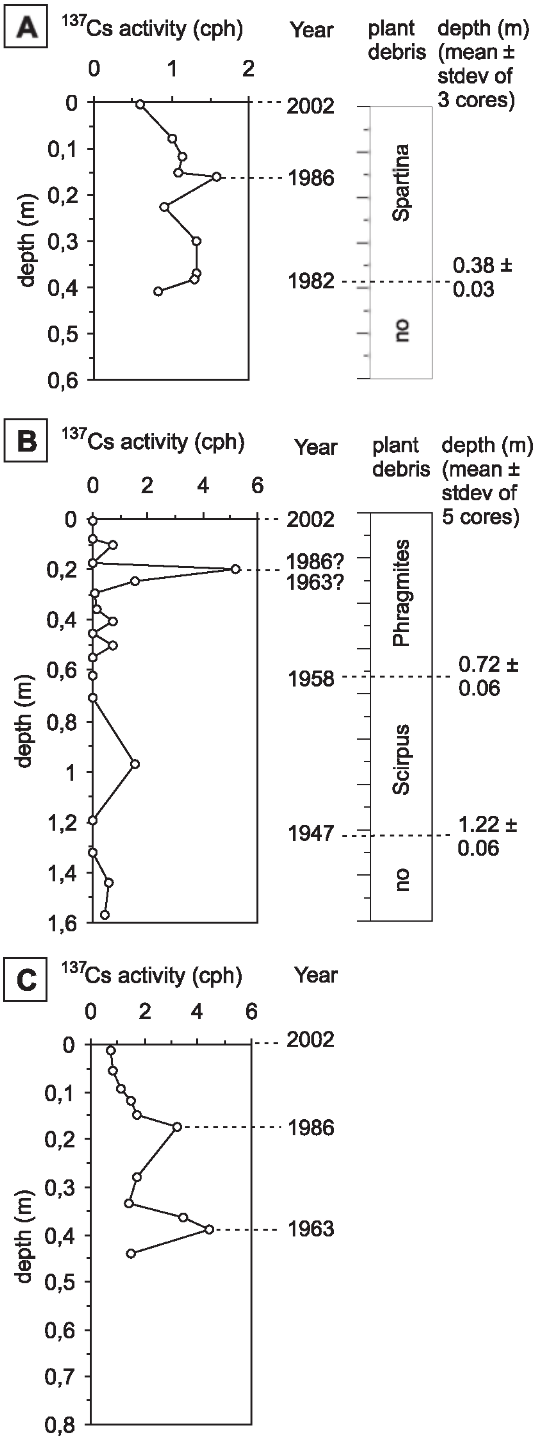

Fig. 6. Results of radiometric dating [^{137}Cs activity in counts per hour (cph)] and paleoenvironmental dating (based on type of plant debris) of sediment cores sampled at (A) site 4, (B) site 22, and (C) site 24.

