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Conditional effects of tides and waves on short-term marsh sedimentation dynamics

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ABSTRACT: Salt marshes are in danger of degradation due to human impact and climate change. A thorough understanding of mechanisms controlling sedimentation and erosion in salt marshes is essential for their conservation and restoration. To understand short-term dynamics of sediment availability and deposition around marsh edges, two contrasting marshes, Rattekaai and Sint Annaland, were studied in the Oosterschelde (southwest Netherlands). Suspended sediment concentration (SSC) was measured by siphon samplers along four transects perpendicular to the marsh edge in each marsh, during nine flood tides between March and December 2013. Each transect was comprised of four sampling sites (−10 m and −1 m on the mudflat and +1 m and +10 m on the marsh plateau, relative to the marsh edge). Sediment deposition was measured along the transects on the marsh, at +1 m and +10 m from the marsh edge, over seven *c.* 14-day intervals during the same 10-month period. Two types of sediment traps were used, one measuring gross sediment deposition (TTD – tube trap deposition) and one measuring net sediment deposition (FTD – filter trap deposition). Wave loggers were deployed 10 m away from the marsh edge on the mudflat at each marsh. The results showed that both SSC and sediment deposition varied greatly through space, both between the two marshes and within each marsh along the marsh edge. The SSC and gross sediment deposition were much higher at Rattekaai than at Sint Annaland. SSC was significantly correlated with wind speed during sampling. Sediment deposition rates (TTD and FTD) and retention ratio (FTD/TTD) were significantly correlated with cumulative wave energy during the measurement period. A conceptual model of local sediment dynamics is proposed to explain the sediment dynamics around the marsh edge. This study highlights the importance of incorporating local sediment dynamics when evaluating marsh vulnerability and stability. Copyright © 2018 John Wiley & Sons, Ltd.

KEYWORDS: sediment supply; deposition; suspended sediment concentration; salt marsh; wave

Introduction

Salt marshes contribute important ecosystem services to estuarine and delta systems, as they constitute important habitats to species and sites of high organic matter production and carbon storage (Costanza *et al.*, 1997; Allen, 2000; Gedan *et al.*, 2009; Barbier *et al.*, 2011). However, many salt marshes are endangered, either by direct human pressure such as land reclamation, or as a consequence of drowning of estuaries and deltas due to sea-level rise, human-induced accelerated soil subsidence and sediment starvation. These factors are closely related to changes in (estuarine and upstream) land use, river management and construction of dams and barriers.

Delta recession resulting from reduced riverine sediment supply has been observed in many places. The sediment delivery to coastal Louisiana has diminished by over 50% during the last 150 years and the delta can no longer grow as it once had due to urbanization and land reclamation (Morang *et al.*, 2013). In the Yangtze delta, riverine sediment discharge has declined by 15% from 1958 to 1978 to 1978–1997 and delta net accretion decreased from 38 mm yr^{-1} in 1958–1978 to 8 mm yr^{-1} in 1978–1997 (Yang *et al.*, 2003).

These changes in sediment supply to estuaries and deltas have consequences for the development and survival of salt marshes, as suspended sediment load is one of the determining factors controlling sediment deposition in these wetlands (French and Spencer, 1993; Middelkoop and Asselman, 1998). Due to compaction and natural subsidence, a minimal rate of sediment deposition is needed to maintain coastal wetlands at a constant height relative to sea level.

Several studies investigated the stability and vulnerability of salt marshes with changes in sediment supply (French, 2006; Mariotti and Fagherazzi, 2010; Kirwan *et al.*, 2011; Mudd, 2011; Weston, 2013; Ma *et al.*, 2014). The progradation and recession of marshes is thought to largely depend on the sediment supply. Increases in sediment supply will result in increased marsh extent while reduction in sediment supply will slow down the progradation or even cause net erosion (Yang *et al.*, 2001; Mudd, 2011).

The existence and survival of tidally dominated and predominantly allochthonous marshes relies not only on system-scale sediment supply but also depends on local hydrodynamic and sedimentary processes (Harrison and Bloom, 1977; Cahoon and Reed, 1995; Allen, 2000; French, 2006; Kirwan and Megonigal, 2013; Kirwan *et al.*, 2016). Storm events and wind-induced waves significantly contribute to deposition and vertical accretion of salt marshes (Stumpf, 1983; Reed, 1989; Christiansen, 1998; Yang *et al.*, 2003; Bartholdy *et al.*, 2004; Turner *et al.*, 2006; Williams and Flanagan, 2009; Coulombier *et al.*, 2012; Schuerch *et al.*, 2012; Schuerch *et al.*, 2013), although these events may also enhance erosion (Leonardi and Fagherazzi, 2014; McLoughlin *et al.*, 2015) It is hypothesized that during storms there is an increased sediment supply to the marshes due to increased re-suspension of sediments on the intertidal flats and in the shallow subtidal areas of the tidal basin in front of the marsh. In addition, depth as well as duration of inundation of the marsh plateau increase during storms (Schuerch *et al.*, 2013). However, waves can also stir up sediment at the edges of the marsh plateau and cause local erosion.

Although the importance of episodic sediment deposition during storm events or high wave periods has been acknowledged and some empirical and modeling work has been carried out, the underlying mechanisms of sediment supply and deposition during such events are still not well understood. Firstly, most studies relating storms or waves to marsh sedimentation have not directly measured wave parameters, but inferred wave events indirectly from wind speed (Stumpf, 1983; Turner *et al.*, 2006) or high water levels (Reed, 1989). Secondly, most studies have investigated the spatial variation of suspended sediment concentration (SSC) and sediment deposition within one single marsh (Coulombier *et al.*, 2012; Temmerman *et al.*, 2005). Thirdly, very few studies have differentiated between gross sediment deposition and net sediment retention in the marsh. In this study, we have measured (1) SSC during spring tides at the mudflat–marsh edge transition and (2) short-term sediment deposition (gross and net) and retention ratio (net deposition/gross deposition) within neap–spring–neap tidal cycles at the marsh edge. This was done in different periods of the year at two different salt marshes in the Oosterschelde (southwest Netherlands), with contrasting elevation within the tidal frame and different wind fetch. We focus on the marsh edge as the most active zone in terms of sediment dynamics. We address the following questions: (1) how do sediment dynamics vary between marshes and along marsh edges within a marsh; (2) what is the role of wind and waves on sediment availability; (3) what is the role of waves and storm setup on sediment deposition and retention ratio at the marsh edge? We propose a conceptual model summarizing sediment dynamics around the marsh edge under different wave and tide conditions.

Study Area

The Oosterschelde is located in the southwest of the Netherlands. Following a destructive storm surge, a storm surge barrier in the mouth of the Oosterschelde and two large compartmentalization dams in the rear ends of the estuary were constructed from 1979 to 1986 (Nienhuis and Smaal, 1994). The tidal range in the middle of the estuary decreased by about 12% and SSCs in the channels dropped by 52–70% (Brinke, 1994; Ma *et al.*, 2014). Today the mean tidal range varies from about 2.5 m near the mouth to about 3.4 m in the landward part of the basin. The time-averaged SSCs in the gullies vary from around 15 $\mathrm{mg\,l^{-1}}$ near the mouth to around 10 $\mathrm{mg\,l^{-1}}$ in the rear ends (Ma *et al.*, 2014), Wave records (1977–1990) indicate that, during the prevailing southwest–northwest (SW–NW) winds, the mean significant wave height declines from around 40 cm near the mouth to 10 cm in the basin of the Oosterschelde. The maximum tidal current velocities are 1–1.5 $\mathrm{m\,s^{-1}}$ in the tidal channels and 0.2–0.4 $\mathrm{m\,s^{-1}}$ on the tidal flats and sandy shoals.

