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Primary Research Paper

Flow hydrodynamics on a mudflat and in salt marsh vegetation: identifying general relationships for habitat characterisations

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Abstract

We present an overview of a large collaborative field campaign, in which we collected a long-term (months) high-resolution (4 Hz measurement frequency) hydrodynamic data set for several locations at the mudflat–salt marsh ecosystem and linked this to data on sediment transport and to a biological description of the organisms on the mudflat and the marsh. In this paper, part of this database has been used to identify general relationships that can be used for making hydrodynamic characterisations of mudflat–salt marsh ecosystems. We observed a clear linear relation between tidal amplitude and the maximum current velocity, both at the mudflat as well as within the marsh vegetation. Velocities in the vegetation were however a magnitude lower than those on the mudflat. This relationship offers promising possibilities for making hydrodynamic habitat characterisations and for validating hydrodynamic models.

Introduction

The well-recognised importance of estuarine mudflat–salt marsh ecosystems (e.g., coastal protection, nursery function, feeding and breeding areas to birds) combined with the continuous demands for human use of the estuary (e.g., navigation, industry, coastal protection) has resulted in protective regulation (e.g., RAMSAR convention [http://ramsar.org/], EU-birds and habitat directive [http://europa.eu.int/comm/environment/nature/legis.htm]). Implementation of such protective regulation requires that governments warrant the maintenance of the existing area of habitats on mudflats and salt marshes. The highly dynamic nature of estuaries complicates maintenance of such habitats for the following two reasons: *Firstly*, habitats are not necessarily in steady states. For example, habitats can be altered due to the biological activity of the protected organisms. As a result, the protected habitat may have a natural cycle, that is difficult to understand from short-term observations (e.g., see van de Koppel et al., 2005). *Secondly*, maintaining human activities in the estuary even without any expansion, often requires continuous engineering that may have significant long-term effects on the morphology of the estuary and its protected habitats (e.g. dredging to maintain channels). Consequently, successful long-term protection of these valuable intertidal ecosystems require fundamental knowledge (often integrated in simulation models) of both (a) long-term morphological development of mudflat–salt marsh ecosystems and (b) habitat requirements of the species populating these ecosystems.

Long-term development of mudflat–salt marsh ecosystems is determined by the interaction between hydrodynamic conditions and sediment (extensively reviewed by Allen, 2000; see his Fig. 4). High hydrodynamic energy either from waves or current velocity and lack of sediment will generally cause mudflat–salt marsh ecosystems to reduce in size due to erosion, whereas high sediment availability combined with low hydrodynamic energy most likely result in vertical accretion and/or lateral extension. Hydrodynamic and sediment characteristics are also the main factors determining species habitats on mudflat–salt marsh ecosystems. Sediment characteristics and current velocities have been shown to be important factors in determining the distribution of benthic organisms in estuaries (Ysebaert et al., 2002), whereas inundation period and wave energy are important factors in explaining the distribution of plant species along the elevational gradient (De Leeuw et al., 1992; Houwing, 2000). *Thus*, general relationships that provide an adequate hydrodynamic characterisation of a mudflat–salt marsh ecosystem would be useful in interpreting long-term predictions on morphological development in terms of available species habitats.

Whereas the interaction between hydrodynamic conditions and sediment affect the distribution of biological organisms, various biological organisms are an important modulator of the interaction between hydrodynamic conditions and sediment. A concise overview of the effect of different classes of biological organisms is presented by Widdows & Brinsley (2002; see their Fig. 1). In short, bioturbating benthic organisms such as Macoma and Hydrobia may enhance erodability on the mudflat, whereas biostabilising organisms such as diatoms may enhance sediment stability and sedimentation rates on the mudflat. On the marsh, sedimentation is enhanced by the marsh

Figure 1. Map indicating the location of Paulinapolder (arrow) in the SW of the Netherlands.

vegetation, which reduces current velocities in between their aboveground structures such as stems and leaves (Yang, 1998; Dame et al., 2000; Davidson-Arnott et al., 2002; Leonard et al., 2002; Widdows & Brinsley, 2002). By trapping sediment, pioneer plant species that grow at the low marsh can extend their habitat onto the mudflat, a process which can be characterised as ecosystem engineering (Castellanos et al., 1994; Sanchez et al., 2001). Positive feedback loops, by which organisms can affect their own environment, can sometimes result in alternative stable states for a single area (e.g., see Van de Koppel et al., 2001). Feedback loops that support ecosystem engineering and alternative stable states are thus important characteristics for understanding the biological influence on the long-term development of mudflat–salt marsh ecosystems. Naturally, such positive feedback loops will only exist if hydrodynamic energy is in agreement with the habitat requirements of the organisms involved; else hydrodynamic energy will be the only structuring force. *Thus*, hydrodynamic habitat characterisations of biota that act as ecosystem engineers and may cause alternative stable states are essential to our predictions on the long-term development of mudflat–salt marsh ecosystems.

In general, few detailed experimental observations exist on the hydrodynamic conditions of mudflat–salt marsh ecosystems, especially in European marshes (Dame et al., 2000; review Allen, 2002). Studies that relate important ecological principles to hydrodynamic factors often use semi-quantitative methods to measure hydrodynamics such as the dissolution block technique (e.g., Bruno, 2000). Due to technical limitations related to translating these types of measurements into rates (Porter et al., 2000), use of such semi-quantitative methods complicates comparing data of different studies. Alternatively, ecological studies may use data from hydrodynamic models, which often have relative large grid sizes (generally 100 m grid, however sometimes as fine as 30 m grid; see e.g., Herman et al., 2001; Ysebaert et al., 2002). The majority of the hydrodynamic models are developed for subtidal areas, and cannot be readily translated to intertidal areas due to a range of non-matching parameters such as e.g., bottom roughness (pers. com. WL | Delft Hydraulics). These observations lead to the conclusion that there is need for:

(A) general relationships that can provide an adequate hydrodynamic (habitat) characterisation of a mudflat–salt marsh ecosystem, across spatial and temporal scales,
(B) high quality databases that allow calibrating and validating existing hydrodynamic (and sediment transport) models for intertidal areas such as mudflats and salt marshes,
(C) databases that enable further inclusion of biological processes that characterise mudflat–salt marsh ecosystems in both the above mentioned points.

Although this set of ambitious questions is relevant to many estuarine ecosystems, the interdisciplinary nature of these questions make that they cannot easily be addressed by a single research group. The objective of our paper is twofold:

(1) To present a complete *overview of a large collaborative inter-disciplinary field campaign*, as an illustration how a database can be generated for addressing the questions A, B and C that are listed above.
(2) To use part of the database to address question A: *identifying general relationships* that can be used as adequate hydrodynamic (habitat) characterisation of a mudflat–salt marsh ecosystem, across spatial and temporal scales.