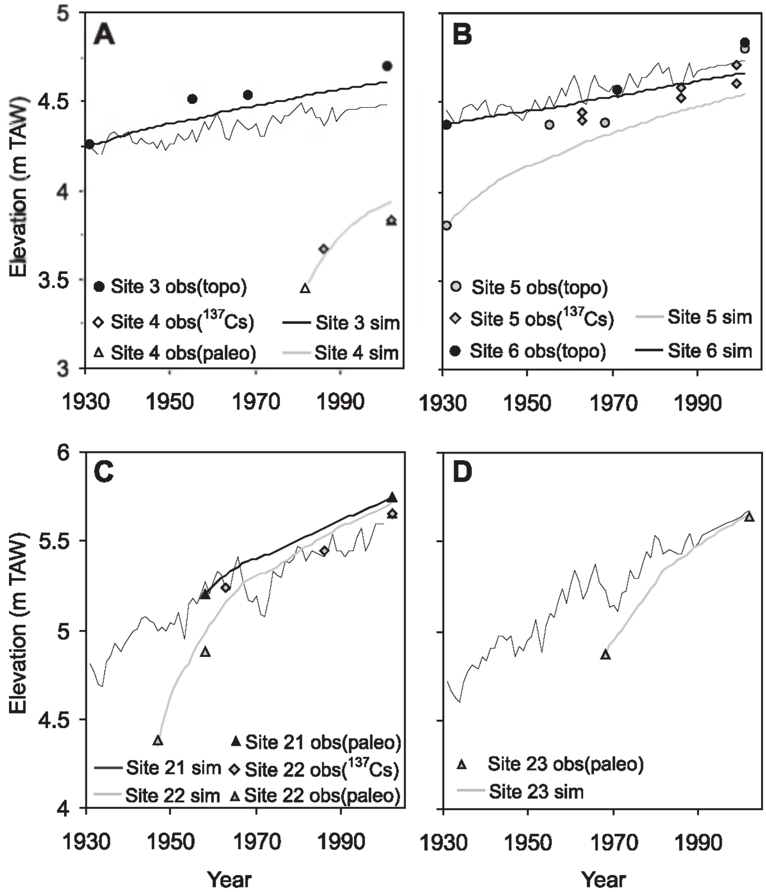

Fig. 7. Example of observed (in symbols) and simulated (in thick lines) marsh elevation change for marsh sites in the Western Scheldt (A,B) and Sea Scheldt (C,D). Old marshes are indicated in black symbols and lines, young marshes are indicated in grey symbols and lines. The time evolution of local mean high water level is indicated in thin black lines.

level relative to MHWL by accumulating as fast as MHWL rises.

For the Sea Scheldt, no data on tidal marsh accumulation is available for the period 1931–1955. However, we know from aerial photos that no important marsh formation occurred in the Sea Scheldt as this was the case in the Western Scheldt. For the period 1955–2002, accumulation rates were generally higher in the Sea Scheldt than in the Western Scheldt (Fig. 8). This may be attributed partially to the much faster MHWL rise in the Sea Scheldt than in the Western Scheldt, which resulted in more frequent and higher marsh inundations and consequently higher accumulation rates. In addition, time-averaged suspended sediment concentrations are considerably higher in the Sea Scheldt than in the Western Scheldt (Fig. 3). This may also partially explain the higher marsh accumulation rates in the Sea Scheldt.

4.2. Model validation against field data

The MARSED model was applied and evaluated for its ability to simulate the observed estuarine variability in marsh accumulation rates. In all, 32 time-elevation points were used to validate the model. Fig. 9a shows that the simulated and observed elevations correspond extremely well (R^2=0.95). The model overestimates the observed elevations by only 0.20 m at most. For 4 of the 32 observations, the model underestimates the observed elevation by more than 0.20 m, up to 0.27 m in the most extreme case.