Rattekaai (RK, 135 ha) and Sint Annaland (SA, 177 ha) are the two largest salt marshes in the Oosterschelde. The dominant plant species include *Spartina anglica*, *Halimione portulacoides*, *Elymus athericus* and *Puccinellia maritima* at RK and *Halimione portulacoides*, *Elymus athericus* and *Festuca rubra* at SA (van Maldegem and de Jong, 2003). In front of RK a much larger mudflat area is present than in front of SA (Figure 1). During high water, the wind fetch at RK is much larger than at SA, at least during north and northwest winds. Maximum fetches are 42.6 and 9 km at RK and SA respectively. Marsh mean elevation is +2.05 m NAP (Dutch Ordnance level, which is similar to local mean sea level) at RK and + 1.71 m NAP at SA (Ma *et al.*, 2014). The yearly mean flood duration is 2.2% and 3.7% at RK and SA respectively (Ma *et al.*, 2014).

Methods

Experimental setup

Marsh edge transects

Within each marsh (RK and SA), four transects, aligned perpendicularly to the marsh edge were set up (Figure 1). Each transect contained four sampling sites. Two sites were located on the mudflat (−10 m and −1 m from the marsh edge); the other two were located on the marsh plateau (+1 m and +10 m from the marsh edge) (Figure 2). The elevation of each site was determined by differential global positioning system (dGPS) (receiver: Leica Viva GNSS GS12; controller: CS15) (Table I, Supporting Information Online Resources 1 and 2). A surface sediment sample was collected at each site using a syringe sediment corer with an inner diameter of 1.5 cm, and a depth of 1 cm in April 2013.

SSCs at the mudflat–marsh edge transition

SSC was measured with siphon samplers (SSs) along these four transects in each marsh, from −10 m in front of the marsh edge on the adjacent mudflat to +10 m within the marsh, during nine spring tide moments (SS1, SS2, SS3, SS4, SS5, SS6, SS7, SS8 and SS9) between March and December 2013 (Figure 3 and Supporting Information Online Resource 3).

The SSs were installed just before spring tide flood and collected manually after one day, i.e. two tidal cycles, to avoid collection of samples during the night (the single filled siphon sampler is assumed not to be influenced by the additional inundation once it is filled). The SSs were made from 1 l plastic bottles with two holes on the cap, one for incoming water and the other for air (Nolte *et al.*, 2013). Within each transect, all SSs were installed at the same elevation, which was determined as the elevation of the highest site in the marsh (i.e. the elevation of either the +10 m or +1 m site). A laser level (laser sender: Trimble precision laser [LL500], laser receiver: Trimble CR 600/HR 500) was used to level all SSs (Online Resource 2). The idea of placing the SSs at the same elevation is to avoid the influence of vertical variation in SSC. Additionally, for comparing the SSC of different transects inside each marsh and between marshes, one reference SS (installed next to the −10 m sites on the mudflat at sampling moments SS5, SS6, SS7, SS8

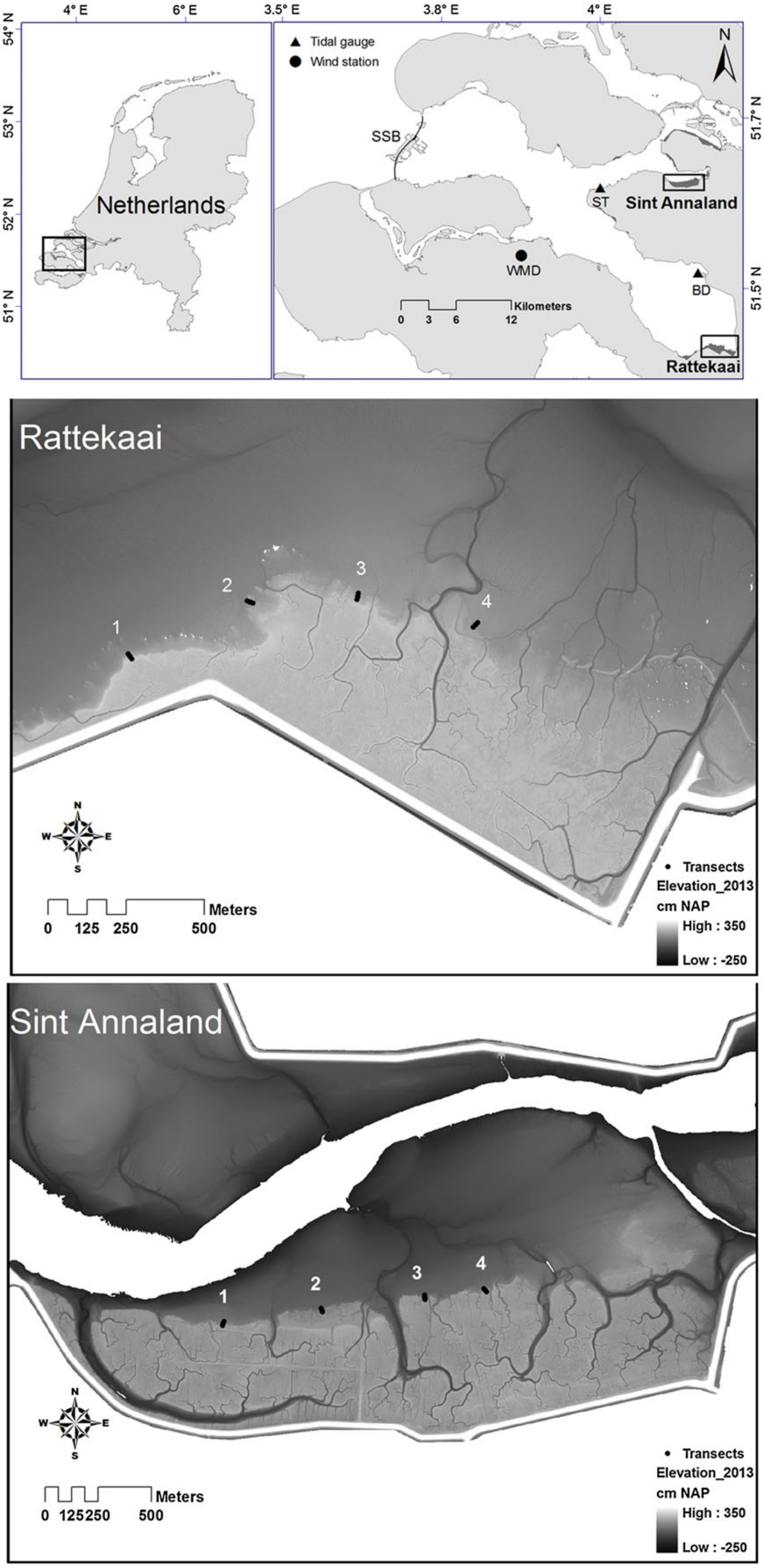

Figure 1. Study area location in the Netherlands (top left panel), the Oosterschelde (top right panel), with indication of the Storm Surge Barrier (SSB), the two marshes (Rattekaai and Sint Annaland), the nearby tidal gauge stations (Bergse Diepsluis west [BD] and Stavenisse [ST]) and the weather station (Wilhelminadorp [WMD]). Middle (Rattekaai) and bottom (Sint Annaland) panels demonstrate the position of the four transects inside each marsh. NAP = Dutch Ordnance Datum. [Colour figure can be viewed at wileyonlinelibrary.com]

and SS9, not at SS1, SS2, SS3 and SS4; Figure 2 and Online Resource 3) was installed at the same level as the mean high water level of that marsh (RK: + 1.86 m NAP obtained from nearby tidal gauge station Bergse Diepsluis west and SA: + 1.58 m NAP obtained from nearby tidal gauge station Stavenisse) (Table I and Online Resource 1; for location of tidal gauge

