Spatial and temporal variation in sedimentation rate on salt marshes

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Abstract

Salt marshes are ecosystems that depend on sedimentation for their growth and survival. The sedimentation rate on the marshes varies both spatially and temporally. The suspended sediment in the water is partly present as flocs of different sizes. The tidal cycle leads to two velocity peaks in the water flow, resulting in a higher suspended sediment concentration (SSC). The SSC is higher during high tide than low tide. Also spring tide, rain and wind-wave activity cause a higher SSC. Furthermore, there is a seasonal pattern in the SSC but this is poorly understood. Flow paths on salt marsh are mainly determined by the creek network, marsh topography and tidal range. In the creeks flow pulses can occur. Elevation determines, in combination with tidal amplitude, the inundation time of the marsh surface, with longer inundation leading in general to higher sedimentation rates.

Vegetation decreases the flow speed and turbidity of the water. Higher vegetation density leads to a larger reduction. Because the largest decrease of flow velocity and turbidity is at the vegetation boundary between the creek and the marsh surface, most sediment is deposited next to the creek. This leads to the development of levees and basins. Vegetation further stabilizes the substrate, inhibiting resuspension and erosion. The abilities of plants to trap sediment and to stabilize it, varies between species. Sedimentation itself has a positive effect on the vegetation.

Sedimentation rate can be at its maximum during the summer, because of the highest vegetation cover and low storm frequencies. However, it is also observed that the highest sedimentation rates were during the winter as a result of storms mobilizing and transporting sediment. In general, the spatial variation in sedimentation rate is determined by the elevation of the marsh surface, the distance from the marsh edge and the creeks, and the vegetation. The main factors controlling the temporal variation are the weather, the tidal cycle, the tidal range and the seasons.

Introduction

Salt marshes are ecosystems vegetated by halophytic plants that are regularly flooded by the sea (Allen, 2000). Salt marshes exist all around the world under a wide range of climatic conditions and in different geomorphical environments, such as river mouths, deltas, estuaries and sheltered areas behind islands and reefs (referred by Davidson-Arnott et al., 2002). Nearly all salt marshes depend on sediment supply for their growth and survival (Boorman, 2003). With the process of sedimentation not just sediment is deposited, but also nutrients and pollutants. This gives salt marshes an important filter function (Temmerman et al., 2006). The stored pollutants can be released with coastal erosion (Allen, 2000).

The process of sedimentation depends on two main factors: the availability of sediment and the opportunity for deposition (Van Proosdij et al., 2007). According to Boorman (2003) deposition occurs when there is:

1.) a stable surface of sediment which can be overflown by the tides for a shorter period than the time of exposure
2.) enough sediment supply in the water
3.) low enough flow velocities for the sediment to settle out

The distance a particle travels is controlled by the mean flow speed of the water and the turbulence intensity (Leonard and Luther, 1995). The size of a particle also plays a role (e.g. Allen, 2000; Allen and Duffy, 1998). The process of sedimentation can lead to lateral and vertical accretion. Here, only vertical accretion will be discussed.

After sedimentation, remobilization and redistribution of the deposited sediment can occur (Boorman, 2003; Brown, 1998; Temmerman et al., 2007). This is why the level of resuspension and erosion always have to be known before net rates and patterns of sedimentation can be determined (Christiansen et al., 2000). In the upper layer of the sediment also other processes can occur that lead to shallow subsidence of the surface elevation, such as sediment compaction, shrink swell from water storage, and plant production and decomposition (Cahoon et al., 1995 in Silva et al., 2009). So the velocity of vertical accretion is not the same as the sedimentation rate. This is why Van Proosdij et al. (2007) refer to studies stating that the collection of deposited material is a better way for short-term measurements of sedimentation rate than measuring vertical accretion.

It is interesting that the deposition of sediment on salt marshes is not uniformly distributed; it varies across the marsh surface as well as through time (e.g. Neubauer et al., 2001; Brown, 1998; Temmerman et al., 2003a; Allen and Duffy, 1998; Stoddart et al., 1989). The aim of this paper is to describe the most important factors that lead to this spatial and temporal variation. Because the deposition of sediment is influenced by a complex network of controls (e.g. Allen, 2000; Van Proosdij et al., 2007; Temmerman et al., 2003a), this paper presents a general overview.

