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SPATIAL AND TEMPORAL FACTORS CONTROLLING SHORT-TERM SEDIMENTATION IN A SALT AND FRESHWATER TIDAL MARSH, SCHELDT ESTUARY, BELGIUM, SW NETHERLANDS

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ABSTRACT

During a one-year period temporal and spatial variations in suspended sediment concentration (SSC) and deposition were studied on a salt and freshwater tidal marsh in the Scheldt estuary (Belgium, SW Netherlands) using automatic water sampling stations and sediment traps. Temporal variations were found to be controlled by tidal inundation. The initial SSC, measured above the marsh surface at the beginning of inundation events, increases linearly with inundation height at high tide. In accordance with this an exponential relationship is observed between inundation time and sedimentation rates, measured over 25 spring–neap cycles. In addition both SSC and sedimentation rates are higher during winter than during summer for the same inundation height or time. Although spatial differences in vegetation characteristics are large between and within the studied salt and freshwater marsh, they do not affect the spatial sedimentation pattern. Sedimentation rates however strongly decrease with increasing (1) surface elevation, (2) distance from the nearest creek or marsh edge and (3) distance from the marsh edge measured along the nearest creek. Based on these three morphometric parameters, the spatio-temporal sedimentation pattern can be modelled very well using a single multiple regression model for both the salt and freshwater marsh. A method is presented to compute two-dimensional sedimentation patterns, based on spatial implementation of this regression model. Copyright © 2003 John Wiley & Sons, Ltd.

KEY WORDS: saltmarsh; freshwater marsh; suspended sediment concentration; sediment deposition; Schelde river

INTRODUCTION

Within the estuarine and coastal environment, tidal marshes play an important role as essential habitats for plants and animals and as sinks and/or sources for nutrients, pollutants and sediments (Allen, 2000). These functions of tidal marshes are strongly affected by sedimentation and changes in marsh surface elevation, whether this is in balance with relative sea level rise or not. Much attention has been paid to the quantification of sedimentation rates on tidal marshes, and especially to the question as to whether or not marsh sedimentation will be able to keep up with sea level rise. A wide range of measuring techniques have been used to quantify marsh sedimentation rates, over time-scales from one single tidal cycle up to several hundreds of years, including sediment traps (e.g. Reed, 1989; French *et al*., 1995; Leonard, 1997; Allen and Duffy, 1998b), artificial or natural marker horizons (e.g. French and Spencer, 1993; Roman *et al*., 1997), sedimentation–erosion tables (e.g. Cahoon *et al*., 2000), and dating of sediment cores using palaeoenvironmental, radiometric or geochemical techniques (e.g. Cundy and Croudace, 1996; Roman *et al*., 1997).

Only a few studies have addressed both spatial and temporal variations in contemporary marsh sedimentation and the physical processes controlling these variations, although such studies are extremely important to understand the basic mechanisms of tidal marsh sedimentation. Furthermore, sedimentation processes were studied mainly on salt marshes. Studies on freshwater tidal marshes are very sparse and have been carried out mainly in US marshes (e.g. Orson *et al*., 1990; Pasternack and Brush, 2001; Neubauer *et al*., 2002), while data from NW European freshwater tidal marshes are lacking. Some studies on salt marshes reported that temporal variations

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in sedimentation rates are mainly controlled by tidal inundation height (Allen and Duffy, 1998a; Christiansen *et al*., 2000). Others indicated that wind–wave activity is the dominant controlling factor, leading in some cases to reduced sedimentation or even erosion (Pethick, 1992; Van Proosdij *et al*., 2000), but in other places to increased sediment inputs and consequently higher sedimentation rates (Reed, 1989; Leonard *et al*., 1995). In addition seasonal patterns are reported and these are often attributed to variations in biological activity (Hutchinson *et al*., 1995; Leonard *et al*., 1995; Leonard, 1997; Pasternack and Brush, 2001). Spatial sedimentation patterns seem to be related to several parameters like marsh surface elevation (e.g. Stoddart *et al*., 1989; Cahoon and Reed, 1995), the tidal creek network (e.g. French and Spencer, 1993; French *et al*., 1995; Leonard, 1997; Reed *et al*., 1999), and differences in vegetation structure (Leonard *et al*., 1995; Leonard, 1997; Boorman *et al*., 1998). However, the relative importance and interactions between the different variables thought to control temporal and spatial variations in marsh sedimentation rates are poorly understood. As a consequence, these overall spatial and temporal variations are difficult to predict.

This paper presents a detailed study on the spatial and temporal sedimentation patterns in two contrasting marsh types within the Scheldt estuary, a salt and freshwater tidal marsh. First, field measurements are carried out to identify the relative importance of the various factors controlling spatial and temporal variations in sedimentation rates. Secondly, it was investigated to what extent both spatial and temporal variations can be correctly predicted using a relatively simple, topographically based model that integrates the effects of the different controlling variables. Finally, special attention is given to whether sedimentation patterns are different within the studied salt and freshwater marsh.

THE STUDY AREA

The Scheldt estuary (e.g. Meire *et al*., 1992), situated in the southwest of the Netherlands and the northwest of Belgium (Figure 1), is characterized by a semidiurnal, meso- to macrotidal regime. The mean tidal range at the mouth in the southern North Sea ranges between 4·46 and 2·97 m during spring and neap tides respectively (Claessens and Meyvis, 1994). As the tidal wave enters the estuary, these mean tidal ranges increase to 5·93 m and 4·49 m at Schelle and then decrease further inland to 2·24 m and 1·84 m near Ghent. The freshwater discharge of the Scheldt catchment varies between 50 $m^3 s^{-1}$ during dry summer and 300 $m^3 s^{-1}$ during wet winter months (Taverniers, 2000). Its influence on water levels is only significant at the inland border of the

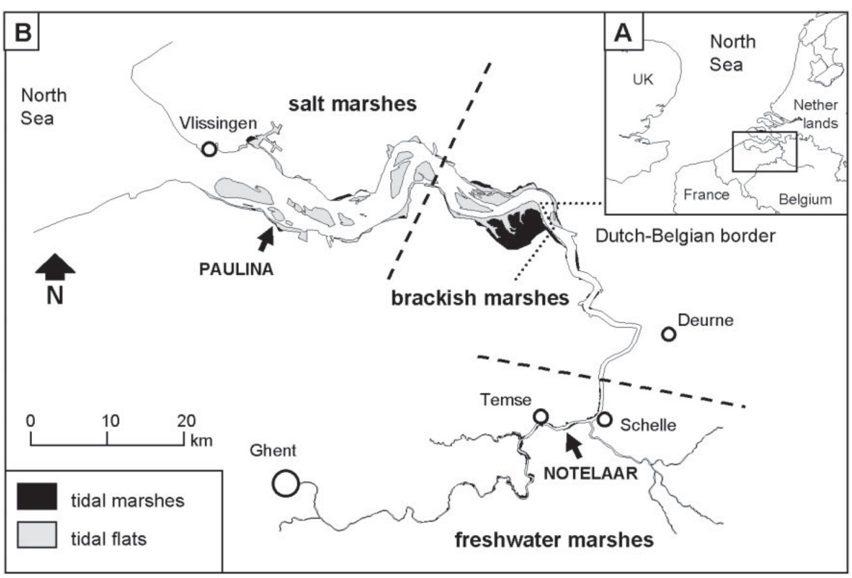

Figure 1. The Scheldt estuary: (A) location within western Europe; (B) location of salt, brackish and freshwater tidal marshes together with the study areas, the Paulina and Notelaar marsh

estuary and decreases rapidly seaward. Strong northwesterly winds can create large storm surges with resulting high water levels 2 to 3 m higher than the mean high water level (Claessens and Meyvis, 1994). Wave action due to wind is expected to decrease landward from the mouth, as a consequence of declining fetch distances along the estuary.