Materials and methods

Field site

We study the Western Scheldt estuary in the southwest of the Netherlands, as a typical example of an estuary where continuous demands for human use (e.g., deepening of the channel for navigation to Antwerp) often conflicts with the ecological values of the system (e.g., the 3rd important habitat for migrating birds in the Netherlands). Regarding these ecological values, the Western Scheldt is protected under the Ramsar convention (www.ramsar.org), the EU Birds Directive (Directive 79/409/EEC), and is also proposed to be part of the Natura 2000 network under the Habitats Directive (Directive 92/43/EEC). Our field site was the mudflat–salt marsh ecosystem of Paulinapolder. It is a typical

Western Scheldt mudflat–salt marsh ecosystem, characterised by an extended mudflat with a rich benthic community and a salt-marsh vegetation that contains all successional stages from pioneer to late-successional. The extended and viable zone of pioneer vegetation mainly consists of *Spartina anglica*. The sand banks in the middle of the Scheldt protect the mudflat–salt marsh ecosystem to some degree from large wind driven waves, by reducing the size of the fetch (Fig. 1). The more exposed marshes in the Western Scheldt are currently suffering from erosion and therefore do not allow us to quantify the hydrodynamic conditions favourable for the establishment of pioneer vegetations.

Hydrodynamic measurements – large transects

Various physical parameters were characterised during the season with maximal biological activity (June till October) on both the mudflat (diatoms and benthos) and the salt marsh (plant growth) as well as during the winter period when hydrodynamic conditions are generally most extreme (December). We used four automated frames (technical details in Table 1) to measure tidal inundation, wave height, current velocity and sediment load in the water column with a frequency of 4 Hz. The frames were programmed to measure 6 h around high water. Over the year, some of the frames were moved after an approx. 1-month period (i.e., two full cycles with neap and spring tides), whereas the other frames were left in place to make data series comparable (see F1 to F8 in Table 1 and Fig. 2). Moving of these frames was a large effort, but useful for two reasons. Firstly, searching for general relationships that can be used as adequate hydrodynamic (habitat) characterisation of a mudflat–salt marsh ecosystem across spatial and temporal scales requires a somewhat explorative experimental design. Secondly, comparing different locations was used to address different specific questions, which are explained in the next paragraph.

Table 1. Equipment mounted on the various automated measuring frames and the locations were individual frames were employed (codes as indicated in Fig. 2a).

	Frame A	Frame B	Frame C	Frame D
Instrumentation				
Pressure sensor	70 mm	130 mm	70 mm	70 mm*
Electric Magnetic Velocity meter	70 mm	70 mm + 150 mm	70 mm	70 mm
Optical Back Scatter	150 mm	150 mm + 250 mm	150 mm	150 mm
Locations (see Fig. 2a)				
Period 1 (11 June–2 July)	F1	F2	F3	F4
Period 2 (2 July–9 Aug.)	F1	F2	F3	F5
Period 3 (9 Aug.–2 Oct.)	F1	F2	F3	F6
Period 4 (26 Nov.–31 Dec.)	–	F2	F7	F8

*At the location of this pressure sensor, the sediment was 70 mm higher than in the middle of the creek, where the Electric Magnetic flow meter was located.

By instrumentation, we indicated for each sensor the height above the sediment as used during period 1. When frames were placed inside the *Spartina* vegetation, the height of the Optical Back Scatter was enhanced till the sensor had an open view above the vegetation.

The reason for moving some of the frames to different locations after an approx. 1-month period (i.e., two full cycles with neap and spring tides) is explained in detail in the Materials and methods. In brief, the first period was aimed at describing the water (and sediment) movement from the mudflat via the creeks towards the marsh, the second, third and fourth period were aimed at establishing the effect of the marsh vegetation on current velocities and turbulence. During the third period, we specifically studied the effect of *Spartina* vegetation on wave attenuation, current velocities, turbulence (and sediment movement) on a fine spatial scale, using an approximately 50-m long transect. The fourth period was aimed at measuring wave attenuation and current velocity profiles on a larger scale.

The frames were programmed to measure 6 h around high water. During this 6 h period, data loggers stored a continuous burst of 2048 records with a frequency of 4 Hz each fifteen minutes (i.e., approx.9 min on, 6 min off). Pressure sensor on the frames were provided by Druck Ltd, Electro Magnetic (⇔induction) Velocity meters by Delft Hydraulics type S40 (i.e., sphere shaped), and Optical Back Scatter sensors (OBS-3) by D&A.

The measurements during the First period (11 June–2 July 2002) were aimed at describing the water (and sediment) movement from the mudflat via the creeks towards the marsh. The second (2 July–9 Aug. 2002), the third (9 Aug.–2 Oct. 2002) and the fourth (26 Nov.–31 Dec. 2002) period were aimed at establishing the effect of the marsh vegetation on current velocities and turbulence. In the third period, there were two campaigns of 1 week during which we measured wave attenuation by *Spartina* vegetation. During these campaigns, current velocities, turbulence and sediment movement were also measured on a finer spatial scale (see next two section for details). The experimental set-up during the fourth period was aimed at measuring wave attenuation and current velocity profiles on a larger scale. Hence, we placed eight pressure sensors (Druck Ltd) with long cables on the salt marsh (Fig. 2) and three acoustic Doppler current profilers (ADCP; RD instruments) near the frames (A's in Fig. 2). Unfortunately, this winter campaign had to be shortened due to a long and severe frost period, which caused ice accumulation around the equipment.

In case that frames C or D (Table 1) were placed in the vegetation, we analysed the vegetation development in a 500 by 500 mm plot near the velocity and pressure sensor, after the measurements were finished (see section on Biological measurements).

Hydrodynamic measurements – small transects

The water velocities and wave energy were quantified along a 50-m transect perpendicular to the fringe of the *Spartina* vegetation, starting 1 m on the mudflat (Fig. 3). During the first campaign (7–15 Aug. 2002) we focused at the velocity close to the sediment surface using a larger spatial grid. The second campaign (5–12 Sept. 2002) was aimed at quantifying velocity profiles and turbulence going from the sediment surface (50 mm height) into the vegetation (450 mm height), to the top of the vegetation (650 mm height) and to the water column above the vegetation (1000 mm height; details in (Fig. 3). At the end of the measurements, the vegetation in a 500 by 500 mm plot near the velocity and pressure sensor was harvested and analysed for its vegetation development (see section on Biological measurements).

Suspended sediment and sedimentation measurements

The spatial pattern of sediment deposition on the marsh surface was measured using a dense network of 50 sampling sites (Fig. 2c), both during two spring–neap tidal cycles (15 days: 5–20 Aug. 2002 and 2–16 Sept. 2002) and four individual tidal inundations (about 4–5 h: 11 + 12 Aug. 2002 and 10 + 11 Sept. 2002).