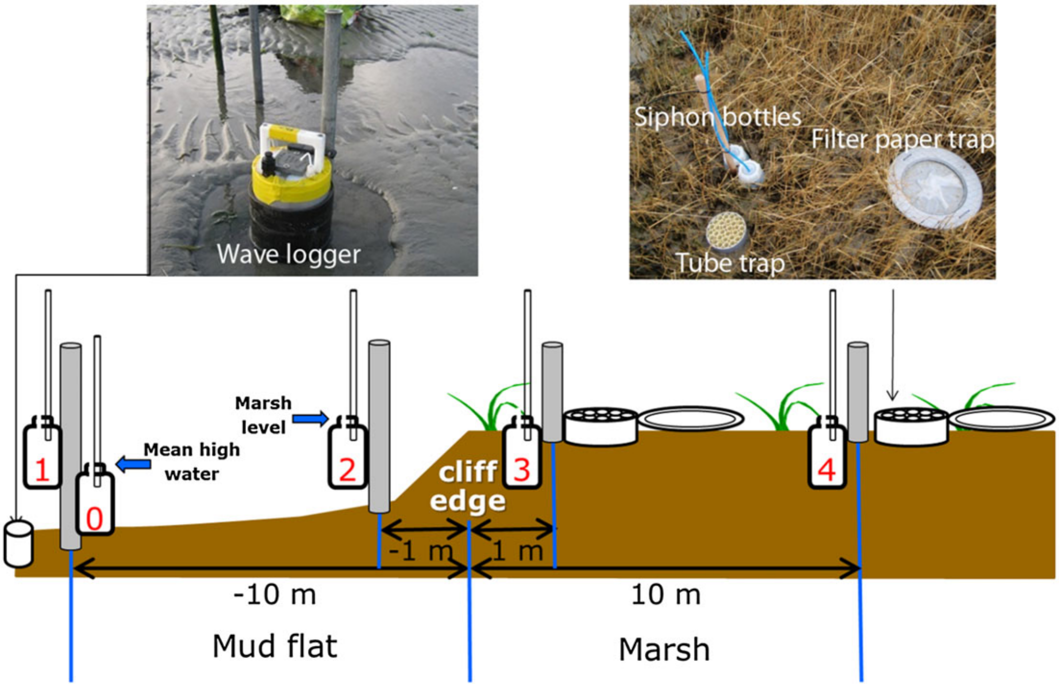

Figure 2. Deployment of the instruments and devices along each transect at the marsh edge. (Distance displayed in the figure is not proportional to real distance.) Along each transect located four fixed sampling sites: −10 m and −1 m on the mudflat, +1 m and +10 m on the marsh platform. One 1 l siphon sampler (bottles 1–4, leveled at the same height as the highest site on the marsh) was installed at each site and two different sediment traps (filter-paper traps [FTs] and tube traps [TTs]) at the two sites on the marsh platform. A reference siphon sampler (bottle 0, leveled to the mean high water of each individual marsh) was placed at site −10 m on the mudflat. A wave logger was installed at site −10 m at one of the transects in each marsh. [Colour figure can be viewed at wileyonlinelibrary.com]

Table I. Physical characteristics of studied transects and sites at Rattekaai and Sint Annaland

	Rattekaai			Sint Annaland		
	N	Mean ± SE	Range	*N*	Mean ± SE	Range
Elevation mudflat (m NAP)	8	1.65 ± 0.05	1.50–1.88	8	0.87 ± 0.07	0.65–1.12
Elevation marsh plateau (m NAP)	8	1.96 ± 0.09	1.66–2.40	8	1.49 ± 0.06	1.25–1.70
D_{50} mudflat (μm)	8	94.2 ± 6.1	70.6–112.9	8	113.9 ± 7.3	83.1–139.9
D_{50} marsh (μm)	8	88.6 ± 2.5	79.7–99.2	8	100.5 ± 1.8	92.6–109.0
Hourly mean wind speed (m s^{-1})	2222	4.9 ± 0.1	0–18	2222	4.9 ± 0.1	0–18
Hourly gust (m s^{-1})	2222	7.9 ± 0.1	1–27	2222	7.9 ± 0.1	1–27
Significant wave height (m)	425	0.071 ± 0.004	0.010–0.364	562	0.047 ± 0.002	0.010–0.574
Wave peak period (s)	425	2.3 ± 0.03	1.3–5.7	562	2.1 ± 0.02	1.1–7.3

Note: Elevation data were collected on October 2013. The sediment samples for grain size analysis were collected on April 2013. SE, standard error; D_{50}, median grain size.

stations see Figure 1). In total, 328 SSs were set up and 268 were actually filled during spring tides; the remaining SSs were not filled due to insufficient water level (Online Resource 3).

Sediment deposition and retention ratio at the marsh edge

Gross sediment deposition and net sediment deposition were measured along the transects at +1 m and +10 m from the marsh edge, using tube traps (TTs) and filter-paper traps (FTs) respectively, over seven (SD1, SD2, SD3, SD4, SD5, SD6 and SD7) 14-day periods (neap–spring–neap tidal cycle) during the same 10-month period (Figure 3 and Supporting Information Online Resource 4).

The sediment deposition determined by TTs and FTs were noted as TTD (tube trap deposition) and FTD (filter-paper trap deposition) respectively. Sediment retention ratio was determined as FTD/TTD. TTs were made from a large PVC tube (12 cm in diameter, 10 cm in height) filled with smaller PVC tubes (1 cm in diameter, 10 cm in height). One end of the large PVC tube was sealed with a PVC cap. The smaller PVC tubes were glued to each other on the long side. FTs consisted of circular filter paper (Whatman, Grade 50 Quantitative Filter Paper Hardened Low Ash, 240 mm in diameter) and filter paper holders (two stacked plastic plates, the center of the upper one was cut off to let the filter paper underneath receive sediment). The exposed filter paper had an area of 0.03 m^2 (Figure 2). Both traps were anchored at each marsh sites (+1 m and +10 m sites) with wooden pins (Figure 2). In total, 96 TTs and 112 FTs were deployed. All 96 TTs and 96 of the FTs were collected respectively after the neap–spring–neap cycle. A preliminary study demonstrated that very little sediment was captured if the traps were deployed over only one or two tidal inundations) (Online Resource 4). In some cases during