Suspended sediment in the water

Allen (2000) divides the sediment of salt marshes in five categories: 1) sediment from rivers discharging in proximity of the marsh, 2) sediment coming from retreating coastal cliffs, 3) sediment from the seafloor, 4) dead organic material and skeletons of organisms, and 5) anthropogenic products such as sewage and industrial wastes. Eisma (1986) refers to deposits from the atmosphere as a sixth category of suspended material in seawater.

The sources of sediment can greatly differ between locations. On Danish salt marshes 60-80% of the accumulated sediment is coming from the North Sea, 10-20% comes from fluvial input and 10-20% from primary production (Pedersen and Bartholdy, 2006). At the marsh Bridge Creek in Great Britain the major source of sediment is the wave-induced erosion of the marsh edge, additioned by sediment coming from the creek itself (Reed, 1988).

Sediment can be present in the water column as single particles and as flocs. Flocs are aggregates composed mainly of mineral particles and often some organic material. This process of flocculation is very important in estuaries and salt marshes, as flocs have a higher settling velocity compared to single particles (Gibbs, 1985 in Chang et al., 2006b). As a result, most of the sediment in estuaries and marshes is deposited as flocs (e.g. Chang et al., 2007; Christiansen, 2000; Voulgaris and Meyer, 2004).

Two types of flocs can be distinguished: microflocs which have a diameter till 125 micrometre and macroflocs with diameters up till 3 millimetre. In microflocs particles are strongly bound together with organic compounds, produced by algae, bacteria and higher plants. Macroflocs are more fragile and are easily broken down to microflocs by turbulent shear (Eisma, 1986). When flocs grow, their density decreases, but at a tidal timescale this still results in an increasing settling velocity (Van der Lee, 2000; Ten Brinke, 1994).

An increased suspended sediment concentration (SSC) results in more and larger flocs (Dyer, 1994), and turbulent shear in smaller flocs. Together with the consumption and production of organic compounds, a continued building and breaking down of aggregates is going on in estuaries and salt marshes (Eisma, 1986).

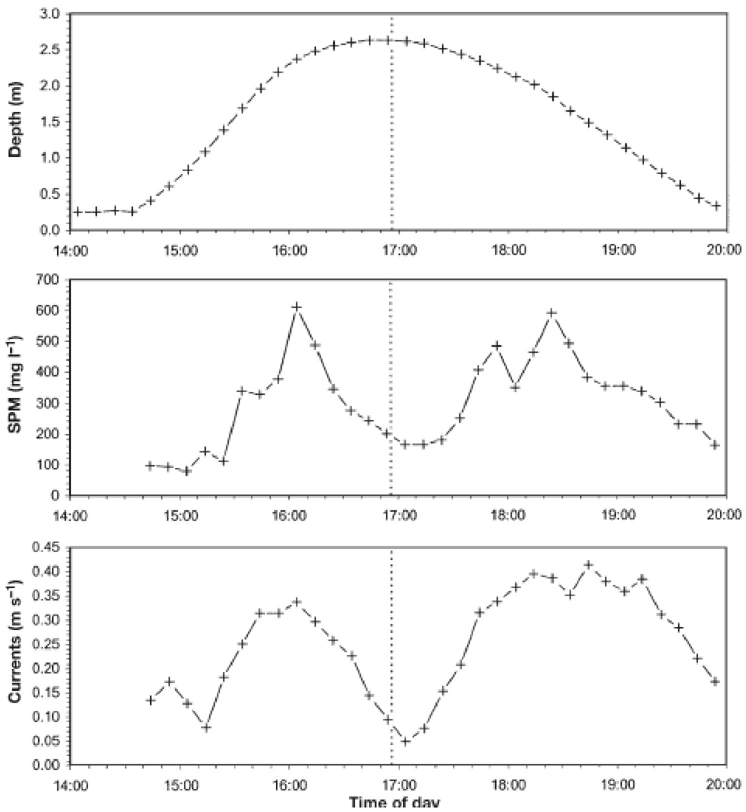

Figure 1. Variation in water depth, concentration of suspended particulate matter (SPM) and current velocity over a tidal cycle in the Westerschelde Estuary, Holland at 03-09-1997 (Widdows et al., 2004).

The tidal cycle

The tide is the central factor in salt-marsh sedimentation. The regular flooding of the intertidal flats and marsh platform is the result of the cycle of low and high tide, with in-between the period of slack water when the sediment can settle out.