For the two spring–neap tidal cycles, circular plastic sediment traps were used to sample the sediment that settled out from suspension. The traps were attached to the marsh surface at neap tide and were constructed with a floatable cover to protect the deposited sediment from splash by raindrops during low tides. At the following neap tide (15 days later) all 50 traps were collected and the dry weight of the deposited sediment was determined. The deposited sediment was further analysed for organic matter content and grain size distribution using a laser diffraction particle size analyser (Coulter LS 13 320).

For the four individual tidal cycles, pre-weighted filter papers, attached at aluminium plates, were used as sediment traps at the same 50 sampling locations. The filter paper traps were placed at the marsh surface just before and collected just after high tide. In addition, during these four individual tides, samples of the flooding water were collected using siphon samplers (1 l bottles with siphon tubes as inlets and filled once the siphon tubes are submerged), which were installed at 10 locations within the creek system and above the marsh surface. Spatial variations in suspended sediment concentrations (in g/l) were determined by filtering these water samples with pre-weighted filter papers (pore diameter = 0.45 μm). Temporal variations in suspended sediment concentrations, in the in- and outgoing water in the beginning of the main creek (position F3 in Fig. 2), were determined from water samples taken every 30 min with an automated ISCO sampler. The Optical Back Scatters attached to the frames (Table 1) were calibrated against the water samples taken by the automated ISCO sampler.

Hydrologic measurements

Ground water levels were monitored at five positions of the marsh (G's in Fig. 2). The groundwater

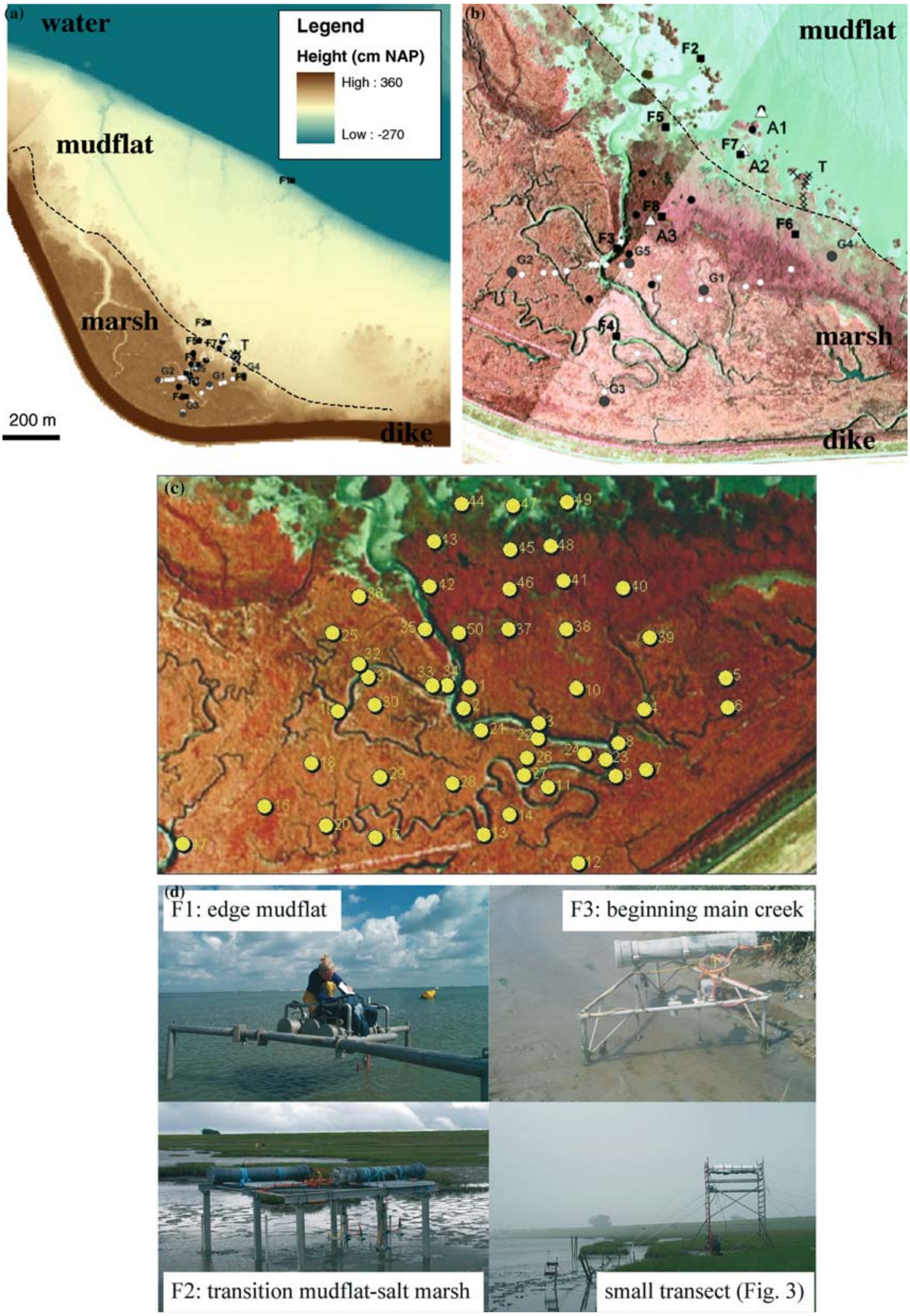
(a)
water
Legend
Height (cm NAP)
High : 360
Low : -270
mudflat
marsh
dike
200 m
(b)
mudflat
F2
F5
A1
F7
A2
T
F8
A3
F6
F3
G5
G4
G2
G1
F4
G3
marsh
dike
(c)
(d)
F1: edge mudflat
F3: beginning main creek
F2: transition mudflat-salt marsh
small transect (Fig. 3)

Figure 2. Visual description of the tidal mudflat–salt marsh ecosystem at Paulinapolder, indicating elevational heights (a), the presence (i.e., dark area below dashed line) or absence (i.e., lighter area above dashed line, with *Spartina* tussocks on the mudflat visible as dark spots) of vegetation cover (b), the sites of sediment measurements (c) and the various experimental set-ups (d). Various measurements and equipment are indicated with the following abbreviations: A = Acoustic Doppler current profilers (Δ); F = automated measuring Frames (*v*; for details on instrumentation and reationale behind locations see Table 1); G = Ground water levels (●); pressure sensors (●); sediment cores (O); T = small transect (*x*; also see Fig. 3).

was measured in an irrigation tube (piezometer) of approximately 3 m with a closed PVC tube on top. The tube was placed into the soil so that the filtering part of the irrigation tube reached the reduction layer (around 1.5 m; but depending on the location). To prevent rainwater from running into the tube, a collar of so-called bentoniet-clay (i.e., swells in contact with water) was placed around the connection between the irrigation tube and the closed PVC tube. Each irrigation tube contained a datalogger (peilbuisdataloger, type Diver, Eijkelkamp Agrisearch Equipment) that measured the water level in the tube every 15 min. In between groundwater gauges (G's in Fig. 2), sediment cores were taken up to 1 m depth (Fig. 2). The cores were divided in layers of 0–10 mm, 10–20 mm, 20–50 mm, 50–100 mm followed by 100 mm slices up to 1 m. All layers were analysed for grain size distribution (laser diffraction method, Malvern Mastersizer), where after mud content (fraction < 63 μm) and median grain size were calculated.