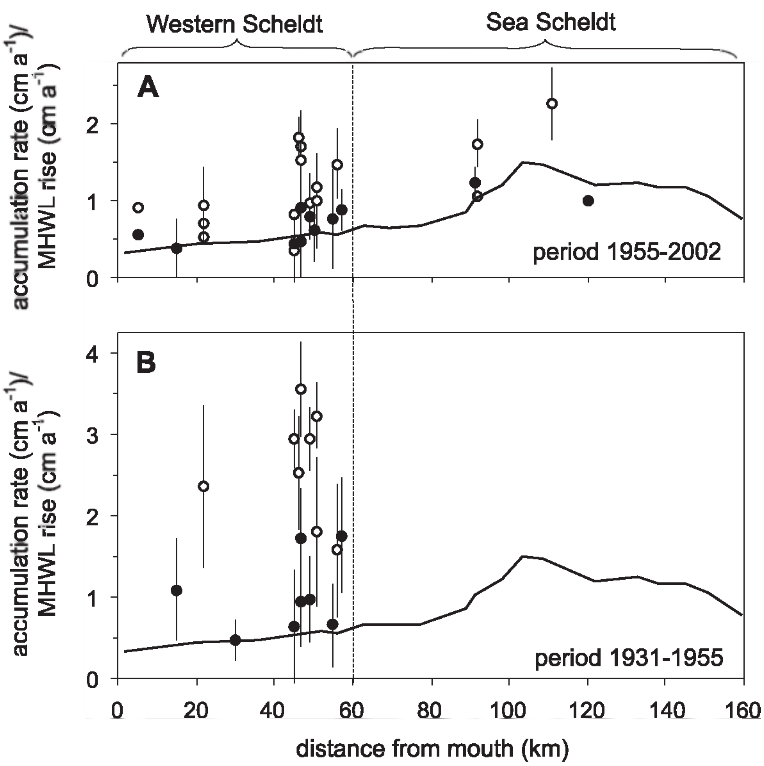

Fig. 8. Observed marsh accumulation rates (mean values in symbols and standard deviations in error bars) in relation to mean high water level (MHWL) rise (in black line) along the Scheldt estuary, for the period (A) 1955–2002 and (B) 1931–1955. Old marsh surfaces in black symbols, young marsh surfaces in white symbols.

Fig. 9b shows that the observed and simulated accumulation rates also correspond fairly well (R^2=0.79). For only 2 of the 32 observations, the model simulations underestimated or overestimated the observed accumulation rates by more then a factor two.

Fig. 7 shows an example of the simulated elevation changes with time for a selected number of sites.

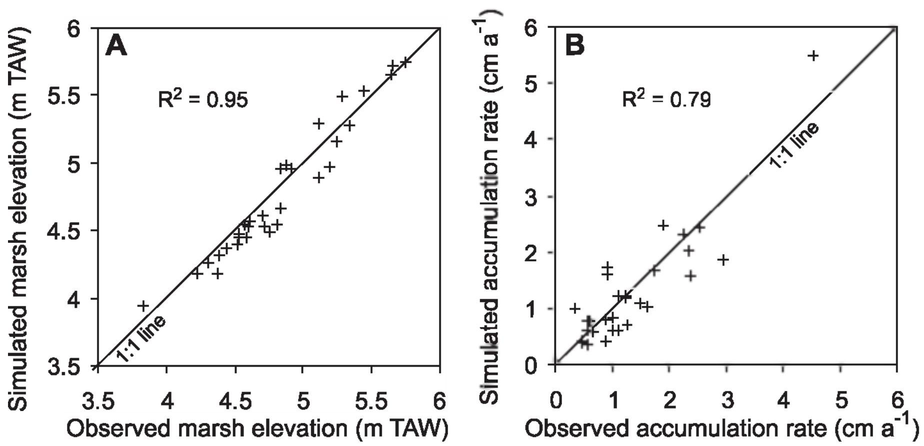

Fig. 9. (A) Observed versus simulated marsh elevations. (B) Observed versus simulated accumulation rates.

In accordance with the field data, the model simulates that, on the one hand, old marshes rise quasi-linearly with time in equilibrium with local MHWL rise. On the other hand, the model simulates that young low marshes accumulate asymptotically up to their equilibrium level around local MHWL. It is important to notice that in the Western Scheldt (Fig. 7a,b), a longer time span is required to reach this equilibrium level than in the Sea Scheldt (Fig. 7c,d) and that this estuarine variation in accumulation rates is successfully simulated by the model. Thus, our assumption that k varies linearly with the average sediment concentration in the Scheldt stream channel allows to simulate successfully the longitudinal variations in sedimentation rates.