The suspended sediment concentration (SSC) in the stream channel of the Scheldt estuary typically varies in time and space, both longitudinally along the estuary and vertically within the water column (Wartel, 1973, 1977). The SSC in the upper part of the water column (which floods the tidal marshes) varies along the 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 (Van Eck *et al*., 1991; Van Damme *et al*., 2001). Further upstream the SSC again decreases to 50–100 mg l^{-1}. Large temporal variations in SSC however occur, depending on semidiurnal, spring–neap and seasonal variations in tidal range and fresh water discharge (e.g. Fettweis *et al*., 1998).

Along the Scheldt estuary a full salinity gradient exists from salt to fresh water. As a consequence the tidal marshes in the estuary range from salt marshes, with typical halophytic vegetation, over brackish marshes, with partially halophytic/helophytic plant species, to freshwater tidal marshes, which are covered only with helophytes (Figure 1B) (Van den Bergh *et al*., 2001). Between these marsh types there is a remarkable difference in vegetation height, which ranges from maximum 0·4–0·8 m on the salt marshes up to 4 m on the freshwater marshes.

Along these estuarine gradients, two contrasting study areas were chosen: (1) the Paulina marsh, a salt marsh near the mouth where average SSC (around 50 mg l^{-1} near the water surface) and mean tidal range (3·9 m) are lowest; (2) the Notelaar marsh, a freshwater tidal marsh near Temse with highest average SSC (100–200 mg l^{-1}) and tidal range (5·3 m) (Figure 1B). Both study sites are similar in surface area and geomorphology, typically consisting of a vegetated marsh platform, dissected by networks of tidal creeks that narrow and shallow inland. The most visible contrasting element is the marsh vegetation. The Paulina marsh is overgrown with typical NW European salt marsh species, such as *Puccinellia maritima*, *Aster tripolium* and *Atriplex portulacoides* in high interior marsh basins and mainly *Elytrigia pungens* on the natural levees. In front of the high Paulina marsh, a lower marsh exists which is typically dominated by *Spartina townsendii* (Figure 2b) (Houtekamer, 1996). On the contrary, the Notelaar marsh has a typical freshwater marsh canopy, with a community of *Phragmites australis* in the lower parts of the marsh and a community of *Salix* sp. in the higher parts (Figure 2a) (Hoffmann, 1993).

METHODOLOGY

Field sampling sites

In order to study the impact of spatial factors on the sedimentation pattern, permanent sampling sites were established along a series of transects covering the main geomorphic units and vegetation types on the salt and freshwater marsh (Figure 2 and Table I). Three transects were chosen perpendicular to three similar first-order marsh creeks, containing one measuring site on the natural levee, bordering the creek, and two sites in the lower inner marsh basin, at a distance of 20 and 40 m from the creek. One transect was established in a typical high salt marsh canopy (sites 10, 11, 12), and two transects in the two dominating freshwater vegetation types, *Phragmites australis* (sites 1, 2, 3) and *Salix* (sites 7, 8, 9). Another two transects were established over the whole width of the marsh perpendicular to the marsh edge, both on the salt marsh (sites 13 to 17) and freshwater marsh (sites 4 to 6). On the salt marsh this transect contains sampling sites on the high marsh as well as on the lower *Spartina* marsh. All transects were surveyed relative to Belgian Ordnance Level (TAW, which is approximately 2·3 m below mean sea level at the Belgian coast), using an electronic total station (Sokkia SET5F). The sites were further described for their vegetative characteristics (plant species and, where possible, stem density and height) and grain size characteristics of surface sediments, sampled with metal rings (0·05 m in diameter and height) and analysed following the standard sieve-pipette method (Table I).

Measuring sediment supply and deposition

Temporal variations in overmarsh suspended sediment concentrations were measured during a one-year period (from April 2000 until May 2001) from an automatic sampling platform located in a central marsh basin in both

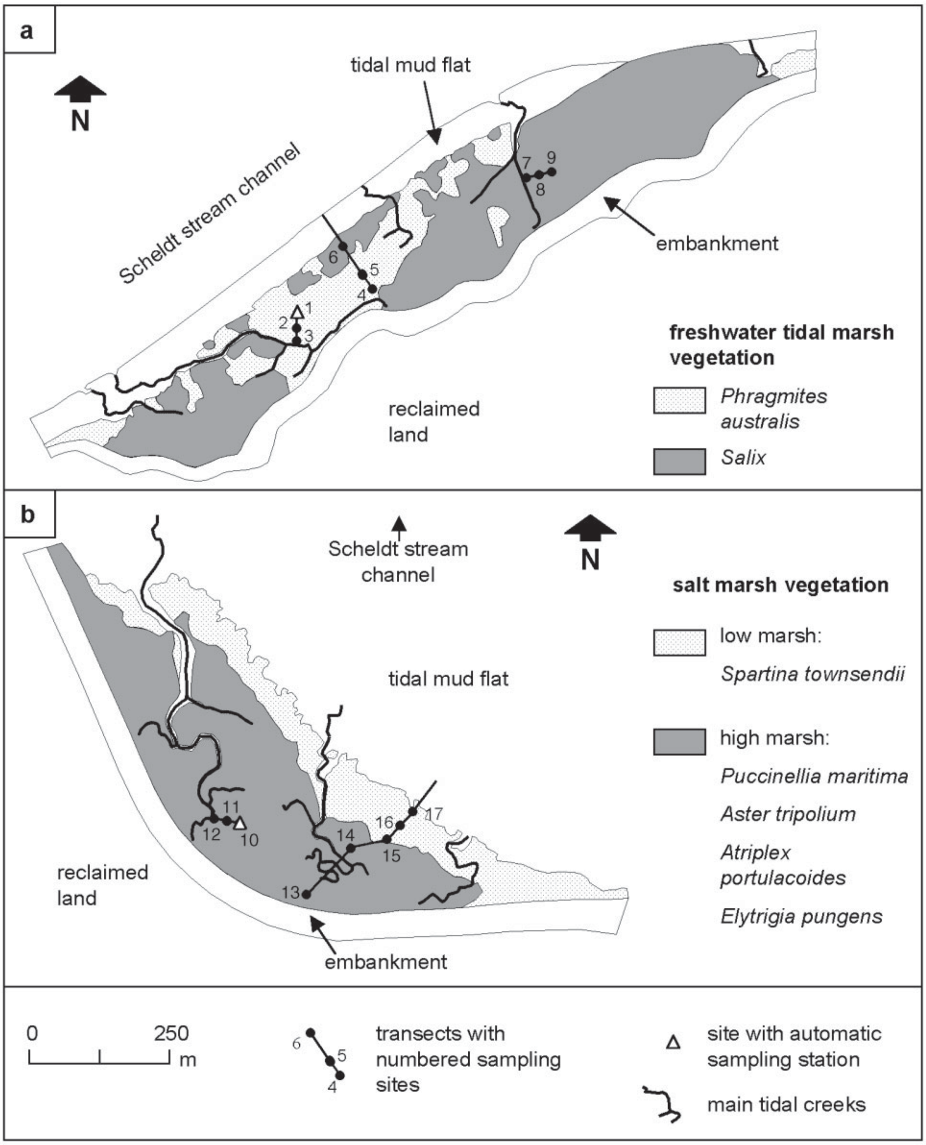

Figure 2. Maps showing vegetative cover and sampling sites at (a) the Notelaar marsh and (b) the Paulina marsh

studied marshes (site 1, 10; Figure 2). For every tidal inundation, the water level above the marsh surface was recorded every 5 min, using an ISCO flowmeter 4220, and 1 litre water samples were pumped up from 0·15 m above the marsh surface, using an ISCO sampler 6700. For each inundation cycle a first sample was automatically taken once the inundation height exceeded 0·15 m. Subsequent samples were taken every 30 min, until the marsh was no longer submerged. Every 15 days (at every neap tide) the filled bottles were collected and new empty ones were placed in the sampler. To determine the suspended sediment concentration (SSC in g l^{-1}), the water samples were filtered in the laboratory with preweighed filter papers (pore diameter 0·45 μm), which were subsequently washed through with deionized water to remove salts. Samples of only four or five inundation events were analysed for each spring–neap cycle, so that the full range of low to maximum inundation events during that spring–neap cycle was covered. In all, 245 samples were analysed, covering 27 per cent of all inundation events during the measuring period.