Biological measurements

In order to provide a basis for further analysis of the hydrodynamic measurements reported in this paper, we also studied relevant biological organisms on the mudflat and the marsh.

Benthic communities on the mudflat (i.e., seven transects perpendicular to the waterline) as well as in the pioneer vegetation (i.e., along four transects perpendicular to the boarder of the *Spartina* vegetation) were sampled. Simultaneously with benthos sampling, we sampled for chlorophyll *a* content at the sediment surface (sample with 15 mm diameter, 10 mm depth) and grain size distribution (15 mm diameter, 10 mm depth). Chlorophyll *a* will be determined by HPLC; grain size distribution by laser diffraction method (Malvern Mastersizer).

Vegetation development during the growing season was monitored by a combination of photographic side views (6 June, 22 July, and 18 Sept. 2002) and destructive harvesting of 500 by 500 mm plots (6 June 2002). Photographic side views of the vegetation were taken by clearing a 1 by 1 m area, and placing a white board 50, 100 and 200 mm into the vegetation. The pictures offer a quantitative vertical distribution of occupied space that offers resistance to water movement. Development was monitored for the following dominant vegetation types: (1) *Spartina anglica* Hubbard at the (1a) lower border and at the (1b) higher border, (2) *Elymus pycnanthus* (Gordon), (3) *Halimione portulaoides*, (4) *Aster tripolium* + *Puccinellia maritima* (Hudson) Parl., (5) *Trigochlin* + *Puccinellia maritima* (Hudson) Parl. In addition to monitoring the vegetation development as described above, we also characterised the vegetation structure of *Spartina* at the locations where we took hydrodynamic measurements (Figs. 2 and 3) or sampled the benthic community within the marsh vegetation. During destructive harvest, dry weight was determined on all bulk samples, whereas in most cases a representative *Spartina* subsample was analysed to derive the vertical distribution (density and diameter) of stems and leaves. This vertical distribution of plant materials was used to relate stem density (stems per m^2) to a quantitative vertical distribution of occupied space that offers resistance to water movement.

Results and discussion

The description of the large collaborative inter-disciplinary field campaign illustrates how an extensive database can be generated, that link data on hydrodynamics, sediment transport and biological activity. To *identify general relationships* that can be used as adequate hydrodynamic (habitat) characterisation of a mudflat–salt marsh ecosystem across spatial and temporal scales, we analysed the 15 min averages of the velocity and inundation measurements (typical example illustrated in Fig. 4). Restricting our analyses to these 15 min averages enabled us to combine data of

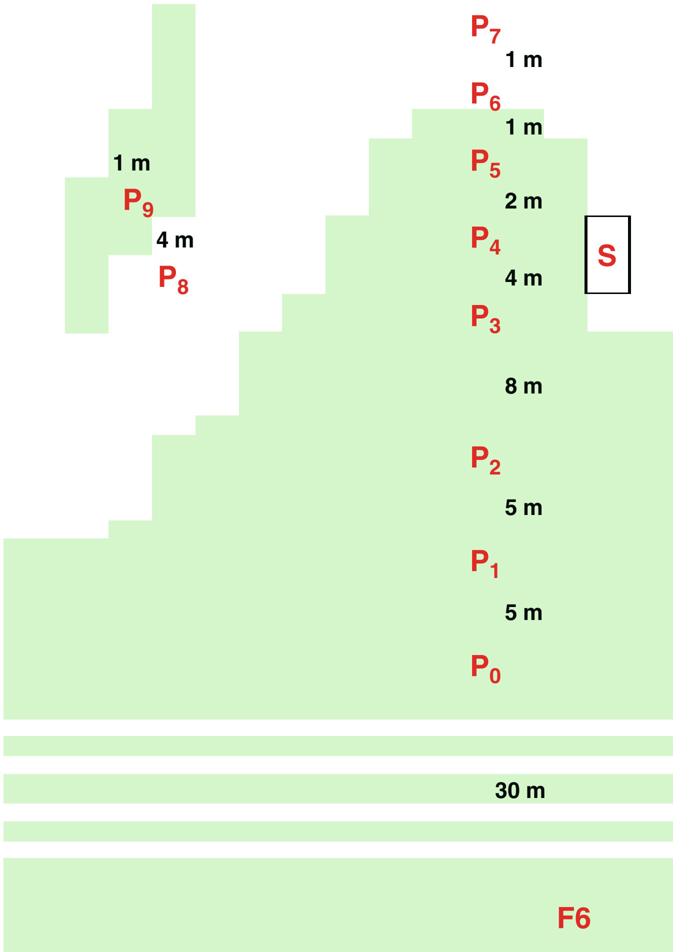

Figure 3. Schematic representation of the small transect perpendicular to the boarder of the *Spartina* vegetation, used to study hydrodynamic in the vegetation at a smaller spatial scale. The transect-point located most into the vegetation consisted of automated measuring frame F6 (see Fig. 1). Each of the 10 locations (P) had a pressure sensor (Druck Ltd) mounted 20 mm above the sediment. During the first campaign (7–15 Aug. 2002), current velocities were measured 50 mm above the sediment surface at P_1 to P_5 plus P_7, P_8 and P_9 and 500 mm above the sediment at P_1 and P_5. During the second campaign (5–12 September 2002) current velocities were measured at two different heights at P_7 (50 and 1000 mm), and at four different heights at P_2 and P_4 (50, 450, 650 and 1000 mm). Current velocities were measured with Electro Magnetic (⇔ induction) Velocity meters made by Delft Hydraulics (mainly using the sphere shaped type S40; at some of the higher locations we used the cylinder shaped type E40). The equipment for data acquisition was stored on a scaffold.

large numbers of tides, which would be impossible when using high-resolution (4 Hz measurement frequency) hydrodynamic data such as needed for analysis of waves and turbulence.