4.3. Simulating the impact of environmental change in past and future

Despite the fact that during the past century the MHWL rise was highest (up to 15 mm a^{-1}) in the inner estuary (the Sea Scheldt), the tidal marshes in the Sea Scheldt could maintain their equilibrium level relative to MHWL (Figs. 5 and 8). Additional model simulations demonstrate that this rapid marsh accumulation in the Sea Scheldt is only possible because the SSC is considerably higher in the Sea Scheldt than in the Western Scheldt (Fig. 3). Model simulations for the Sea Scheldt marshes (sites 21 up to 25), using a lower suspended sediment input which is representative for the Western Scheldt (k=0.05), resulted in predicted present-day (2002) elevations that are 0.20 to 0.30 m lower than the originally predicted elevations. Thus, if sediment concentrations in the Sea Scheldt had been lower, the marshes would not have been able to follow the rapid MHWL rise, and they might have degraded to bare tidal flats.

The simulation of future scenarios shows that under the current trend of MHWL rise and SSC, all marsh sites will be able to maintain an elevation around MHWL during the next 100 years (Fig. 10). Even if MHWL rise would increase by a factor 1.5, no considerable changes in marsh surface elevation relative to MHWL would occur by 2100, given the present-day SSC values observed along the Scheldt estuary. However, a decrease in SSC values by a factor 0.5 would result in 2100 in marsh surface elevations up to 0.27 m below local MHWL (under the scenario of the current MHWL rise) and up to 0.38 m below MHWL (under the scenario of an increased MHWL rise; Fig. 10). On the contrary, an increase in SSC values by a factor 2 would result in increased marsh elevations up to 0.31 and 0.25 m above local MHWL (under the current and increased trend of MHWL rise, respectively). These changes in marsh surface elevation are considerable and would result in increased or decreased tidal flooding and consequently in significant ecological changes, such as changes in vegetation composition.

5. Discussion and conclusions

5.1. Modelling marsh response to environmental change

Assessment of the impact of environmental change, such as sea-level rise, on tidal marsh ecosystems is currently a hot issue: numerical models are increasingly being used to simulate long-term (10–100 years) sediment accumulation rates in comparison to rates of sea-level change (e.g., Allen, 1990; Callaway et al., 1996; Day et al., 1999; French, 1993; Rybczyk and Cahoon, 2002; Temmerman et al., 2003a; Van Wijnen and Bakker, 2001). In contrast with existing modelling studies, where independent model validation against field data has been limited (e.g., Temmerman et al., 2003a), this study presented the validation of the MARSED model against field data for 13 marsh sites with highly varying accumulation rates. The model was not only capable of simulating the observed tendencies but also of simulating absolute marsh sedimentation rates with good accuracy (Fig. 9). Nevertheless, detailed input data on incoming sediment concentrations and settling velocities are often not available. Our results show that if these model parameters are estimated using proxy data on average sediment concentrations and median sediment grain sizes, the observed variations in sedimentation rates can be simulated very well.

Although validated here for a particular estuary, the MARSED model has a high potential to be applicable to other tidal marsh areas in the world. The quick asymptotic rise of young, low marshes up to an equilibrium elevation relative to mean sea-level, and the tendency of old, high marshes to maintain this