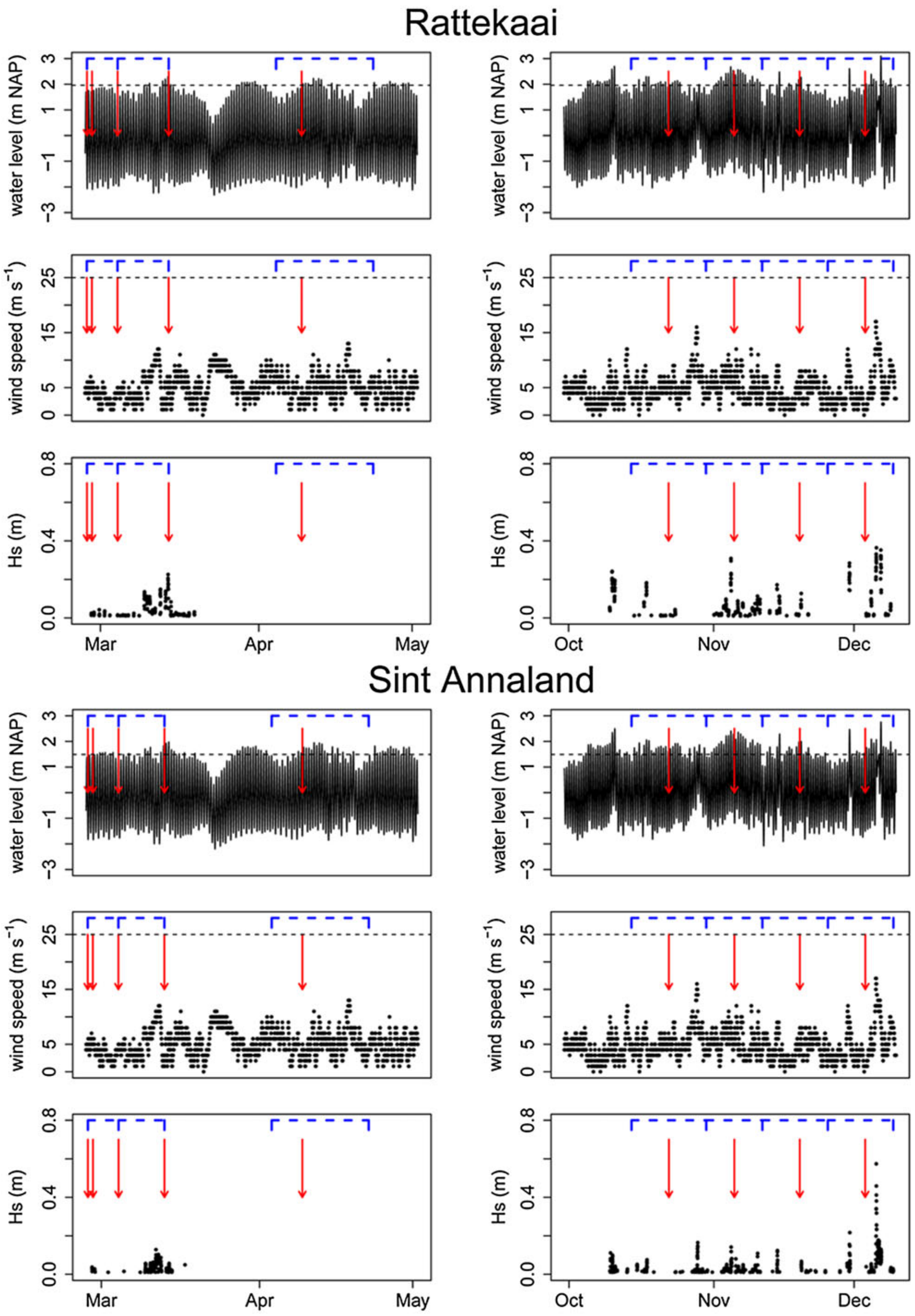

Figure 3. Suspended sediment concentration (SSC) and sediment deposition measuring schemes in 2013 at Rattekaai and Sint Annaland with corresponding water levels, wind conditions and wave conditions. Water levels are derived from the nearby tidal gauge stations, wind conditions from the nearby weather station (for the location of tidal gauge stations and weather station see Figure 1). Wind speeds are presented as hourly mean wind speed. The horizontal dash lines in the water level and wind plots indicate the mean marsh elevation (+2.05 m NAP at Rattekaai and +1.71 m NAP at Sint Annaland) and boundary wind speed for storm ($> 25\ \mathrm{m\ s^{-1}}$) respectively. Wave conditions are derived from locally measured water pressure and converted to significant wave height (Hs), no wave data are available in April since no wave loggers were deployed during April. The vertical red arrows indicate the deployment moments (*c.* spring tide) of the siphon samplers (from left to right, SS1–SS9); the blue dashed line segments indicate the deployment periods of filter-paper traps (FTs) (from left to right, SD1–SD7). Tube traps (TTs) deployment periods are the same as FTs except that the first deployment (from the end of February to around the middle of March) of the TT (from the end of February to around the middle of March) covered both the periods SD1 and SD2. [Colour figure can be viewed at wileyonlinelibrary.com]

storm events, a few FTs were dislodged, resulting in loss of measurement (Table I).

Wave measurements

To measure incoming wave intensity at the marsh edge, a wave logger was deployed on the mudflat (−10 m site) at the second transect of each marsh (Figure 2). Wave measurements were carried out in two different periods by pressure transducer sensors: from February to April 2013 and from October to December 2013 (for detailed observation scheme see Figure 3). OSSI-010-003B (Ocean Sensor Systems. Inc) loggers were used in the first period and MacroWave (Coastal Leasing. Inc) loggers were used in the second period to measure local wave activity. The sampling frequency of OSSI-010-003B in the first period was set to 5 Hz, sampling interval was 15 minutes and each burst (about nine minutes) contained 2700 records; the sampling frequency of MacroWave was set to 10 Hz, sampling interval was 15 minutes and each burst (about 3.4 minutes) contained 2048 records. .

Laboratory work

Samples from SSs were filtered (Whatman GF/F, 47 mm filters) immediately after arrival at the laboratory. The filter papers were rinsed with deionized water to remove salt. After filtration, the filter papers with sediment were dried in the oven (45°C, 12 hours). The sediment in the SS was determined as the weight difference between the dried filter paper with sediment and the original pre-dried blank filter paper. When the sediment in the SS was visually identified as a potential blockage (layer of around 0.5 mm thickness) for the filter paper, the samples were processed in two steps: first, most of the unmixed samples were passed through the filtration system; then, the residue left on the bottom of the bottle was well-mixed and transferred into a centrifuge tube. After centrifugation, the clear water on top was removed carefully and the residual sediment was oven-dried (45°C, 12 hours). The sediment in the SS was the combination of the two parts. Finally, the determined sediment mass in the SS was divided by the volume of the water sample. The SSC is expressed as mg l^{-1}.

The collected TTs were kept overnight in the refrigerator for sediment settling before further processing. The overlying water was removed carefully using a siphon. Then, the residual sediment was diluted with 10-times deionized water to minimize the influence of salt. After the suspended sediment was settled again, the overlying water was removed carefully using a siphon. Then the sediment was transferred into containers to freeze dry. The TTD was determined as the weight of freeze dried sediment divided by the area of TT opening and days the traps were in place. The retrieved FTs were disassembled carefully to prevent disturbing of the sediment deposited on top of the filter papers. The filter papers with sediment were folded into a funnel and attached to glass funnels. After the filter papers and sediment were rinsed carefully (plant detritus was removed) with deionized water, they were dried in the oven to constant weight (45°C). The FTD was determined as the weight difference between dried filter paper with sediment and the original pre-dried blank filter paper divided by area of FT and days the traps were in place. The TTD and FTD are expressed as g m^{-2} d^{-1}.

The surface sediment samples, collected in April 2013, were freeze dried and analyzed for grain size distribution by laser diffraction method with a Malvern Mastersizer 2000.

Data analysis

Wind data of 2013 from the KNMI (Royal Netherlands Metrological Institute) weather station Wilhelminadorp (Figure 1) were used to retrieve hourly mean wind speed (WH) and maximum wind gust (WX) during the whole observation period. Spectral analysis of pressure data was applied to compute the significant wave height (Hs) and peak period (Tp). SSC was related to wind speed and significant wave height at the sampling moment. Sediment deposition (TTD and FTD) were related to cumulative wave energy and flood duration. Cumulative wave energy is the time-integrated wave energy on the mudflat during immersion of the marsh plateau. Wave energy was calculated according to Callaghan *et al.* (2015). Flood duration was calculated according to Ma *et al.* (2014).