Table I. Description of measuring sites for geomorphic situation, dominant plant species, stem density and height (at the end of the growing season), mean sand and clay content of surface sediment

Site	Geomorphology*	Dominant plant species	Stem density† (m^{-2})	Stem height (m)	Sand (%)	Clay (%)
1,2,4,5	Ba	*Phragmites australis*	90–140	3·7–4·0	1·2	28·9
3	Le	*Impatiens glandulifera*	60–90	2·2–2·9	1·1	32·9
6,7	Le	*Salix* sp.	–	>4·0	25·6	26·7
8,9	Ba	*Salix* sp.	–	>4·0	1·4	44·1
10,11,14	Ba	*Puccinellia maritima,*		0·1–0·3	2·5	31·2
		Atriplex portulacoides	–	0·2–0·5		
12	Le	*Elytrigia pungens*	–	0·3–0·7	51·4	17·0
13	Ba	*Elytrigia pungens*	–	0·3–0·7	1·7	26·2
15	Lo	*Aster tripolium,*	40–50	0·4–0·7	16·5	23·4
		Salicornia	180–240	0·1–0·3		
16,17	Lo	*Spartina townsendii*	400–600	0·4–0·6	11·4	31·5

* Geomorphic units: Ba, inner basin; Le, levee; and Lo, low marsh without basin–levee morphology.
† –, Stem density was not estimated given the nature of vegetation cover (grass, trees).

During the same one-year period, we also sampled the sediment that settled out from suspension on the marsh surface using on all sampling sites circular plastic sediment traps (diameter 0·233 m). The traps were attached to the marsh surface using steel claws and were constructed with a floatable cover to protect the deposited sediment from splash by raindrops during low tides. Every 15 days (at neap tide after each spring–neap cycle) the traps were collected and replaced by clean ones. In the laboratory, the deposited sediment was washed from the traps and rinsed with deionized water, to remove salts, and sieved at 707 µm, to remove macroscopic plant and/or shell material that floated and deposited on the traps. The remaining sediment was then oven-dried at 105 °C and weighed to determine the deposition rate of suspended sediment (in g m^{-2}). In all, 425 samples were analysed, covering all 25 spring–neap cycles during the year and all 17 sampling sites.

Data assessment and analyses

The water surface was assumed to be horizontal at high tide, so that for each inundation event and every sampling site maximum inundation height was calculated based on the water level measurements at sites 1 and 10 on the Paulina and Notelaar marsh respectively, and considering the elevation differences between the sites. Corresponding inundation time was calculated using the observed relationship between maximum inundation height and time ($R^2 = 0{\cdot}89$ and 0·96 for the Paulina and Notelaar marsh respectively). By adding up inundation times of individual inundation events, cumulative inundation times were calculated for each spring–neap cycle. Since cumulative inundation time reflects both the magnitude and frequency of inundations during a spring–neap cycle, this parameter was found to be the best to characterize tidal marsh inundation during this time period, over which sedimentation rates were measured. Daily mean wind velocities and directions at Vlissingen (Royal Dutch Meteorological Institute, KNMI) and Deurne (Royal Meteorological Institute of Belgium, KMI) were used as proxy data for wave activity near the Paulina and Notelaar marsh respectively (Figure 1B).

These time-series of wind–wave and tidal activity, together with data on spatial factors like topographic situation and vegetation cover, were analysed for influence on measured SSC and sedimentation rates, using t-test procedures, one-way analysis of variance (ANOVA) and regression analysis. All statistical analyses were performed using SAS/STAT software (SAS Institute Inc., 1989). Based on regression models, maps of the spatial sedimentation pattern were computed in IDRISI (Eastman, 1994).

RESULTS

Exploratory data representation

In Figure 3 the distribution of sedimentation rates is summarized by boxplots, representing both the spatial variations between the sampling sites and temporal variations between spring–neap cycles. Time-averaged

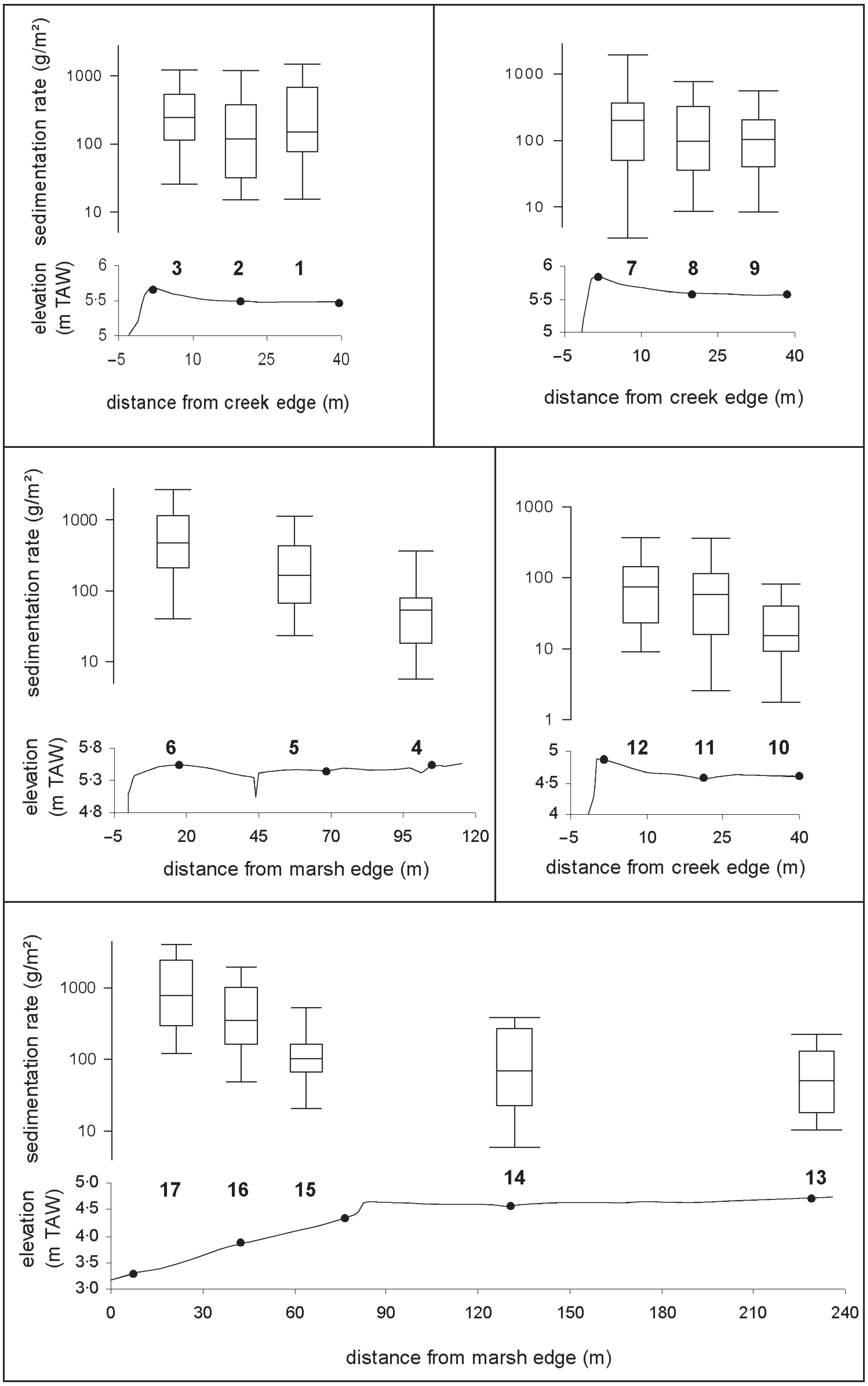

Figure 3. Whisker boxplots of sedimentation datasets, obtained by measurements over 25 spring-tidal cycles at 17 sampling sites. The boxplots are plotted with respect to the position of sampling sites along the transects, situated as shown on Figure 2