Hydrodynamics in creeks and at the transition mudflat–salt marsh

As a control, we correlated observed inundation heights for various automated measuring frames (Fig. 5a). The high-correlation demonstrates the quality of the measurements and the extent of our database. The intercepts of the regression line with the *x*-axis merely indicate differences in absolute height between the frame locations, which will also be present in the other graphs. Plotting for individual tides (Figs. 5b–d) the inundation level during inflow and outflow through the creeks (F3 & F4) against the inundation level observed at the transition mudflat–salt marsh (F2), reveals that the water level in the creeks shows a hysteresis effect during certain conditions. This hysteresis effect is

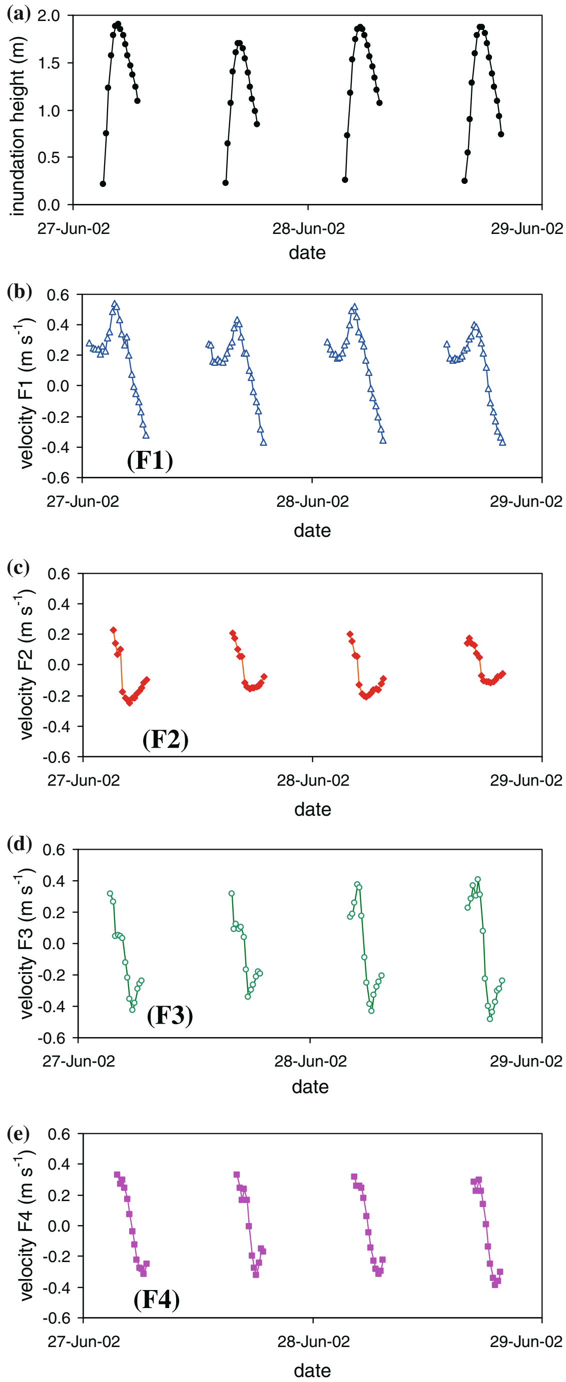

Figure 4. Typical example of the current velocities that are measured at locations F1 (edge mudflat; Δ), F2 (transition mudflat–salt marsh; ♦), F3 (beginning main creek; O) and F4 (small creek branch in the marsh; ■) during the tidal cycle. Positive velocities indicate incoming tides; negative velocities return flows. Each point represents the average over a 15-min period.

most noticeable for the creeks furthest into the marsh (F4; see Fig. 2), and becomes larger with increasing tidal amplitudes (i.e., maximum inundation height of an individual tide). It is particularly noticeable during overmarsh tides, when water flows over the creek bank onto the marsh, so that the marsh becomes a buffering reservoir. Emptying of this reservoir can extend the duration of high water levels in the creeks by extending the outflow period (Fig. 5d). The lack of hysteresis effect (i.e., nearly overlapping lines for inflow and outflow) in case of undermarsh tides, when creeks do not flood the marsh, indicate that the resistance of the creek system is relatively small (Fig. 5b and c). At-a-station flow in tidal creeks is well measured and modelled (extensively reviewed by Allen, 2000; also see Reed, 1988; Stoddart et al., 1989; French & Stoddart, 1992; Allen, 1994; Leonard et al., 1995; for Western Scheldt see also Verbeek & Storm, 2001). Similar to earlier studies, we observe in the creeks the highest velocities during overmarsh tides (Fig. 6c and 6d). Velocities remain much lower during undermarsh tides, when creeks do not flood the marsh. These contrasting velocities give different functions to the different classes of tides: accumulation of sediment into the creeks during low dynamic undermarsh tides vs. sedimentation on top of the marsh during high dynamic overmarsh tides (Allen, 2000). Storm events are another important factor in this process (e.g., Leonard et al., 1995).

In his review, Allen (2000) concludes that “the local hydraulics of channels has undoubtedly been overemphasised at the expense of what are in effect tidal floodplains.” In our study, we combined measurements on the creek system with those on the mudflat and the lower pioneer zone of the salt marsh. We observed that current velocities at the transition mudflat–salt marsh (F2) are only comparable to that in the creeks during undermarsh tides (Fig. 6). Acceleration of current velocity as observed in creeks upon flooding of the creek banks (i.e., shifting from undermarsh to overmarsh tide) is absent at the transition mudflat–salt marsh (F2). Consequently, during overmarsh tides, velocities at the transition mudflat–salt marsh are much lower than those in the creeks. This is an mportant observation, as the transition mudflat–salt marsh covers a large area of the salt-marsh ecosystem, including the pioneer zone.