To improve the normality, raw data of SSC, TTD and FTD were $\log_{10}$ (value + 1) transformed and marked as SSC1, TTD1 and FTD1. Analysis of variance (ANOVA) was used to compare SSC1, TTD1 and FTD1 by factors marsh location, period and distance to marsh edge, and their interactions. Tukey's HSD (Honestly Significant Difference) tests were applied when ANOVA reported significant ($P < 0.05$) differences. A *t*-test was applied to compare differences between the two marshes (significance level $P < 0.05$). Pearson correlation was applied to explore the relationship between sediment dynamics and environmental factors (significance level $P < 0.05$).

Results

Characteristics of the two marshes

The mean elevation of the marsh edge plateau sites at RK (1.96 ± 0.09 m NAP) was higher than that at SA (1.49 ± 0.06 m NAP) and the range on values was also larger at RK (1.66–2.40 m NAP) than at SA (1.25–1.70 m NAP). The mean elevation of the mudflat sites was also similarly higher near the RK (1.65 ± 0.05 m NAP) than at SA (0.87 ± 0.07 m NAP), but the range was larger at SA (0.65–1.12 m NAP) than at RK (1.50–1.88 m NAP). The elevation profiles of each transect are shown in Online Resource 1. The median grain size (D_{50}) of surface sediment from SA was larger than from RK, both at the marsh plateau (101 μm versus 89 μm) and the mudflat (114 μm versus 94 μm). The sediment on the marsh plateau was finer than on the mudflat. Detailed sediment composition, vegetation type and ground elevation data of each site are given in Online Resource 2.

During the sediment trap deployment periods, the average hourly mean wind speed (WH) was 4.9 m s^{-1} (range 0–18 m s^{-1}). Maximum wind gust (WX) recorded exceeded 25 m s^{-1} on October 28 and December 5, 2013. Average significant wave height (Hs) during sediment trap deployment periods (excluding period SD3 when no wave loggers were deployed) was significantly higher for RK (0.071 ± 0.004 m) than for SA (0.047 ± 0.002 m) (*t*-test, $P < 0.001$); ranges were between 0.010–0.364 m and 0.010–0.574 m respectively (Table I).

Spatial variation in SSC

The reference SSs showed that average SSC at RK (602 ± 261 mg l^{-1}) was significantly higher than at SA (13 ± 2 mg l^{-1}) (*t*-test, $P < 0.001$).

The mean value of SSC (excluding the reference SSs of each transect) at RK (576 ± 137 mg l^{-1}) was significantly higher than that at SA (34 ± 5 mg l^{-1}) ($P < 0.001$, Table II). In each individual measuring period, the mean SSC at RK was consistently higher than at SA in the same period (except for SS4) (Online Resource 3).

The SSC increased from −10 m to +1 m and then declined from +1 m to +10 m along the marsh edge transects at both RK and SA (Figure 4). The mean SSC at +1 m site was significantly higher than at −10 m site (Table II, Tukey test, $P < 0.05$). The highest SSC values recorded at RK and SA were 10 666 mg l^{-1} (from SS8) and 287 mg l^{-1} (from SS3) respectively.

Spatial variation in sediment deposition and retention ratio

The mean sediment deposition at RK (TTD: 1013 ± 176 g m^{-2} d^{-1}; FTD: 35 ± 7 g m^{-2} d^{-1}) was several times higher than at SA (TTD: 344 ± 92 g m^{-2} d^{-1}; FTD: 7 ± 2 g m^{-2} d^{-1}). Mean

Table II. Analysis of variance (ANOVA) results for SSC1 (excluding reference ones), TTD1 and FTD1

Dependent variable	Independent variables	df	Sum squared	Mean squared	*F* Value	Pr(>*F*)
SSC1	Marsh (RK and SA)	1	46.78	46.78	563.928	***
	Moment (SS1–SS9)	8	45.28	5.66	68.232	***
	Distance[a] (-10, -1, +1, +10 m)	3	2.74	0.91	11.016	***
	Marsh–moment	8	11.77	1.47	17.734	***
	Marsh–distance	3	0.13	0.04	0.537	NS
	Moment–distance	24	3.61	0.15	1.815	*
	Marsh–moment–distance	24	1.52	0.06	0.766	NS
TTD1	Marsh (RK and SA)	1	12.217	12.217	37.766	***
	Period (SD1–SD7)	5	21.447	4.289	13.259	***
	Distance[a] (+1, +10 m)	1	9.303	9.303	28.759	***
	Marsh–period	5	2.167	0.433	1.34	NS
	Marsh–distance	1	0.386	0.386	1.192	NS
	Period–distance	5	2.962	0.592	1.831	NS
	Marsh–period–distance	5	0.436	0.087	0.269	NS
FTD1	Marsh (RK and SA)	1	6.632	6.632	43.122	***
	Period (SD1–SD7)	6	3.48	0.58	3.771	**
	Distance[a] (+1, +10 m)	1	1.127	1.127	7.325	**
	Marsh–period	6	1.298	0.216	1.407	NS
	Marsh–distance	1	1.175	1.175	7.642	**
	Period–distance	6	2.118	0.353	2.295	*
	Marsh–period–distance	6	0.199	0.033	0.216	NS

[a] Distance to marsh edge.

SSC1 = $\log_{10}$ (SSC+1); TTD1 = $\log_{10}$ (TTD+1); FTD1 = $\log_{10}$ (FTD+1).

SSC, suspended sediment concentration; TTD, tube trap deposition; FTD, filter-paper trap deposition.

NS = non-significant ($P > 0.05$);

*$P < 0.05$;

**$P < 0.01$;

***$P < 0.001$.

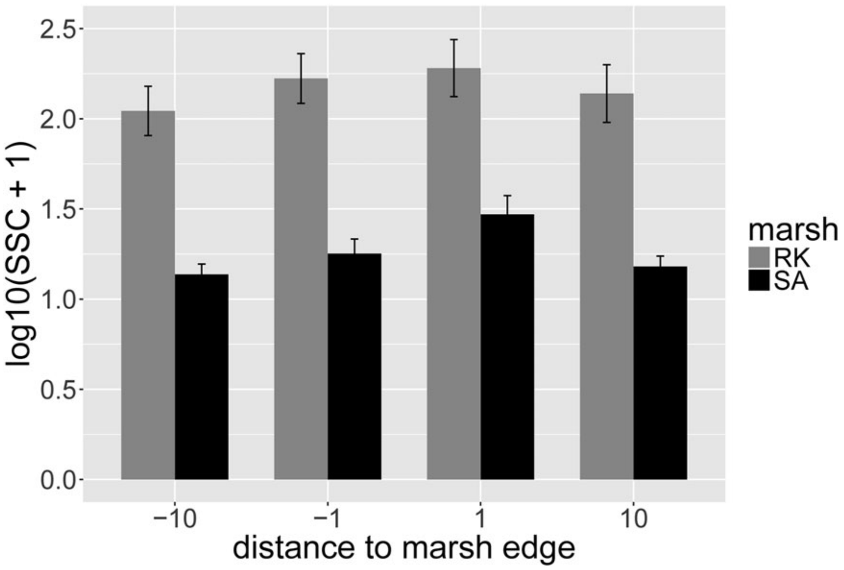

Figure 4. Spatial variation of suspended sediment concentration (SSC, in mg l^{-1}, log transformed) by factors marsh (RK – Rattekaai and SA – Sint Annaland) and distance to the marsh edge. Sampling points at a distance of −10 m and −1 m refer to the mudflat, sampling points at a distance of +1 m and +10 m refer to the marsh.

values of TTD and FTD were all higher at RK than at SA during all periods (Online Resource 4). The TTD from +1 m sites (1273 ± 276 g m^{-2} d^{-1} at RK and 514 ± 157 g m^{-2} d^{-1} at SA) had significantly higher mean values compared to the more inland +10 m sites (753 ± 210 g m^{-2} d^{-1} at RK and 175 ± 421 g m^{-2} d^{-1} at SA) (Figure 5 and Table II). The +10 m sites (56 ± 11 g m^{-2} d^{-1}) at RK had significantly higher mean FTD than at +1 m sites (13 ± 3 g m^{-2} d^{-1}) (Tukey test, $P < 0.05$) (Figure 5). In contrast, differences in FTD at SA at the +10 m sites (8 ± 3 g m^{-2} d^{-1}) and at +1 m sites (6 ± 1 g m^{-2} d^{-1}) were not significant (Tukey test, $P > 0.05$) (Figure 5).