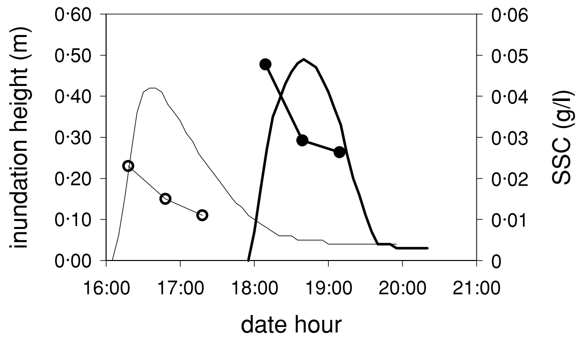

Figure 4. Typical example of the temporal evolution of the inundation height above the marsh surface (in solid lines) and suspended sediment concentration (SSC; in symbols and lines) during a tidal inundation at the Paulina marsh (thin lines and white symbols) and Notelaar marsh (thick lines and black symbols)

Table II. *P*-values resulting from unpaired t-tests comparing initial suspended sediment concentration (ISSC) and sedimentation rate data (logSR) between winter and summer period at each measuring site (since variances of summer and winter data sets are unequal, *P*-values using Satterthwaite's computational method are presented here (SAS Institute Inc., 1989)). *P*-values in bold indicate that the difference between winter and summer period is *not* significant ($\alpha = 0{\cdot}01$) at these sites. For all other sites there is a significant difference between winter and summer data

Data	Site	*P*	Data	Site	*P*	Data	Site	*P*
ISSC	1	<0·0001	logSR	6	**0·0393**	logSR	12	**0·0235**
	10	<0·0001		7	0·0027		13	**0·0525**
logSR	1	0·0002		8	0·0003		14	0·0037
	2	<0·0001		9	0·0009		15	0·0051
	3	0·0082		10	0·0054		16	**0·0400**
	4	0·0008		11	0·0020		17	**0·0561**
	5	0·0041						

sedimentation rates spatially range from 40 to 1650 g m^{-2} per spring–neap cycle, while at each sampling site temporal variations are high, ranging in the order of 1 to 10^3 g m^{-2} per spring–neap cycle. The sedimentation data sets are typified by skewed distributions, and are therefore first log transformed for each sampling site to enhance normality for further t-tests and ANOVA.

Temporal patterns of sediment dynamics

During all sampled inundation cycles SSC is found to decrease with time, indicating that the suspended sediment is continuously settling during the whole duration of inundation and that no resuspension occurs during ebb tide (e.g. Figure 4). However the initial SSC (ISSC), measured at the beginning of marsh flooding, varies considerably from one tide to another. Figure 5 shows that the ISSC linearly increases with maximum inundation height, recorded at high tide, for all sampled inundation events, both at the Notelaar and Paulina marsh. In addition this increase of ISSC with inundation height is greater during the winter period (October–March) than during the summer period (April–September). An unpaired t-test showed that the difference in ISSC between winter and summer is significant for both studied marshes (Table II).

The measured sedimentation rates vary between spring–neap cycles following a similar temporal pattern. Figure 6 shows that sedimentation rates increase exponentially with cumulative inundation time. Especially for inner marsh sites sedimentation rates are significantly higher during winter than during summer for the same inundation time, while for sites situated next to creeks or marsh edges this seasonal difference is not always significant (Figure 6, Table II).

Apart from tidal and seasonal influence, the role of wind–wave activity was examined. Table III shows that for most sampling sites no significant relationship could be found between ISSC or sedimentation rates (SR) on

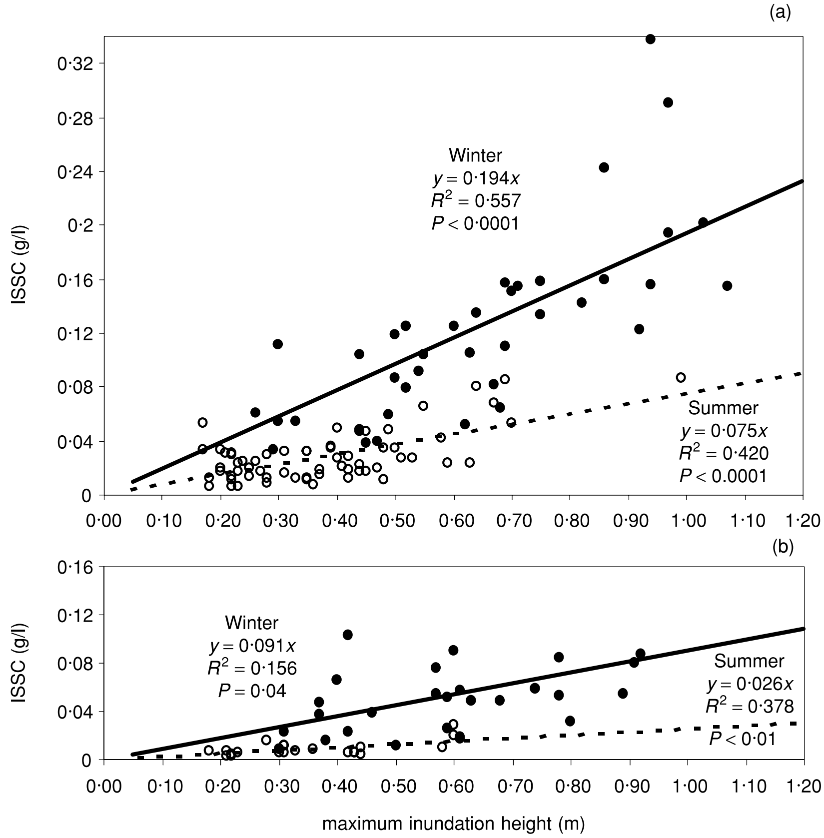

Figure 5. Linear relationship between initial suspended sediment concentration (ISSC) and maximum inundation height observed at (a) the Notelaar marsh (site 1) and (b) the Paulina marsh (site 10). Note the difference between summer (April–September; indicated in white symbols and broken line) and winter (October–March; in black symbols and solid line) observations. Part (a) reprinted from Temmerman *et al.* (2003), Figure 8, with permission from Elsevier Science

the one hand and average wind speeds on the other hand (see columns (b) and (e) in Table III). The relationship with tidal inundation height or time is on the contrary highly significant for most sites (columns (a) and (d)). For these sites the remaining variation, expressed by the residuals resulting from regression between ISSC/SR and inundation height/time, is also not significantly related to average wind velocity (columns (c) and (f)). Only for sites 15–17, situated on the *Spartina* marsh, sedimentation rate is not significantly related to inundation time and better related to average wind velocity, especially for the winter period. This may be an indication that these marsh sites, situated on the lower *Spartina* marsh bordering the marsh edge, are more sensitive to wind–wave activity.