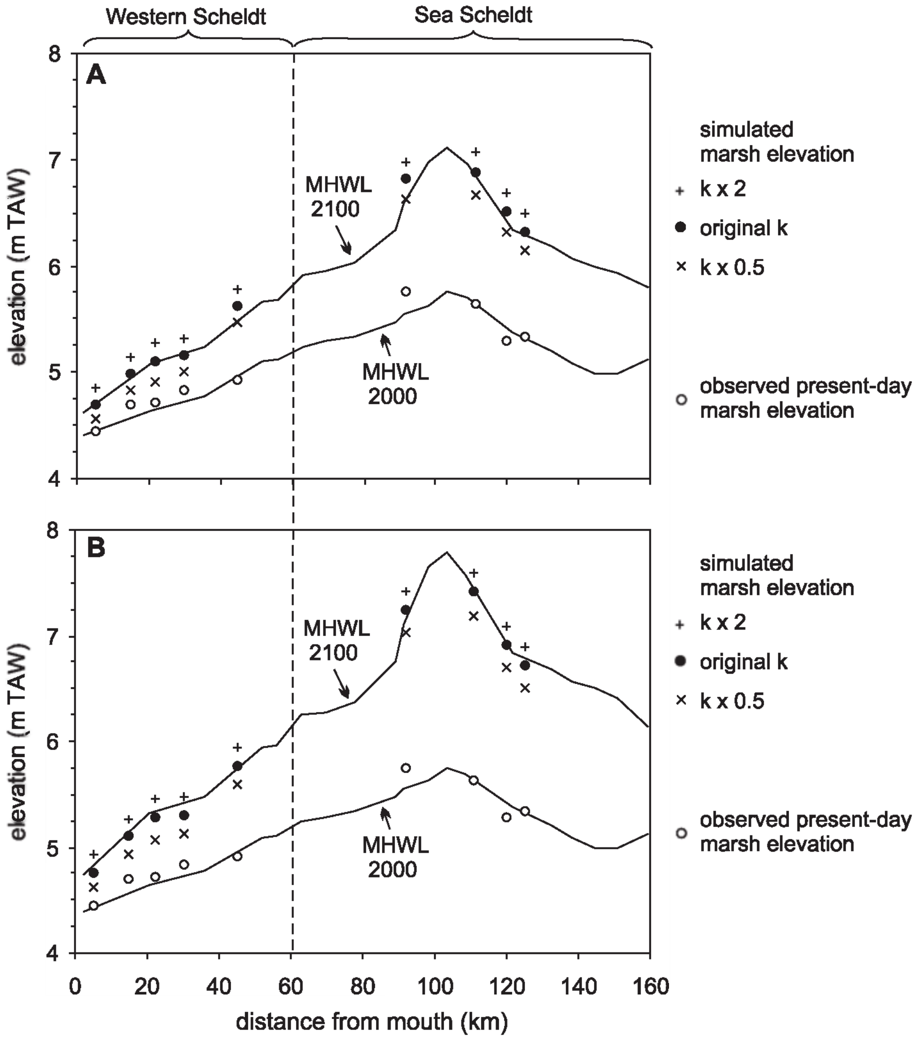

Fig. 10. Simulation of marsh accumulation along the Scheldt estuary for the next 100 years under different scenarios of mean high water level (MHWL) rise and suspended sediment concentrations (SSC): (A) extrapolation of the 'current' rate of MHWL rise, (B) 1.5 times the 'current' rate of MHWL rise. For both MHWL rise scenarios, three scenarios of SSC were simulated using in Eq. (4): (1) the original present-day k values, (2) these k values multiplied by 0.5, and (3) multiplied by 2.

equilibrium elevation relative to the rising sea-level, are not only observed in the Scheldt estuary but are also widely reported from other tidal marsh areas (e.g., Pethick, 1981; Allen, 1990). The broader applicability of our results is further supported by the validation of the MARSED model for marsh sites experiencing a wide range of sedimentation rates (3.5–45.5 mm a^{-1}), rates of MHWL rise (3–15 mm a^{-1}), and incoming SSC (20–200 mg l^{-1}). Nevertheless, in its present form, the MARSED model is especially applicable to macrotidal marshes, where vertical accretion is dominated by deposition of mineral suspended sediment. For microtidal marshes, where vertical elevation changes are dominated by organic matter deposition and compaction, it is clear that the model variables dS_{org}/dt and dP/dt in Eq. (1) may not be treated as constant, as in this study, but need to be further modelled as time-varying variables (e.g., Callaway et al., 1996; Rybczyk and Cahoon, 2002).