The sediment retention ratio is defined as the ratio between FTD and TTD. The retention ratio is lower at the +1 m site than at the +10 m site further inland on both marshes (Figure 5). The mean retention ratios were comparable between RK and SA in +1 m and +10 m sites. Around 15% of sediment originally deposited on the +10 m sites was ultimately retained. For the +1 m sites, which are very close to marsh edge, only around

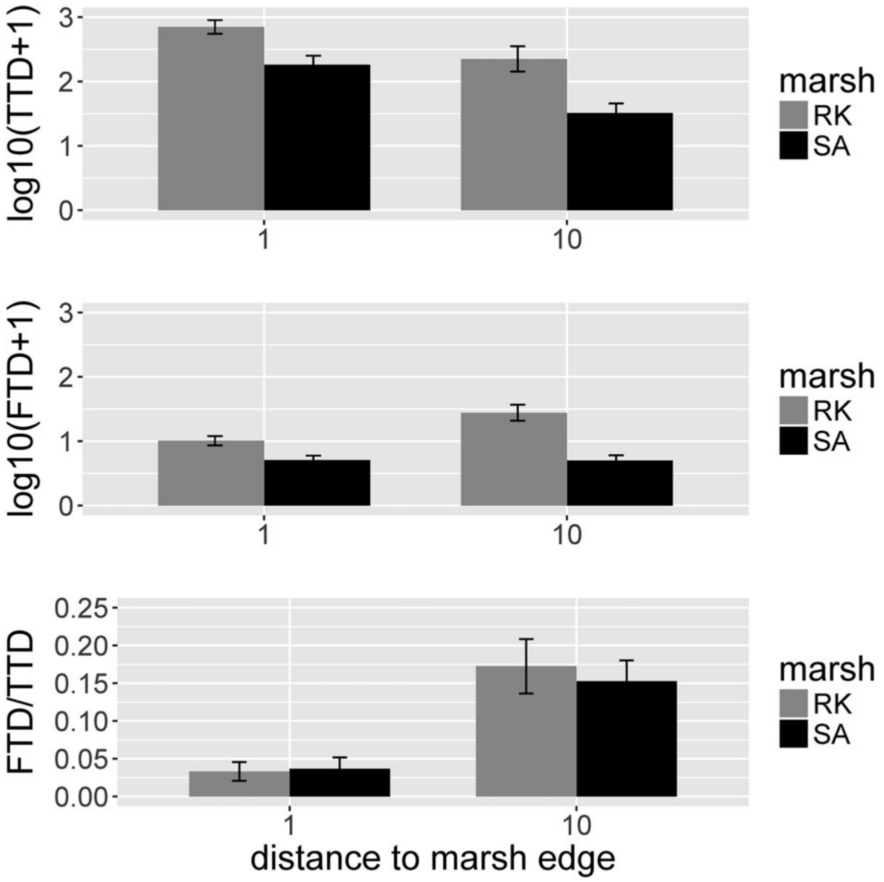

Figure 5. Spatial variation of sediment deposition (TTD and FTD, in g m^{-2} d^{-1}, log transformed) and retention ratio (FTD/TTD) by factors marsh (RK – Rattekaai and SA – Sint Annaland) and distance to marsh edge (+1 m and +10 m into the marsh, respectively). TTD, tube trap deposition; FTD, filter trap deposition.

2.5% of the sediment originally deposited was retained on the marsh (Figure 5).

Relationship between SSC and wind and wave conditions

The SSC was significantly correlated with wind speed at the sampling moment (Pearson correlation, $P = 0.047$), while the SSC was not significantly correlated with significant wave height at the sampling moment (Pearson correlation, $P = 0.538$) (Figure 6).

The mean SSC at sampling moments SS3, SS7 and SS8 showed significantly (Tukey test, $P < 0.05$) higher values than the other sampling moments at RK, but no significant difference was reported among these three sampling moments (Tukey test, $P > 0.05$). At SA, the mean SSC at SS3, SS4 and SS8 had significantly (Tukey test, $P < 0.05$) higher values than the mean SSC from the other sampling moments; the difference among these three sampling moments again was not significant (Tukey test, $P > 0.05$). To illustrate the temporal variation of environmental factors at the two marshes, Supporting Information Online Resource 5 shows water level, significant wave height and peak wave period during SS9.

Relationship between sedimentation, wave and flooding conditions

Short-term sediment deposition (TTD and FTD) and retention ratio significantly correlated with cumulative wave energy at the mudflat (RK and SA data together, Pearson correlation, all $P < 0.01$). However, there was no significant correlation between sediment deposition and flood duration (RK and SA data together, Pearson correlation, all $P > 0.1$) (Figures 7 and 8).

Sediment deposition (both TTD and FTD) showed an increase from SD3 to SD7 at both RK and SA (Online Resource 4). The highest TTD was observed in period SD7 at both RK and SA, while the highest FTDs occurred at SD5 at RK and SD7 at SA.

Discussion

Variation in SSC

Our study demonstrated that SSC, both on the mudflat before the marsh and on the marsh itself, was higher at RK than at SA. This finding is in agreement with a previous study, in which higher average SSC values were measured on the mudflat (one site about 30 m away from the marsh edge) at RK (120 mg l^{-1}) than at SA (26 mg l^{-1}) (Schoot and van Eerdt, 1985). The mudflat in front of RK is much wider than that in front of SA. These mudflats serve as potential source of re-suspended sediments to the marshes (Anderson *et al.*, 1981; Schuerch *et al.*, 2014). In addition, the larger open area in front of RK makes it more exposed to wind than SA, which was confirmed by the higher mean significant wave height at RK than at SA.