Spatial sedimentation patterns

Figure 3 illustrates well that the spatial sedimentation pattern is influenced by the marsh surface topography. A first topographic control is exerted by marsh surface elevation: low-lying marshes, such as the *Spartina* marsh (sites 15, 16, 17), are characterized by much higher sedimentation rates than high marshes (sites 10 to 14), due to more frequent, higher and longer inundations during the same spring–neap cycle (Figure 7a). However, measuring sites which are situated next to tidal creeks or marsh edges do not follow this relationship. Only when these sites are omitted from Figure 7a is a strong relationship found between sedimentation rate and elevation.

A second topographic control is exerted by distance from the sediment source: along each sampling transect sedimentation rates decrease with increasing distance from the creek or marsh edge (Figure 3). ANOVA confirms that sedimentation rates in inner marsh basins are not significantly different from each other, while they

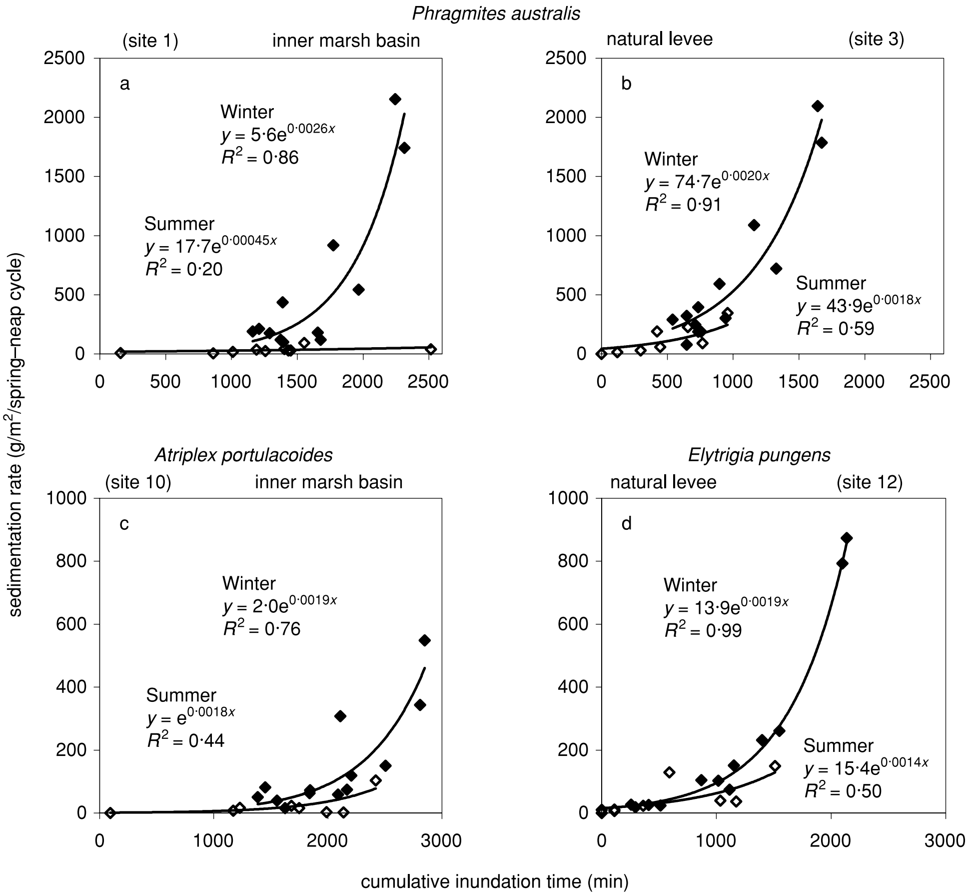

Figure 6. Exponential relationship between sedimentation rate (per spring–neap cycle) and cumulative inundation period (added up over all inundation cycles during a spring–spring cycle). Examples are shown for (a) a freshwater *Phragmites australis* marsh basin (site 1), (b) the adjoining natural levee (site 3), (c) a high salt marsh basin (site 10) and (d) the adjoining levee (site 12). Note the differences in axis. Summer (April–September) and winter (October–March) observations are plotted in white and black symbols respectively. The sampling site locations are shown on Figures 2 and 3

are significantly higher on the levees (Table IV). Figure 7b shows that for all sampling transects the time-averaged sedimentation rate, expressed relative to its value next to the creek or marsh edge, decreases exponentially with increasing distance from the creek or marsh edge. However, sampling sites 16 and 17 do not fit this model and are omitted, because sedimentation is here strongly influenced by the much lower marsh elevation. Our data further suggest that absolute sedimentation rates are highest at the marsh edge and decrease along marsh creeks with increasing distance from the marsh edge (Figure 7c).

The influence of the different marsh vegetation types on the spatial sedimentation pattern is illustrated by the time-averaged sedimentation gradients, as measures for the efficiency of sediment trapping perpendicular to marsh and creek edges. Surprisingly, these gradients are the same for all studied vegetation types (Figure 7b), indicating that the intensity of sediment trapping is not influenced by the large differences in plant species, height and growing density (Table I). ANOVA confirms that sedimentation rates in freshwater tidal marsh basins with *Phragmites australis* or *Salix* vegetation are not significantly different (Table IV). The difference between low (*Spartina townsendii)* and high salt marsh vegetation (mainly *Puccinellia maritima, Aster tripolium* and *Atriplex portulacoides*) is significant (Table IV), but this is a consequence of difference in surface elevation rather than in vegetation structure (Figures 3 and 7a). Also the significant difference between freshwater and salt marsh basins (Table IV) may not be attributed to the vegetation cover, but to marsh topography.

Table III. R^2 and P-values resulting from linear regression analyses: (a) between initial suspended sediment concentration (ISSC) and maximum tidal inundation height (I_h); (b) between ISSC and daily mean wind velocity (W_d); (c) between the residuals from regression (a) ($ISSC_{Res}$) and W_d; (d) between sedimentation rate per spring–neap cycle (logSR) and cumulative tidal inundation time (I_t); (e) between SR and daily mean wind velocity averaged over the whole spring-neap cycle W_{sn}; (f) between the residuals from regression (d) (SR_{Res}) and W_{sn}. All regression analyses (a to f) are carried out for winter and summer data separately. Notice that for most sampling sites significant relationships ($P < 0{\cdot}05$) are found only between ISSC/logSR and tidal inundation height/time (indicated in bold). Only for sites 15–17, situated on the low *Spartina* marsh near the marsh edge, is sedimentation rate better related to mean wind velocity

Site	ISSC summer data						ISSC winter data					
	(a) ISSC × I_h		(b) ISSC × W_d		(c) $ISSC_{Res} \times W_d$		(a) ISSC × I_h		(b) ISSC × W_d		(c) $ISSC_{Res} \times W_d$	
	R^2	P	R^2	P	R^2	P	R^2	P	R^2	P	R^2	P
1	**0·42**	**<0·01**	<0·01	0·75	0·03	0·21	**0·56**	**<0·01**	0·04	0·20	<0·01	0·70
10	**0·38**	**<0·01**	0·07	0·34	0·14	0·15	**0·16**	**0·04**	0·02	0·43	<0·01	0·79