The tidal cycle not only leads to an elevation in the water level but to two peaks in flow velocity, too. The increased velocity of the currents during rising and falling water results in a higher SSC (Figure 1) (Fettweis et al., 1998; Widdows et al., 2004). The sediment concentrations are significantly higher during high tide compared to low tide (Fettweis et al., 1998; Reed, 1988). Immediately after high water, the SSC decreases. This indicates deposition of sediment when the water flows over the salt marsh (Murphy and Voulgaris, 2006; Reed, 1988; Voulgaris and Meyer, 2004).

The tidal range

Another cycle associated with the tides are the spring and neap tides, resulting in variation of tidal amplitude. A higher tidal amplitude leads to raised turbulence and flow speed of the water, and therefore to an increased ability of the water to hold sediment in suspension (Allen and Duffy, 1998). All studies unanimously agree that the tidal height increases the SSC (e.g. Murphy and Voulgaris, 2006; Leonard and Reed, 2002; Voulgaris and Meyer, 2004). The SSC closely follows the pattern of tidal height, increasing when the tide rises towards spring tide and decreasing till neap tide (Figure 2).

According to French (1993, in Allen and Duffy, 1998) the increased SSC is a result of the increased immersed sedimentary surface. Fettweis et al. (1998) think that with increased tidal amplitudes currents are faster and are able to erode more substrate and to hold more particles in suspension. Even when tides have the same height, variation in suspended sediment is still possible. This is due to relative small differences in velocity patterns (Reed, 1988). When the water can hold more sediment in suspension during spring tides, the grain size of the suspended particles also increases (Allen and Duffy, 1998).

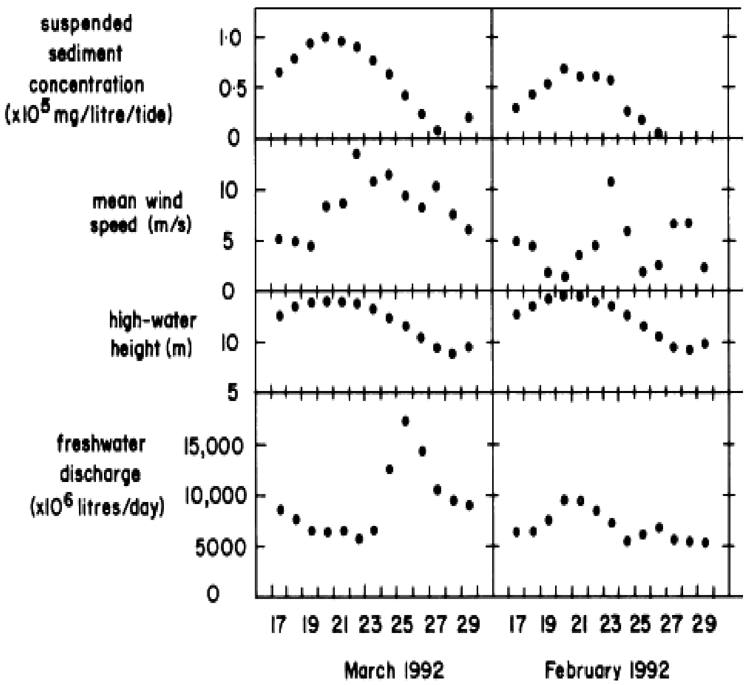

Figure 2. Variation of SSC, mean wind speed, high-water height and freshwater discharge over a spring-neap cycle in Severn Estuary, U.K. The SSC follows closely the high-water height (Allen and Duffy, 1998).

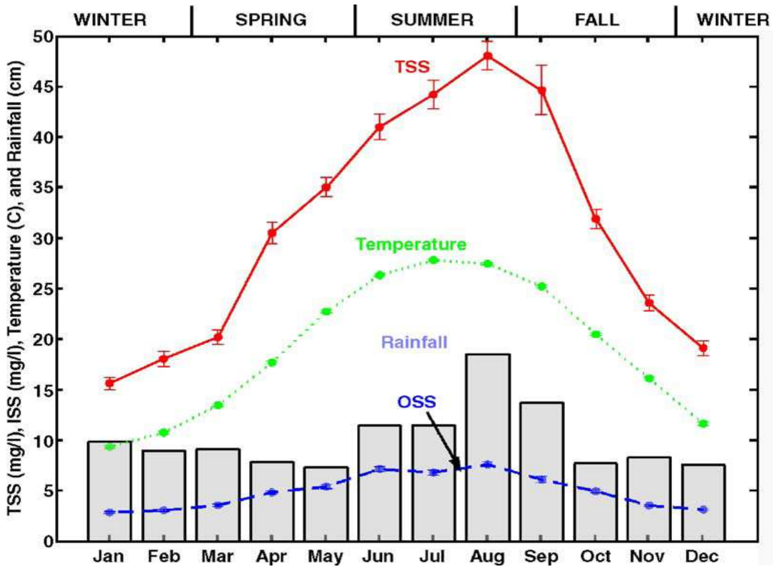

Figure 3. Average monthly total suspended sediment (TSS), organic suspended sediment (OSS), water temperature, and rainfall between 1981–1993 at North Inlet, U.S.A. (Murphy and Voulgaris, 2004).