SSC was not only different between marshes, but also showed local differences at small scales within the transects crossing the marsh edge. SSC increased over the mudflat from −10 m to −1 m in front of the saltmarsh, and between −1 m

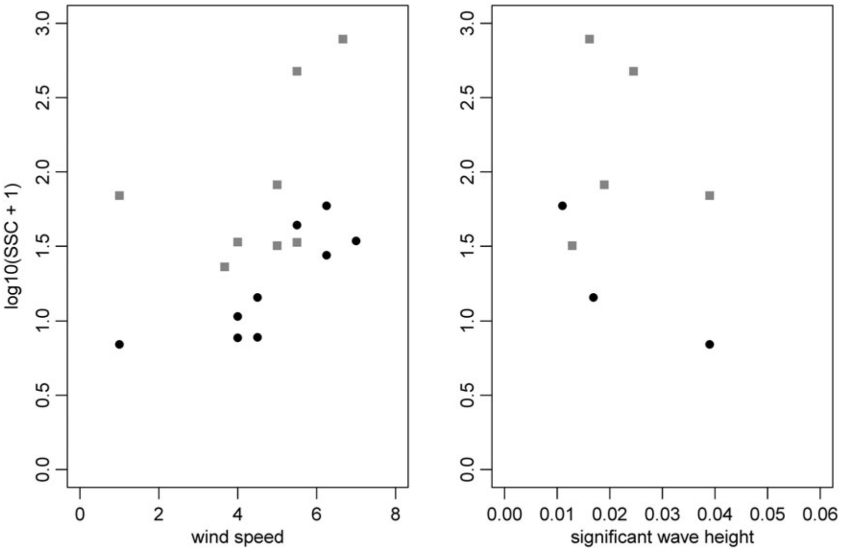

Figure 6. Relationship between suspended sediment concentration (SSC, in mg l^{-1}, log transformed) and wind speed (in m s^{-1}) and significant wave height (in meters) during the sampling moment. A significant correlation between SSC and wind speed during the sampling moment is observed (Pearson correlation, P = 0.047, r = 0.474). The correlation between SSC and significant wave height is not significant (Pearson correlation, P = 0.538). Data from Rattekaai (RK) are indicated with gray squares and data from Sint Annaland (SA) are indicated with black dots.

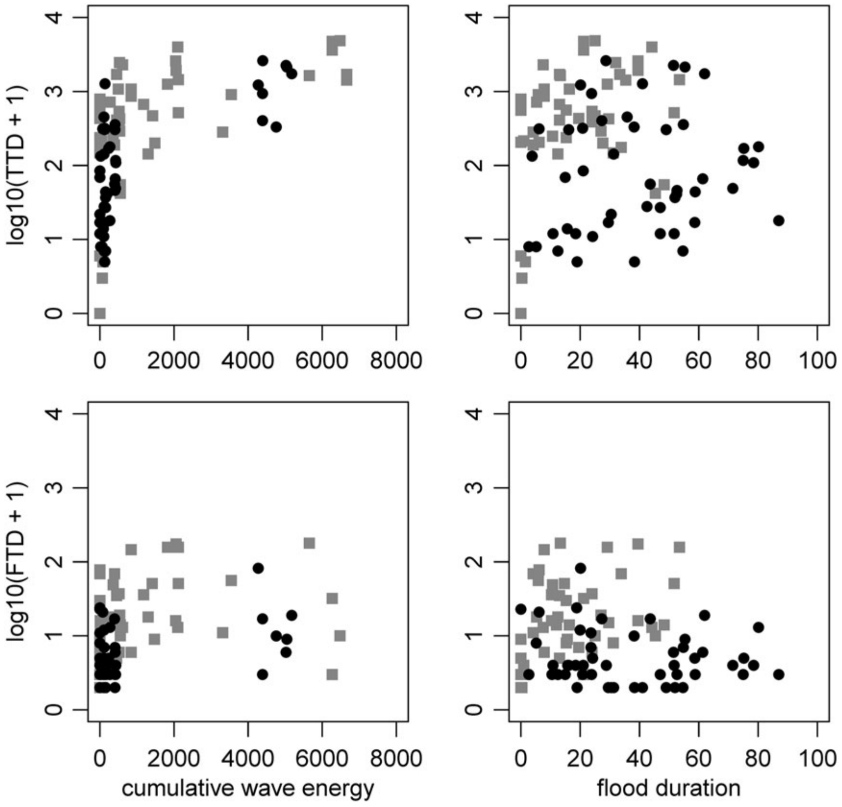

Figure 7. Relationship between sediment deposition (TTD and FTD, in g m^{-2} d^{-1}, log transformed) and hydrodynamics (cumulative wave energy, in Joules and flood duration, in hours). Data from Rattekaai (RK) are indicated with gray squares and data from Sint Annaland (SA) are indicated with black dots. TTD, tube trap deposition; FTD, filter trap deposition.

in front of the marsh to +1 m into the marsh. The decrease of SSC from +1 m into the marsh to +10 m into the marsh agrees with the declining SSC from the marsh–creek edge to the inner marsh in other marshes, such as Delaware (Christiansen *et al.*, 2000) Chesapeake bay (Stumpf, 1983) and the Westerschelde (Temmerman *et al.*, 2003). From open water or channel to mudflat close to the marsh edge, the shoaling of wind-generated waves was assumed to be the main process explaining sediment re-suspension close to the marsh edge (Yang *et al.*, 2007). The investigation of intertidal hydrodynamics in the Westerschelde (southwest Netherlands) demonstrated the obvious wave shoaling and attenuation from the tidal flat to the pioneer zone to the mature marsh (Callaghan *et al.*, 2010). The decline of SSC from +1 m into the marsh to +10 m into the

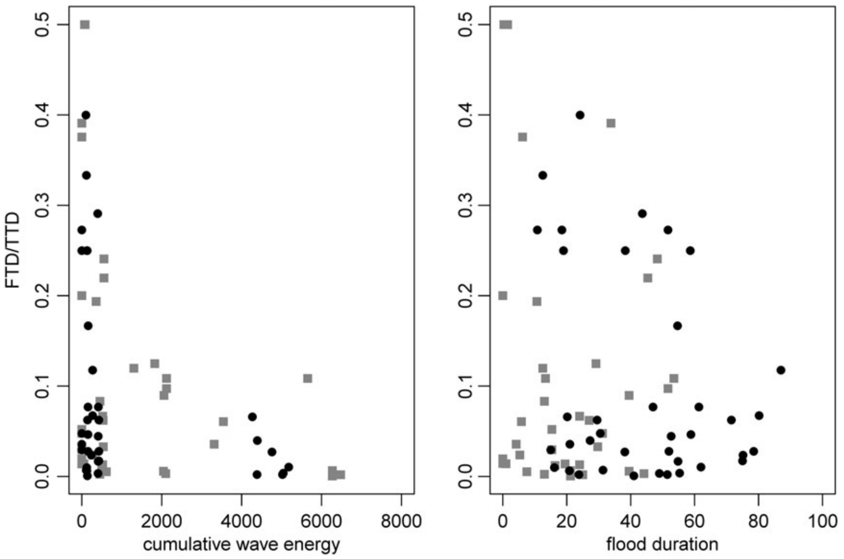

Figure 8. Relationships between sediment retention ratio (FTD/TTD) and cumulative wave energy (in Joules) and flood duration (in hours). Data from Rattekaai (RK) are indicated with gray squares and data from Sint Annaland (SA) are indicated with black dots. TTD, tube trap deposition; FTD, filter trap deposition.

marsh is probably resulting from the trapping effect (Li and Yang, 2009) and wave attenuation (Callaghan *et al.*, 2010) by the vegetation.

Our study at the mudflat–marsh transition also showed that mean SSC significantly correlates with mean wind speed instead of significant wave height at the sampling moment. Previous studies found increased SSC with higher wind speed in shallow estuaries and coastal bays. In the Ems estuary, at the border of the Netherlands and Germany, an increase in wind speed from below 7 m s^{-1} to around 10 m s^{-1} produced an increase in SSC of 4–5 times on the mudflat (de Jonge and van Beusekom, 1995). At Hog Island Bay, a shallow coastal lagoon in Virginia (USA), the increase of wind speed from 8 to 14 m s^{-1} caused an increase in SSC of 2.5 times (from around 40 mg l^{-1} to around 100 mg l^{-1}) (Lawson *et al.*, 2007). Furthermore, SSC was found to have a linear relationship with wind speed averaged over three high-water periods preceding sampling in the Wadden Sea (de Jonge and van Beusekom, 1995), and to significantly increase with wave activity above the marsh surface at Allen Creek marsh in the bay of Fundy, USA (van Proosdij *et al.*, 2006).