Site	SR summer data						SR winter data					
	(d) logSR × I_t		(e) SR × W_{sn}		(f) $SR_{Res} \times W_{sn}$		(d) logSR × I_t		(e) SR × W_{sn}		(f) $SR_{Res} \times W_{sn}$	
	R^2	P	R^2	P	R^2	P	R^2	P	R^2	P	R^2	P
1	0·35	0·07	0·02	0·78	0·03	0·73	**0·54**	**<0·01**	0·09	0·36	0·05	0·51
2	**0·41**	**0·04**	0·15	0·40	0·03	0·71	**0·58**	**<0·01**	0·09	0·36	0·01	0·74
3	**0·71**	**<0·01**	0·39	0·13	0·44	0·11	**0·76**	**<0·01**	0·18	0·19	<0·01	0·78
4	**0·67**	**<0·01**	0·13	0·42	<0·01	0·88	**0·59**	**<0·01**	0·28	0·10	0·06	0·48
5	**0·59**	**<0·01**	0·42	0·12	0·28	0·22	**0·82**	**<0·01**	0·20	0·16	0·10	0·36
6	**0·77**	**<0·01**	0·08	0·53	0·20	0·31	**0·64**	**<0·01**	0·19	0·18	0·02	0·67
7	**0·85**	**<0·01**	0·07	0·58	0·09	0·51	**0·87**	**<0·01**	0·16	0·23	0·02	0·65
8	**0·70**	**<0·01**	0·33	0·17	0·20	0·31	**0·60**	**<0·01**	0·05	0·51	0·13	0·29
9	**0·84**	**<0·01**	0·11	0·47	<0·01	0·86	**0·76**	**<0·01**	0·21	0·15	<0·01	0·81
10	0·23	0·20	0·02	0·74	0·03	0·68	0·12	0·30	0·16	0·22	0·33	0·07
11	**0·46**	**0·04**	<0·01	0·93	0·03	0·66	**0·64**	**<0·01**	0·02	0·64	0·17	0·19
12	**0·60**	**0·01**	<0·01	0·98	<0·01	0·83	**0·97**	**<0·01**	<0·01	0·85	0·13	0·25
13	0·28	0·15	0·21	0·22	0·18	0·26	**0·86**	**<0·01**	0·03	0·61	0·12	0·27
14	**0·59**	**0·01**	<0·01	0·82	0·04	0·61	0·10	0·33	0·03	0·62	0·07	0·41
15	0·43	0·05	0·41	0·07	**0·55**	**0·02**	0·08	0·37	**0·47**	**0·01**	**0·34**	**0·05**
16	0·16	0·29	<0·01	0·89	0·01	0·77	0·07	0·44	0·18	0·19	0·21	0·15
17	0·07	0·52	<0·01	0·88	0·07	0·48	0·06	0·46	**0·39**	**0·03**	0·24	0·10

An integrated spatio-temporal model

The above-described analyses showed that spatial variations are partly explained by elevation differences, which are in fact equivalent to differences in tidal inundation height and duration, which are the main factors controlling temporal variations in sedimentation. It is then worthwhile to investigate to what extent both spatial and temporal sedimentation patterns can be described in terms of a limited number of controlling parameters, which interrelate and act synergistically.

A multiple non-linear regression model of the following form is proposed:

$$SR = k e^{lH} e^{mD_c} e^{nD_e} \tag{1}$$

where SR = the sedimentation rate (g m^{-2} per spring–neap cycle), H = the intensity of tidal inundation (this parameter will be further specified below), D_c = the distance to the nearest creek or marsh edge (m) and D_e = the

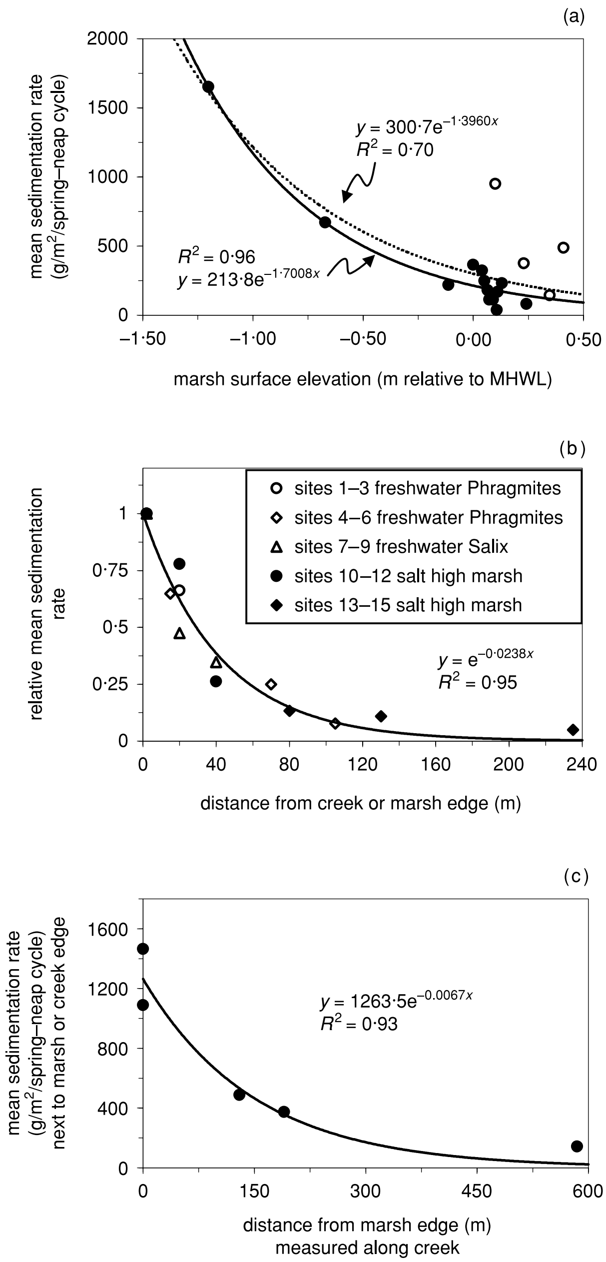

Figure 7. (a) Mean sedimentation rate per spring–neap cycle in relation to marsh surface elevation (expressed relative to local mean high water level) for all sampling sites. White dots indicate data points from levees (sites 3, 6, 7, 12) and are incorporated in the construction of the broken regression line but omitted in the construction of the solid regression line. (b) Relative mean sedimentation rate in relation to distance from the creek or marsh edge for all sampling transects situated within different vegetation types (see Figure 2 for location of the transects). (c) Absolute mean sedimentation rate next to creek or marsh edges in relation to distance from the marsh edge, measured along the creek system

distance to the marsh edge (m), measured along the nearest creek. For sampling transects perpendicular to the marsh edge, D_e is set to zero. The model parameters *k*, *l*, *m* and *n* are determined using a non-linear regression procedure in SAS/STAT (SAS Institute Inc., 1989).

First, regression analysis was carried out with sedimentation rates averaged over the one-year measuring period as the dependent variable and incorporating the spatial variation between all salt and freshwater marsh

Table IV. One-way ANOVA results for intercomparison between measuring sites during the winter, summer and whole one-year measuring period. Pr > F-values in bold indicate that the difference in ISSC or sedimentation rate (SR) between compared sites is *not* significant ($\alpha = 0.05$). In all other cases there is a significant difference between sites

Data type	Intercomparison between	Compared sites	Pr > F		
			Winter	Summer	Year
SR	Fresh basins	1, 2, 5, 8, 9	**0·3733**	**0·3074**	**0·4236**
	Fresh basins & levees	1, 2, 5, 8, 9, 3, 6, 7	**0·0739**	0·0160	0·0278
	Salt basins	10, 11, 13, 14	**0·1904**	**0·6411**	**0·6881**
	Salt basins & levees	10, 11, 13, 14, 12	0·0042	**0·2853**	0·0236
	Salt high & low marsh	10 to 17	<0·0001	<0·0001	<0·0001
	Fresh & salt basins	1, 2, 5, 8, 9, 10, 11, 13, 14	<0·0001	0·0165	<0·0001
ISSC	Fresh & salt basin	1, 10	<0·0001	<0·0001	0·0028

Table V. Model parameters (k, l, m, n) and R^2-values resulting from multiple non-linear regression analyses using Equation 1 (see text)

SR data	k	l	m	n	R^2
Whole year average per site	1174·9	−0·3165	−0·0195	−0·0058	0·95
Winter average per site	1565·5	−0·3352	−0·0174	−0·0046	0·93
Summer average per site	737·3	−0·2036	−0·0298	−0·0137	0·98
Winter all data	275·8	0·3006	−0·0216	−0·0043	0·68
Summer all data	129·6	0·3943	−0·0392	−0·0075	0·56

sites. In this case H is estimated by surface elevation relative to local mean high water level. Figure 8a compares sedimentation rates as observed and estimated by the regression model. It can be seen that the model is able to predict almost all of the observed spatial variability ($R^2 = 0.95$) without considering the large differences in vegetation structure between the salt and freshwater marsh sites.