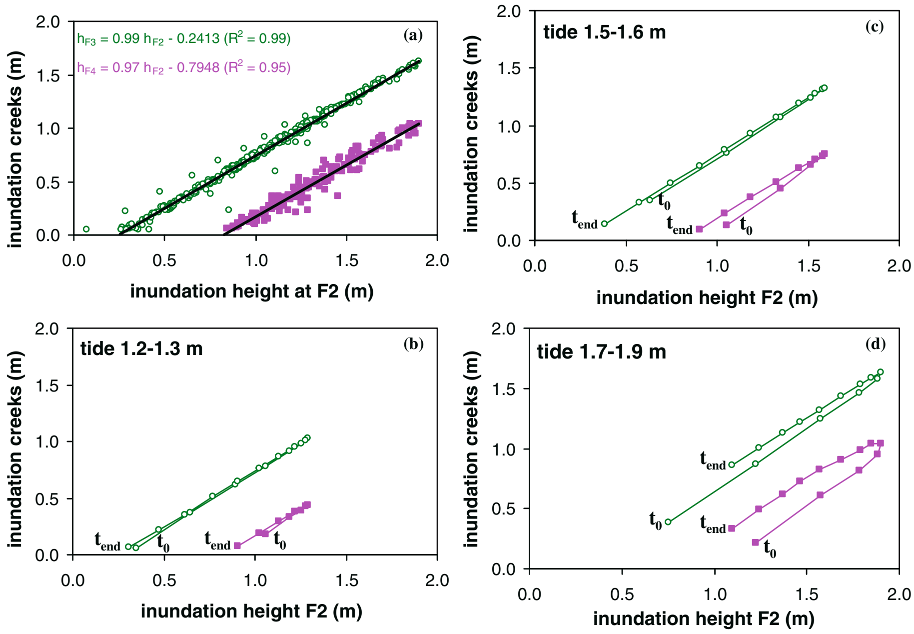

Figure 5. The relation between the inundation height at the transition of mudflat–salt marsh (F2; *x*-axis) and the inundation height in the beginning of the main creek (F3;O) and a small creek branch further into the marsh (F4; ■). The observed inundation heights show a strong correlation; differences in absolute inundation heights are due to differences in elevation of the frame locations (a). Points t_0 and t_{end} indicate creek filling and creek emptying (b–d). Water movement in the creek system shows a clear hysteresis effect in case water flows over the creek bank (d); such effect is much less pronounced if water remains in the creeks (b and c). The creek bank is flooded at an inundation height of about 1.4 and 0.8 m for locations F3 and F4, respectively. Each point represents a 15-min average within a single tidal cycle.

Hydrodynamics in the pioneer zone have a key role in future marsh evolution (Houwing, 2000 vs. Yang, 1998). The frame at the transition mudflat–salt marsh (F2) suggests that the marsh is a flood-dominated system for two reasons. *Firstly*, the flooding period (i.e., positive rates; Fig. 6b) is shorter than the period that the marsh empties (ebb period ⇔ negative velocities; Fig. 6b), as can be derived from the fewer number of data points for the flood than the ebb period (i.e., each point represents a 15 min period). *Secondly*, the highest velocities tend to be early in the flooding period (i.e., positive velocities; Fig. 6b). The high negative velocities (⇔ ebb period) observed around maximum inundation are directed parallel to the fringe of the marsh, so that the mudflat has in fact become part of the water movement in the estuarine river (Fig. 7). This is in-line with observations of Wang et al. (1993) and Leonard (1997), who found that only at the beginning and end of an overmarsh tide, water moved in right angles to the creeks, whereas in between the water flow was parallel to the creek. Where the observations of Wang et al. (1993) and Leonard (1997) account for a creek, we observe the same phenomena on a much larger scale, by looking at the fringe of the marsh that is situated along an estuarine river (Fig. 1). In general, flood dominated systems tend to be importing sediment, which is also the case for the salt marsh at Paulinapolder (Temmerman et al., 2003a,b). This agrees well with hydrodynamic and sediment data in a restored marsh in the Western Scheldt (Verbeek & Storm, 2001; Eertman et al., 2002).

General hydrodynamic relationships for estuarine mudflat–salt marsh ecosystem

An interesting relation was found between the amplitude (i.e., maximum inundation height) of a particular tide and the maximum velocity reached during that particular tide (Fig. 8). This pattern was present at all locations, be it most pronounced (see R^2 in Fig. 8) at the transition mudflat–salt marsh (F2) and in the beginning of the main creek

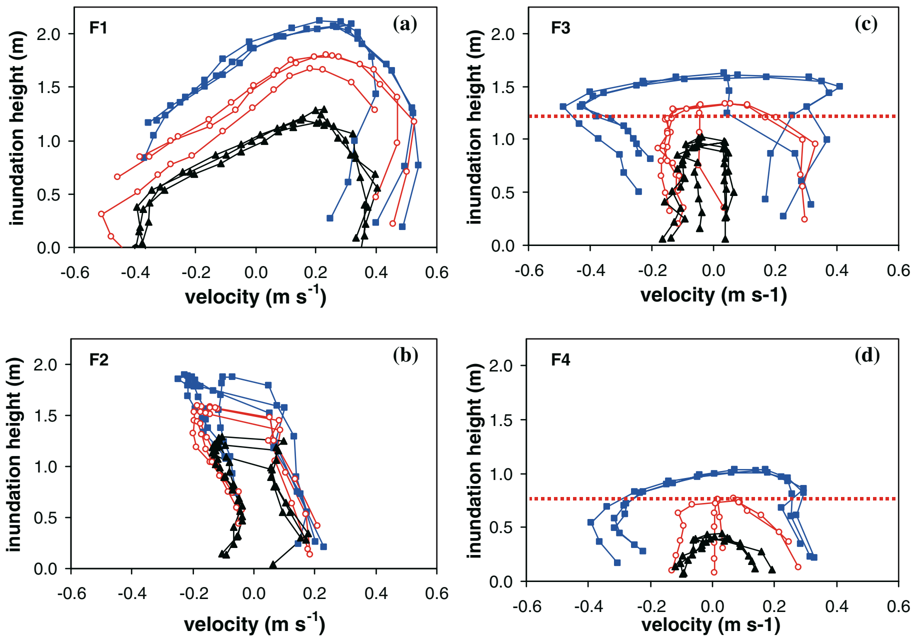

Figure 6. The relation between current velocities and inundation heights, as measured at locations F1 (edge mudflat; a), F2 (transition mudflat–salt marsh; b), F3 (beginning main creek; c) and F4 (small creek branch in the marsh; d). In each graph, we distinguished tides with an inundation height of 1.2–1.3 m (▲), 1.5–1.6 m (O) and 1.7–1.9 m (■). Positive velocities indicate incoming tides; negative velocities return flows. Each point represents the average over a 15-min period. The creek bank is flooded at an inundation height of around 1.4 and 0.8 m, for location F3 and F4, respectively (indicated by dashed lines).