The effect of weather

The weather can disturb the cyclic pattern of the SSC with the tidal cycle and tidal range. Wind speed with the subsequent wave activity increases the SSC significantly (French et al., 2000; Van Proosdij et al., 2006). Also the grain size in the suspended sediment is enhanced. Together with the decreased opportunity for the finer particles to settle out during the high energy conditions, this results in deposition of coarser sediment (Chang et al., 2006a; Christiansen et al., 2006).

Rain is also involved in the SSC. Murphy and Voulgaris (2004) report that the SSC is on average 25% higher during wet conditions than during dry conditions. The size of the effect of rain depends on the stage of the tidal cycle. When the water is low, large exposed intertidal areas are susceptible for erosion. When it rains during a flooding current, the recently eroded sediment can flow back immediately to the marsh surface. But when the current is retreating, so moving towards the sea, it will take the sediment with it. When the water is high, rain has a negligible impact on the SSC because much of the marsh surface is inundated. In short, as a result of the rainfall the SSC is high during the whole tidal cycle. During dry conditions, the SSC is only increased at high tide.

The seasons

A third cycle resulting in variation in suspended sediment is caused by the seasons; the SSC is not uniformly distributed around the year. Gardner et al. (1989) measured the highest concentration of suspended sediment in the summer and the lowest during winter at a salt marsh in South Carolina (U.S.A.). Only a part of this increase can be caused by an increased primary production, as the increase in organic suspended sediment is far lower than the increase in SSC. The authors attribute the raised levels to more bioturbation during summer, because organisms are more active at higher temperatures. Due to this disturbance of the substrate, the sediment is more easily suspended and transported. A recent study of Murphy and Voulgaris (2004) at the same location shows the same results (Figure 3). Here also the increased SSC cannot be the result of increased primary productivity. They also think bioturbation is the main factor regulating the SSC.

In contrast, several studies in the Scheldt estuary at the border of Belgium and the Netherlands revealed that the SSC is higher during winter (Chen et al., 2005; Fettweis et al., 1998; Temmerman et al., 2003b). Also at a salt marsh in Norfolk (U.K.) the SSC is highest during winter as well in the tidal inlet as the creek systems (French, 1989 in French and Spencer, 1993). Fettweis et al. (1998) come with several possible explanations for the nonuniform distribution of sediment during the year: variation in freshwater discharge, variation in temperature, and variation in land erosion. More rainfall occurs in winter, which leads to an increased freshwater discharge. Their research gives some indications that this results in more turbidity and causes an increase in the sediment concentration.

Secondly, during winter more terrestrial erosion is possible because there is more rainfall and less vegetation cover. Thirdly, the increase in temperature is coupled to an increase in biological activity. Micro-organisms can increase the erosion threshold of the mud on intertidal areas by the formation of biofilms, a process which is also mentioned by Hughes (2001). In addition, there is more production of organic compounds, enhancing the formation of flocs. Unfortunately, there are no data to test if the second and third factor have an effect on the increased sediment concentration during winter.

Chang et al. (2006b; 2007) have discovered that there is indeed a seasonal pattern in flocculation. In winter, rough weather results in the break-up of flocs and resuspension of the particles, leading to more and smaller flocs in the water. During summer, floc formation is the dominant process, resulting from the increased production of biopolymers associated with the higher water temperatures. Bigger flocs have higher settling velocities, and more deposition takes place.

The SSC of the water is during summer further decreased with the lower availability to keep sediment in suspension. Warmer water has a lower viscosity and in this way it can support only small particles (Allen and Duffy, 1998). The lower viscosity also leads to less mobile sediment; particles of the same size will have higher settling velocities during summer (Chang et al., 2006a). Consequently, more fine-grained sediment will settle out in summer, leading to higher clay ratios of the sediment. This pattern is enhanced by the generally lower energy levels during summer (Chang et al., 2006a).