Secondly, a similar regression analysis was carried out, taking the distinction between winter and summer sedimentation into account. Again, observations and model predictions are in good agreement (Figure 8a; $R^2 = 0.93$ and 0·98 for winter and summer respectively). The model parameter k is larger for the winter than for the summer period, indicating that sediment input is larger during winter (Table V). The parameter l is more negative during winter, which means that elevation differences have then a more pronounced effect on variations in sedimentation rate. Seasonal differences in m and n values suggest that sedimentation gradients along and perpendicular to tidal creek edges are less pronounced during winter than during summer. This confirms that sediment trapping during flooding from the creeks to the inner marshes is greater during summer and consequently less sediment reaches the inner marsh basins (see also Figure 6).

Finally, it was also investigated whether both temporal and spatial variations between spring–neap cycles and between sampling sites can be modelled using Equation 1. In this case H is estimated by cumulative inundation height and is both time- and space-dependent. Figure 8b shows that the presented model structure can partly explain the observed spatio-temporal sedimentation pattern ($R^2 = 0.68$ and 0·56 for winter and summer respectively).

Based on the regression models it is now possible to generate maps of the fully two-dimensional sedimentation pattern in a raster-based geographical information system (GIS). For each raster cell that represents the marsh surface a value of H, D_c and D_e has to be calculated. This was done for a raster image with 1 m by 1 m cells of the Paulina marsh, where elevation data are available from airborne laser altimetry conducted by the Dutch Rijkswaterstaat Meetkundige Dienst (minimum density 1 point/16 m^2, guaranteed minimal vertical accuracy of 0·20 m) (Van Heerd and Van 't Zand, 1999). From these elevation points a digital elevation model was

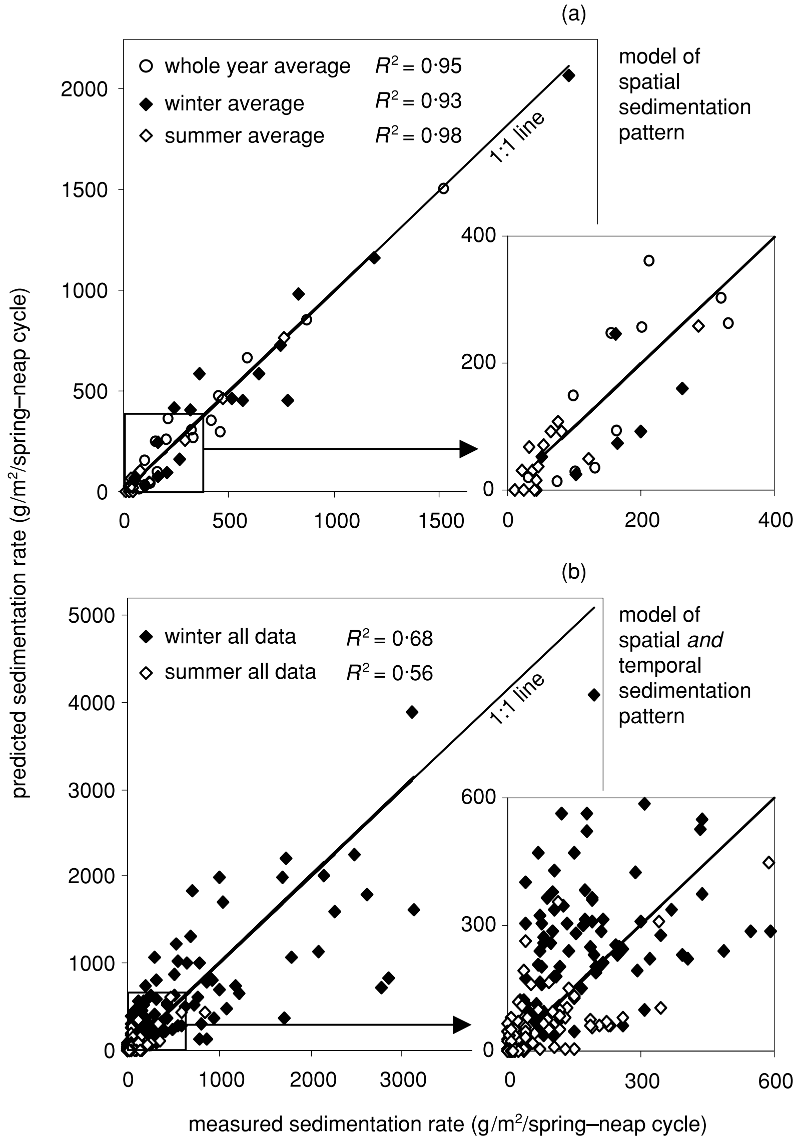

Figure 8. Comparison of sedimentation rates per spring–neap cycle as measured and predicted using multiple non-linear regression (see text). (a) The model incorporates only the spatial sedimentation pattern by using for all sampling sites sedimentation rates averaged over the whole one-year measuring period, over the winter and over the summer period. (b) The model incorporates both the spatial and temporal sedimentation pattern by using sedimentation rates as measured at each sampling site and for each individual spring–neap cycle during the year. Regression was carried out separately for all winter and all summer data

computed using a triangulation with linear interpolation method. The tidal creek network was digitized based on georeferenced recent aerial photographs and converted to a raster image. For each marsh surface cell, the distance to the nearest tidal creek cell (D_c in Equation 1) and the distance of this nearest tidal creek cell to the creek mouth at the marsh edge, measured along the creek (D_e in Equation 1), was calculated using the program modules DISTANCE, COST and ALLOCATE in IDRISI (Eastman, 1994). Finally the sedimentation rate in every marsh surface cell was calculated by solving Equation 1 and using the calculated values of H, D_c and D_e. Maps of the whole year averaged and summer and winter averaged sedimentation rate per spring–neap cycle were made using the appropriate model parameters in Table V. Figure 9a clearly shows that the calculated sedimentation pattern is the result of the combined influence of surface elevation, the creek network, and