Because the model is validated for tidal marshes, which are subject to spatially varying rates of MHWL rise and incoming SSC, the model should also be able to predict marsh response to temporal changes in sea level and SSC. In the case of the Scheldt estuary, model predictions for the next 100 years showed that the tidal marshes will maintain their present-day elevation relative to MHWL, only if MHWL rise and SSC would not change drastically (Fig. 10). Such model predictions can be useful to evaluate the effect of different management options for estuaries and coasts: they indicate that human interventions that would lead to increased MHWL rise, such as intensive dredging, and other measures that would result in a decrease in SSC, such as soil erosion control measures (e.g., Verstraeten et al., 2003), could potentially lead to the failure of tidal marshes to keep up with the rising MHWL and finally result in drastic ecological changes.

However, apart from vertical accretion, tidal marshes can also be subject to lateral extension or erosion at the marsh edge. Thus, in the case that model predictions suggest that tidal marshes will be able to accumulate vertically with the rising MHWL, this does not exclude that the tidal marsh area can be lost due to lateral erosion of the marsh edge (e.g., Cox et al., 2003). The modelling of lateral extension and erosion of marshes and the response to environmental changes, such as sea-level change, was not considered in this study and needs more research.

5.2. Factors controlling estuarine variations in marsh sedimentation

The field data presented in this study demonstrate that tidal marshes within an estuary accumulate at rates that strongly vary in time and space. We found that accumulation rates are higher in the inner part than in the outer part of the estuary (Fig. 8), which is in accordance with some studies in other estuaries. Orson et al. (1990) and Ward et al. (1998) indicate that this pattern of estuarine sedimentation may be related to high riverine inputs of suspended sediments, resulting in declining marsh accumulation rates with increasing distance from the riverine sediment source. Allen and Duffy (1998) suggest that spatio-temporal changes in the tidal range may also be involved.

However, by combination of field data and modelling, we were able to quantify the factors that control the spatial and temporal variations in estuarine marsh sedimentation. On the one hand, long-term accumulation rates are determined by MHWL and the rate of MHWL rise: young low marshes quickly accumulate up to an equilibrium elevation relative to MHWL, while old high marshes tend to maintain this equilibrium level by accumulation at a similar rate as MHWL rises (e.g., see also Pethick, 1981; Allen, 1990).

On the other hand, our field data and model simulations underline the importance of variations in SSC: they show that (1) the rate of asymptotic rise of young marshes and (2) the ability of old marshes to maintain their equilibrium level strongly depend on incoming SSC in the water that floods the marshes. In the case of the Scheldt estuary, the rate of asymptotic rise of low marshes is lower in the outer estuary than in the inner estuary (Fig. 7). Model simulations show that this is because the SSC is lower in the outer than in the inner estuary. The old marshes are all able to maintain their equilibrium level. Model simulations showed that this ability strongly depends on SSC: (1) if SSC in the inner estuary, where MHWL rise is fastest, would have been lower, marshes would not have been able to follow the fast rise of MHWL; (2) simulations of future scenarios indicate that the marshes will only be able to follow MHWL rise if incoming SSC would not decrease (Fig. 10).

We can conclude then that long-term sediment accumulation in tidal marshes is determined by a combined influence of MHWL (or sea level) rise and SSC. The rate of sea-level rise determines the minimal rate at which tidal marshes need to accumulate sediments to maintain their equilibrium level and to survive sea-level rise. However, the actual ability to maintain this equilibrium level depends on the available SSC. In this study, a model was presented, which allows to quantify and simulate this combined effect of sea-level change and incoming suspended sediment concentration.

Acknowledgements

This study was funded by the Institute for the Promotion of Innovation by Science and Technology in Flanders (IWT). Special thanks are addressed to Tom De Bruyn, Frederik Francken, Dirk Lauwaet, Kristof Van Oost, and Gert Verstraeten, who helped during the field work. We further wish to thank Dick De Jong, Bram Schouwenaar, Gertjan Zwolsman (Rijkswaterstaat RIKZ and RIZA), Fran Dyer (Southampton Oceanography Centre), and Stefan Van Damme (University of Antwerp) for use of their data. Finally, we thank Dr. J. French and an anonymous reviewer for their constructive comments.

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