(F3), which are the most relevant locations for understanding the system. The transition mudflat–salt marsh (F2) is particularly relevant because it describes hydrodynamic conditions of both (i) the mudflat where benthos communities live, and (ii) the pioneer zone of the marsh where expansion of the marsh vegetation by establishment of new seedlings is determined. The beginning of the main creek (F3) is relevant as it describes the total water movement to all creek branches and thus the

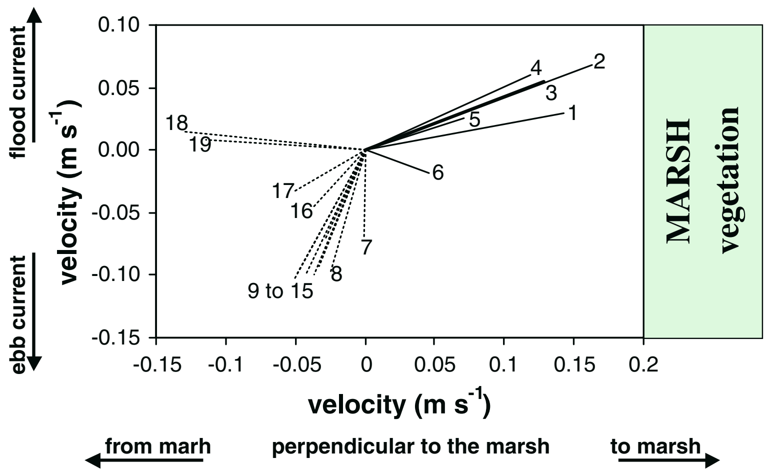

Figure 7. Illustration of how current velocities change during the time course of single tidal cycle. Data are from frame F2 that is located at the transition mudflat–salt marsh (see Fig. 2). Lines indicate both the direction and the velocity (length of the line) of the current. Numbers at the end of the lines indicate subsequent 15-min periods.

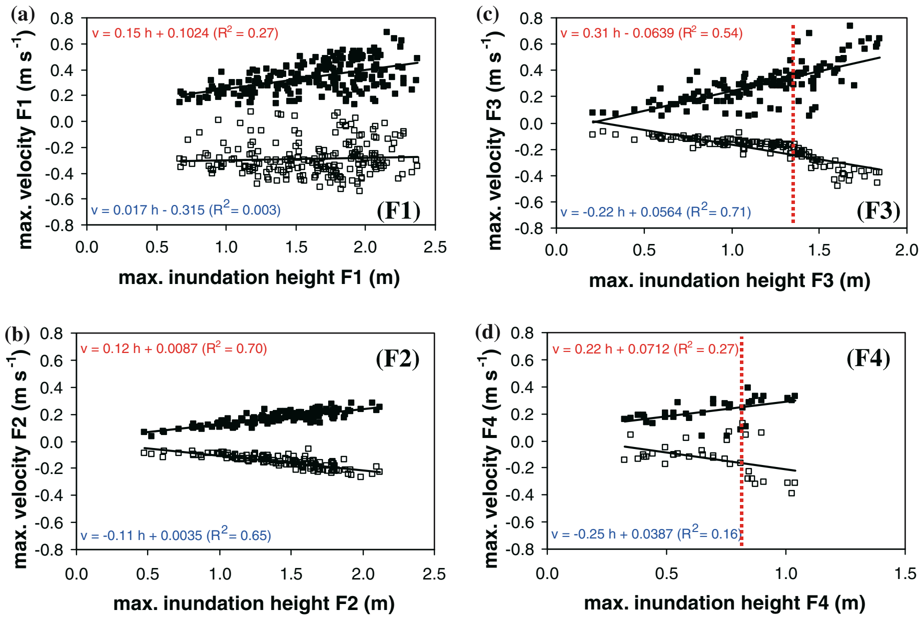

Figure 8. The relation between the maximum current velocities and the maximum inundation height, as derived by combining long-time series over many tidal cycles. Each point represents a single tide. Positive velocities (■) indicate the incoming tide; negative velocities (□) the return flow. The creek bank is flooded at an inundation height of around 1.4 and 0.8 m, for location F3 and F4, respectively (indicated by dashed lines).

complete creek water supply to the marsh in case of overmarsh tides (F3). Hence, measurements at this location are particularly relevant to making the water balance of a marsh. The relation between tidal amplitude and maximum velocity was less strong at the edge of the mudflat (F1) and the small creek branch in the marsh (F4). The relative weak relation at the edge of the mudflat may be partly ascribed to the position of frame F1. Due to placement by ship, frame F1 was located somewhat too far into the gully at a lower elevation along the slope in front of the mudflat. Consequently, the readings at F1 do not perfectly reflect hydrodynamics on the mudflat as are obtained by frame F2, and unidentified processes in the gully may have caused the scatter observed by frame F1. The relative weak relation in the small creek branch at frame F4 is difficult to evaluate regarding the small number of measurements, as this frame was used to move between locations (see Fig. 2 and Table 1). If we focus on the most relevant locations (F2 at the transition mudflat–salt marsh and F3 at the beginning of the main creek), we see that the effect of tidal amplitude on maximum velocity (*slope* regression lines Fig. 8) was less strong at the transition mudflat-salt marsh (F2) than in the creek (F3). This may however be an artefact, as the relation between tidal amplitude and maximum velocity in the creek seems to consist of two lines; a relative flat line for the undermarsh tides vs. a steeper line for the overmarsh tides (Fig. 8c). The latter would be in agreement with the observed acceleration upon flooding of the creek banks (Fig. 6). However, separation into 2 lines is not possible as only a minor fraction of all tides are overmarsh tides (Fig. 8). From Figure 8, and in particular b and c, we conclude that the simplicity and clarity of the relationship between tidal amplitude and maximum velocity, makes it a useful tool for hydrodynamic (habitat) characterisation of a mudflat-salt marsh ecosystem. This is especially true because the relationship holds well at both the transition mudflat–salt marsh (F2; see Fig. 8b) and in the beginning of the main creek (F3; see Fig. 8c), which are most relevant locations for understanding the system.

An exponential increase in velocity with increasing height above the sediment surface is a well-established profile, both in field (Leonard &

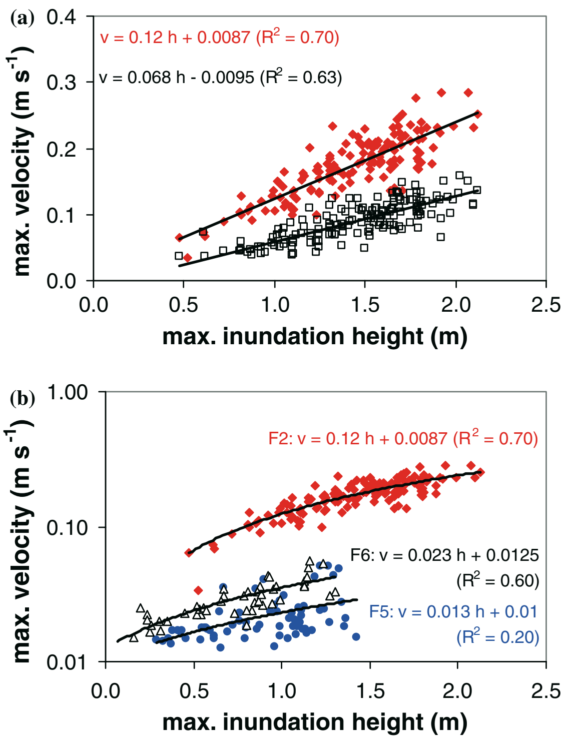

Figure 9. The effect of height above the sediment surface (a) and vegetation cover (b) on the relation between the maximum current velocities and the maximum inundation height. At the transition mudflat–salt marsh (F2), velocity was measured at 70 mm (□) and 150 mm (♦) above the sediment surface. Velocities measured at the transition mudflat–salt marsh (F2; ♦) was compared to velocities measured at a nearby positions in the vegetation (F5; ●) and a position close to our small transects (F6; Δ). Each point represents a single tide.