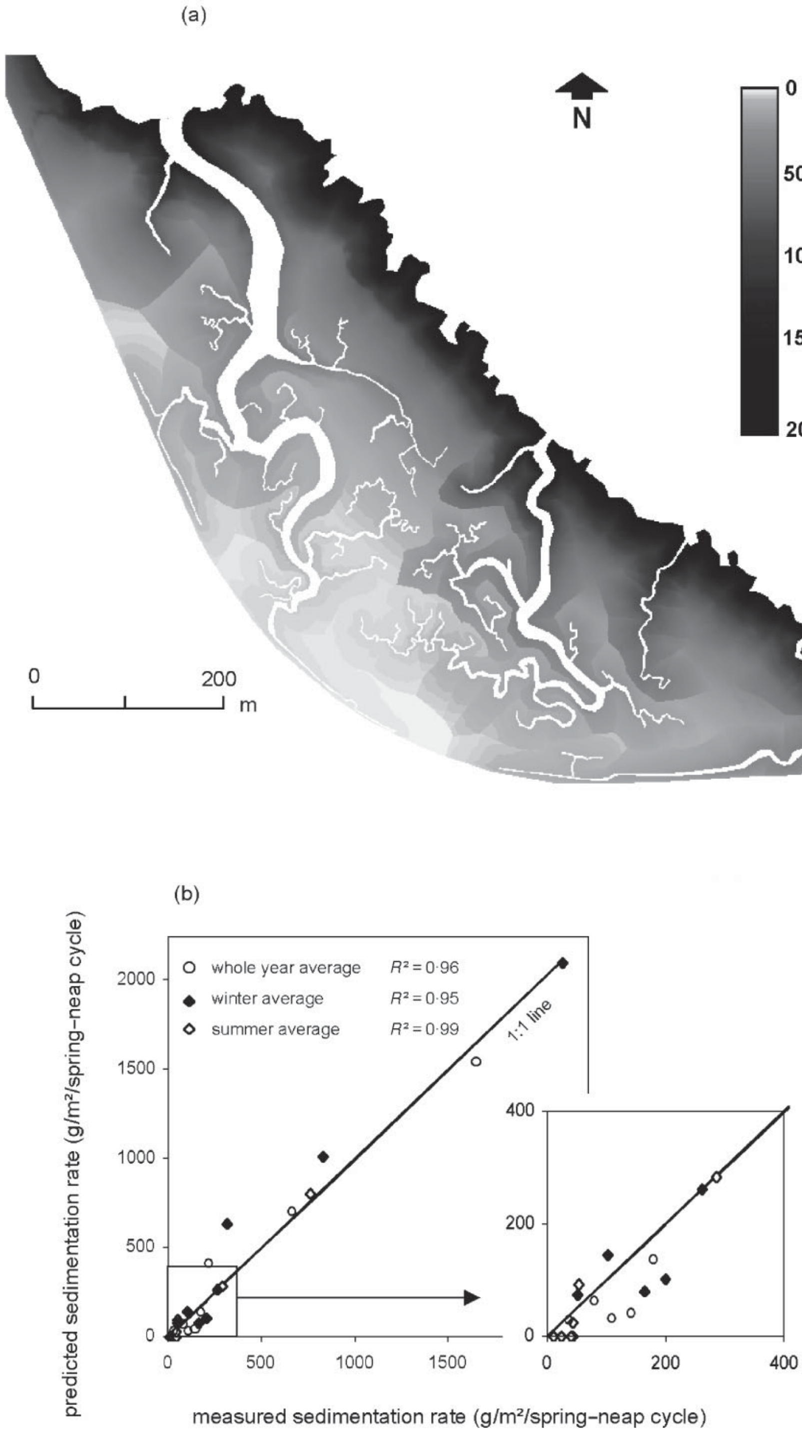

Figure 9. (a) Simulation of the spatial sedimentation pattern at the Paulina marsh averaged over one year (in g/m^2/spring–neap cycle). (b) Comparison between sedimentation rates per spring–neap cycle as measured and predicted after implementation of the regression model in a GIS (see text) for sedimentation rates averaged over one year, over the winter and over the summer period

distance to the marsh edge. Measured and calculated sedimentation rates at the measuring sites are in very good agreement (Figure 9b), indicating that the proposed method is very useful to compute two-dimensional patterns of tidal marsh sedimentation.

DISCUSSION AND CONCLUSIONS

As reported from earlier studies, short-term temporal sedimentation patterns are in some tidal marshes mainly controlled by wind–wave activity (Reed, 1989; Leonard *et al*., 1995; Van Proosdij *et al*., 2000), while other studies indicate that tidal influence is more dominant (Allen and Duffy, 1998a; Christiansen *et al*., 2000). In the meso- to macrotidal Scheldt estuary the tide is the most important factor that governs temporal patterns of tidal marsh sedimentation.

For almost all sampling sites we observed an exponential increase of marsh sedimentation with increasing inundation time. The exponential nature of this relationship can be explained as a consequence of a linear increase in ISSC with maximum inundation height. Based on numerical modelling, Temmerman *et al.* (2003) showed that the relationship between sedimentation rate and inundation time is exponential when ISSC increases linearly with inundation height, while the relationship between sedimentation rate and inundation time is linear when ISSC is assumed to be constant. The fact that an exponential relationship between sedimentation rate and inundation time is found for most sampling sites suggests that the linear increase of ISSC with increasing inundation height is a general mechanism that controls suspended sediment supply to the marsh surface.

Seasonal variations in sedimentation rates on tidal marshes are reported by several authors (e.g. Hutchinson *et al*., 1995; Leonard *et al*., 1995; Leonard, 1997). Higher sedimentation rates are often found during the summer period, which is explained by higher bioturbation of bottom sediments, leading to higher SSC and tidal marsh sedimentation rates. However, we observed higher overmarsh SSC and sedimentation rates during the winter period for the same inundation height or time. This is in accordance with the higher SSC values observed in the stream channel of the Scheldt during the winter period (Fettweis *et al*., 1998).

The difference between winter and summer sedimentation rates is most important in inner marsh basins, while this seasonal difference is not significant near creek and marsh edges. One possible explanation could be that sediment trapping along flow paths from creeks to inner marshes is enhanced during the summer period, as a consequence of higher growing densities and hydraulic resistance by marsh plants during summer (see also Boorman *et al*., 1998) or by higher settling velocities of the suspended sediment during summer, for example due to enhanced bioflocculation. Consequently less sediment is reaching the inner marsh basins during the summer period. At this moment, however, quantitative data are lacking and further research is needed to fully understand this seasonal sedimentation pattern.

Our study shows that the spatial depositional pattern on the tidal marshes along the Scheldt estuary can be predicted from three morphometric variables only. As has been widely reported from other salt marshes, sedimentation rates decrease with increasing surface elevation (e.g. Stoddart *et al*., 1989; Cahoon and Reed, 1995) and with increasing distance from tidal creeks (e.g. French and Spencer, 1993; French *et al*., 1995; Leonard, 1997; Reed *et al*., 1999). Our study further shows that sedimentation rates along creek edges decrease with increasing distance from the marsh edge, measured along the creek system. While former studies focused on the identification of the different possible controlling variables, our study clearly shows that both spatial and temporal sedimentation patterns can be well predicted using a single multiple regression model that only incorporates the three controlling variables discussed above.

The fact that the same model very well predicts the sedimentation patterns and rates on a salt and freshwater marsh, located at the extremes of the estuarine gradient, suggests that the physical–sedimentological processes controlling tidal marsh sedimentation are similar over the whole estuarine gradient of the Scheldt estuary. The differences in vegetation characteristics, which strongly vary between and within the studied salt and freshwater marshes, seem to have no detectable influence on the spatial sedimentation pattern. Marsh vegetation of course reduces tidal currents and therefore promotes sediment deposition (Leonard *et al*., 1995; Leonard and Luther, 1995). However, it seems that very high and dense vegetation, which is typical for a freshwater *Phragmites australis* or *Salix* marsh, is not more effective in tempering flow speeds and trapping sediments than typically lower salt marsh plants such as *Puccinellia maritima* and *Atriplex portulacoides*.

In former studies, two-dimensional sedimentation patterns were calculated from a spatial network of measuring sites, using conventional spatial interpolation techniques like kriging (French and Spencer, 1993; Leonard, 1997) and bilinear interpolation (French *et al.*, 1995). French *et al.* (1995) especially emphasized the difficulties of calculating sedimentation rates based on interpolation of spatially distributed measurements. In this regard, this paper presents an alternative method to calculate two-dimensional spatial sedimentation patterns, by spatially implementing an empirical model that takes into account the physical variables that determine the spatial distribution of sediment over the marsh surface. Inundation frequency, height and duration are reflected in the model by surface elevation, while the transport pathways of the sediment are reflected by the distance from the creeks and the distance from the marsh edge measured within the creek system. Although the combined influence of surface elevation and the creek network is successfully modelled, our approach also has certain limitations. Especially where creek basins with an important difference in distance from the creek mouth are adjacent, strong discontinuities in sedimentation rates may appear (Figure 9a). In order to handle such difficulties a more hydrodynamically based model has to be used, which takes into account the complex flow of water and suspended matter over the marsh surface topography and through the marsh vegetation cover.

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