Variation in sediment deposition

In this study of short-term sedimentation, both gross sediment deposition (TTD) and net sediment deposition (FTD) were higher at RK than at SA. A study of long-term marsh accretion at RK and SA has shown that RK had higher accretion rates than SA (Ma *et al.*, 2014). This concordance between long-term and short-term sedimentation rates points to a generic difference in vertical growth ability of RK and SA.

A decreasing trend in sedimentation from the marsh or creek edge towards the landward extent of the marsh has been observed in many American and European marshes (Christiansen, 1998; Reed *et al.*, 1999; Temmerman *et al.*, 2003; Ma *et al.*, 2014). In this study, the gross sediment deposition (TTD) was significantly lower at +10 m sites than +1 m sites both at RK and SA. In contrast, the net sediment deposition (FTD) was significantly higher at +10 m than +1 m at RK or showed no significant difference at SA. This difference can be attributed to the design and the purpose of these two kinds of sediment traps. The tube sediment traps allow the sediment to deposit but not to be washed away by waves or currents, therefore indicating gross sediment deposition. In contrast, sediment deposited on the FTs can be washed away by currents and waves, therefore indicating net sediment deposition. The +1 m sites were close to the marsh edge and the originally settled sediment on the FTs was more easily re-suspended during high wave exposure. Wave energy may increase by 8% over a stretch of 5 m from mudflat to the top of the marsh cliff (Möller and Spencer, 2002). It is then reduced rapidly upon entering the marsh (Möller and Spencer, 2002; Ysebaert *et al.*, 2011). Thus, the +10 m sites were in relatively wave-sheltered conditions as compared to the +1 m sites, decreasing the re-suspension probability of the deposited sediment. This demonstrates the complexity of the small-scale, short-term sediment dynamics, especially around marsh edges.

Previous studies have shown that sediment deposition in wetlands is controlled by flood/inundation conditions (French and Spencer, 1993; Reed *et al.*, 1999; Temmerman *et al.*, 2003), although some studies have found that marsh accretion did not correlate with flood frequency and duration (Ma *et al.*, 2014; Boyd *et al.*, 2017). Other studies indicated that salt marsh sedimentation was associated with wind and wave conditions (Reed, 1989; van Proosdij *et al.*, 2006). Our data showed that gross sediment deposition and net sediment deposition were both significantly correlated with cumulative wave energy. In addition, the gross sediment deposition showed a continuous increase with increasing cumulative wave energy. Net sediment deposition first increased with cumulative wave energy conditionally, but decreased at the highest cumulative wave energy observed during our measurement campaign. This finding suggests that during low or moderate wave energy conditions, waves enhance sedimentation, while during high wave energy conditions the effect is counterbalanced because more sediment is washed away from the FTs.

We have used the sediment retention ratio (FTD/TTD) as an indicator of the effectivity of sediment trapping. The sediment retention ratio increased with distance away from the marsh edge, resulting from more sheltered conditions going from the marsh edge further into the back marsh. We identified a negative relationship between the sediment retention ratio (FTD/TTD) and cumulative wave energy measured on the mudflat.

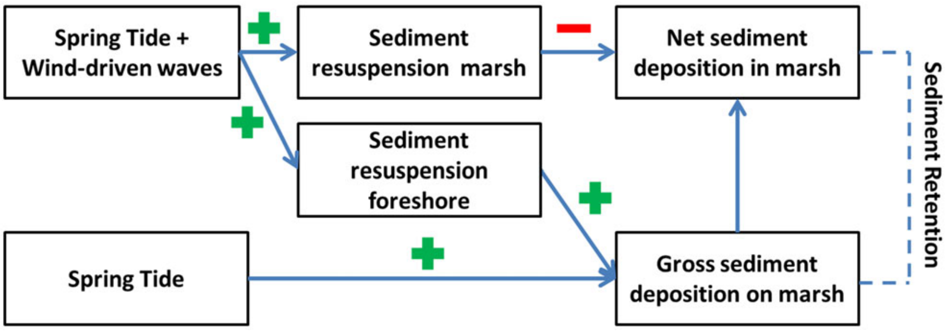

Figure 9. A conceptual model of sediment dynamics around the marsh edge. Spring tide together with waves can enhace both the sediment re-suspension on the foreshore and sedimentation on the marsh. The sediment retained (net sediment deposition) on the marsh compared with the sediment originally deposited (gross sediment deposition) on the marsh are defined here as sediment retention. [Colour figure can be viewed at wileyonlinelibrary.com]

This indicates that during conditions with high waves, a lower fraction of the sediment may be retained within the marsh.

A conceptual model for the sedimentation during different conditions

Based on our results, a conceptual model is proposed (Figure 9). Sediment dynamics (deposition and retention ratio) around the marsh edge are mainly controlled by local hydrodynamic and morphodynamic conditions. The marshes in the Oosterschelde are only flooded during spring tides (Ma *et al.*, 2014), restricting sediment deposition to spring tide high waters. During calm spring tide conditions, suspended sediment in the water column can settle down on the marsh surface, but the water carries only relatively small amounts of SSC. Under these circumstances, only a negligible fraction of the deposited sediment on the marsh surface is re-suspended due to lack of waves. During spring tides with high waves, sediment re-suspension from the mudflat in front of the marsh will enhance the SSC in the water column and contribute to an increased gross sediment deposition onto the marsh. However, sediment re-suspension from the marsh plateau surface reduces the fraction of this sediment deposition that is retained on the marsh. The variation of sediment retention ratio, here defined as the ratio between net sediment deposition and gross sediment deposition, reflects this dynamic balance of deposition and re-suspension under local complex hydrodynamic conditions.

Conclusion

SSCs varied greatly between the two marshes in this study and along the mudflat–marsh transition. The variation in SSC significantly correlated with the wind speed during sampling. Gross sediment deposition decreased with distance away from the marsh edge, while net sediment deposition increased from the marsh edge to the inner marsh due to a decrease of sediment re-suspension by waves. Sediment deposition and retention ratio significantly correlated with cumulative wave energy instead of flood duration. The results show that it is vital to consider the local wave conditions and SSCs, resulting from complex interactions between the marsh and the adjacent mudflat, when evaluating marsh sedimentation.

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Supporting Information

Additional Supporting Information may be found online in the supporting information tab for this article.

Data S1. Supporting information
Online Resource 1. Elevation profiles of each transect at both marshes (RK – Rattekaai and SA – Sint Annaland, the number on top of the figure indicate the transect of each marsh). The red dash lines indicate the highest water level experienced during observation period (3.10 meter NAP at RK and 2.76 meter NAP at SA on 2013 December 6th).
Online Resource 2. Vegetation type, elevation, grain size distribution of each site at Rattekaai and Sint Annaland.
Online Resource 3. Summary of suspended sediment concentration (SSC) by different marshes (marsh, Rattekaai-RK and Sint Annaland-SA), periods (prd, SS1:SS9). ″ref″ indicates whether the measurement is from a reference (“y” for “yes” and “n” for “no”). (n - number of valid observation, N - total set-ups, mean_SM - mean value of the SSC, se_SM - standard error of mean SSC).
Online Resource 4. Summary of sediment trap deposition by two kinds of sediment traps (Tube trap - TT and Filter paper trap - FT) at different marshes (Rattekaai - RK and Sint Annaland - SA), periods (prd, SD1: SD7). (n - number of valid observation, N – total set-ups, mean_DR – mean value of the deposition rate, se_SM – standard error of mean deposition rate).
Online Resource 5. Water level, significant wave height and peak wave period in SSC sampling moment SS9.