Luther, 1995; Allen, 2000; Dame et al., 2000; Betteridge et al., 2003) and flume (Jonsson et al., submitted) conditions. In addition to this general pattern, present results show that the linear relationship between tidal amplitude and the maximum velocity can be observed at different heights above the sediment (Fig. 9a). Although we lacked sufficient sensors to show this relationship for a complete velocity gradient, our results indicate that such relationship will be present.

It has also been long-time recognised that vegetation decreases current velocities (e.g., see Leonard & Luther, 1995; Yang, 1998; Christiansen et al., 2000; Dame et al., 2000; Davidson–Arnott et al., 2002; Leonard et al., 2002; Widdows & Brinsley, 2002), and that velocity profiles within vegetations need not always be exponential (Pethick et al., 1990; Shi et al., 1995, 1996; Dame et al., 2000). In addition to the well-established velocity reduction within vegetations, our data show that even within vegetation, there is a clear linear relation between the maximum velocity and the amplitude of a particular tide (Fig. 9b). Differences between the vegetated locations are likely to originate from a combination of different stem densities and different distances to the fringe of the marsh. We speculate that the larger scatter for F5 than for F6 (Fig. 9b) may be due to the closeness of F5 to the gully (Fig. 2), which may complicate the local water movement on to the marsh. However, on a larger scale, present results once again indicate that the relationship between tidal amplitude and maximum velocity is useful for giving a hydrodynamic (habitat) characterisation of a mudflat–salt marsh ecosystem. This is especially true, because the relationship holds for measurements at different heights on the mudflat (F2) but also within vegetations (F5 & F6). We are not aware of earlier studies that show such relationship, which is probably due to the lack of monitoring series that are long-enough to cover several neap–spring tide cycles.

Remaining gaps in our knowledge

Implications of the observed relationship between tidal amplitude and maximum velocity both on the mudflat as within the marsh vegetation (Figs. 8 and 9) indicates that measuring velocities during a number of neap and spring tides, and regressing these data against inundation height, offers a simple way to characterise hydrodynamic *flow* conditions on a mudflat and pioneer zone of a marsh. However, two important questions remain to be resolved.

Firstly, present analyses give limited insight in the importance of more fine scaled spatial variation. Earlier studies that use hydrodynamic models to link a spatial explicit description of hydrodynamics and biota indicate that large differences in current velocities occur over relative small distances (e.g., Molenplaat study on benthos; Herman et al., 2001). The importance of local conditions is underlined by differences between the edge of the mudflat (F1; Fig. 8a) and the transition mudflat–salt marsh (F2; Fig. 8b) as well as differences between two locations within the vegetation (F5 vs. F6; Fig. 9b). Obtaining a spatially explicit description of local hydrodynamic conditions may only be possible by using models. This does however require data sets for model validation, which will always contain a limited number of measuring points. Because of the integrative nature of the relationships between tidal amplitude and maximum velocity (Figs 8 and 9), this relationship seem ideal for validating hydrodynamic models over a large number of neap and spring tides.

Secondly, present analyses are obtained during relative quite conditions, with relative small waves (0.1–0.2 m amplitude; data not shown). These small amplitudes may be characteristic for estuarine marshes with relative narrow channels, offering a limited fetch for waves to be generated. This would indicate that the maximum velocities of tidal currents are the main structuring force in such estuarine systems, underlining the importance of the relationship between tidal amplitude and maximum current velocity (Figs 8 and 9). However, it is possible that hydrodynamic conditions during extreme events (e.g., storms with large waves) may temporarily impose stronger forces on the system, than the forces due to tidal currents. This implies that depending on system characteristics such as e.g., fetch size combined with the exposure to the main wind direction, extreme events may have an additional structuring impact on the dynamics of the ecosystem (e.g., see Leonard et al., 1995; Van de Koppel et al., 2005). Thus, in addition to the relationships we derived in this paper for the average conditions that are present during the season (June till October) with maximal biological activity on both the mudflat (diatoms and benthos) and the salt marsh (plant growth), we need quantitative data that describe extreme events such as e.g., storms. Only the combination of both the kind of relations presented in this paper (Figs. 8 and 9) and quantitative data on extreme events will enable realistic modelling of long-term development of mudflat–salt marsh ecosystems, and the dependence of such development on tidal influences vs. extreme events.

Relevance and future use of the database

The description of the large collaborative interdisciplinary field campaign illustrates how an extensive database can be generated, that link data on hydrodynamics, sediment transport and biological activity. To our knowledge, no such long-term (months) high-resolution (4 Hz measurement frequency) hydrodynamic data set exists for any of the natural Western Scheldt mudflat–salt marsh ecosystems, and will also be very rare for other estuaries. The most closely related hydrodynamic studies in the Scheldt estuary that we are aware of, have a very different focus from the present study. Those papers describe respectively the hydrodynamic and morphodynamic evolution of the creeks system at a restored marsh that is flooded through a single inlet (Verbeek & Storm, 2001), and the factors that control cohesive sediment transport near the harbour of Antwerp (Fettweis et al., 1998).

In the *present study*, we revealed a clear linear relationship between tidal amplitude and maximum current velocity. The presence of this relationship in different parts of the mudflat–salt marsh ecosystem, makes it useful for hydrodynamic habitat characterisation in mudflat–salt marsh ecosystems across spatial and temporal scales. The extensive nature of the database does allow for various additional types of analysis: (i) wave attenuation by a *Spartina* vegetation, (ii) small scale studies on current velocities and turbulence levels in *Spartina* vegetations, (iii) calculating the water and sediment balance for part of the marsh system, (iv) calibrating and validating hydrodynamic and sediment transport models for the study area, while including biological activity. These types of additional analyses will further deepen our understanding of which are the key processes that determine the short- and long-term development of the mudflat–salt marsh ecosystems and their organisms.

Conclusions and perspectives

In this article some typical relations for hydrodynamic conditions on intertidal mudflats and estuarine salt marsh were described. Especially the linear relation between tidal amplitude and the maximum current velocity (Figs. 8 and 9) are valuable as a general descriptor of average hydrodynamic conditions. Hence, this relationship can be applied to both habitat characterisation and for validating hydrodynamic models. After having derived these kinds of general relationships, the next challenge is to collect data series to describe extreme events such as storms to further increase our understanding of the relationship between hydrodynamics and habitats.

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