Flow paths

Creeks are internal flow paths across a salt-marsh surface. By influencing the distribution of the water with suspended sediment, they are an important factor controlling sedimentation rate and patterns (e.g. Reed, 1988; Stoddart et al., 1989). But not all import and export of water occurs via the creek networks. On a marsh in the U.K. up to 40% of the water flux occurs via the marsh margin at high spring tides (French and Stoddart, 1992 in French and Spencer, 1993). Van Proosdij et al. (2007) even found that most of the incoming water flows over de marsh edge. Only at the beginning and the end of the tidal cycle, flow is restricted to the creeks.

Temmerman et al. (2005b) demonstrate that the portion of water exchange via the marsh edge depends on the level of high water and the marsh topography. At high marshes, where well developed creek systems with levees and basins are present, flow paths depend on the height of the water level during the tides. When the water level is less than 0.2 m above the creek bank levees, all water is imported to the high marsh via the creek system. During higher levels (0.2-0.6 m), the proportion of water supplied via the marsh edge increases with increasing water level. They explain this relation to water level by the easier occurring sheet flow during high tides, when vegetation and small-scale topography differences are overtopped. Although the percentage of water entering the marsh via the creek system decreases with increasing water level, the absolute amount of water increases. At the low marsh, most of the water enters via the marsh edge instead of the creek systems.

Flow directions

The flow directions in creeks and on the marsh surface are influenced by interacting factors such as topography, tidal stage, and wind-wave activity. The flooding of the marsh surface leads to a larger effect of wind and waves while a decrease in water depth leads to an increased role of the creeks (Davidson-Arnott et al., 2002).

At the low marsh flow paths are perpendicular to the marsh edge at the beginning and end of the inundation, and more parallel to the marsh edge at the moment of maximum flooding. This is due to the downward seaward slope and few tidal creeks (Temmerman et al., 2005b). At the high marsh a similar pattern is observed, with flow directions perpendicular to tidal creeks during the beginning and end of an inundation cycle. At peak flows, the directions were more perpendicular to the seaward marsh edge (Wang et al.,1993 and Leonard, 1997 in Temmerman, 2005b). According to Temmerman et al. (2005b), this indicates that water level influences the flow path. They do not have their own observations to prove this for the Scheldt estuary, but they do expect it.

Flow speed

The dominant factor determining the mean flow speed is the tidal cycle, generating one velocity peak with low tide and one with high tide (Figure 1) (e.g. Christiansen et al., 2000; Widdows et al., 2004). There is disagreement between studies about the difference in height between the two peaks and the explanation for this. Just like Widdows et al. (2004), Christiansen et al. (2000) found that the maximum flow speed is higher during low tide than during high tide. They think this is partly due to the seaward landscape slope. Furthermore, with the water movement inward the salt marsh, the flow resistance increases. This can also cause a decrease in water speed of the flow towards the marsh and an increase in velocity of the flow leaving the marsh. According to Davidson-Arnott et al. (2002) higher velocities during ebb are due to the funneling of water in the creeks when it leaves the marsh. Stoddart et al. (1989) observed that the difference in the maximum velocities depends on the tidal range. At normal conditions symmetrical velocity distributions were observed: maximum flow speeds during high tide were the same as during low tide. But at spring tides when the water exceeded the creek systems and flooded the marsh, the maximum flow speed was much higher during ebb.

According to Dyer (1994), friction increases with decreasing water depth. This means that in estuaries where the tidal range is relative large compared to water depth, water travels more quickly into an estuary than it will leave the marsh. This results in a quick rise of the water level and an associated high velocity peak at the beginning of high tide and a slow fall with low flow speed towards low water. The studies of Temmerman et al. (2005b) and Bouma et al. (2005) in the Scheldt estuary in the Netherlands confirm the higher maximum flow velocity during high water.

Flow pulses

In creek systems flow velocities can be suddenly increased and decreased quickly afterwards: velocity pulses. Two major types of velocity pulses seem to exist, both related to the tide. The first one happens during under-marsh tides at the moment the water reaches the dry channel (Allen 1994; Allen, 2000; Temmerman et al., 2005a). During over-marsh tides, when the tides flood the marsh surface, another process produces velocity pulses. At the moment the water exceeds the bank, a huge storage capacity becomes available. As a result, a huge volume of water is transported through the creeks towards the marsh, generating a peak in flow velocity (Allen 1994, Stoddart et al., 1989). Temmerman et al. (2005a) explain the pulses completely different with a computer model. The presence of vegetation on the marsh platform results in an obstructed water flow, so the flood wave moves faster trough the low resistant creek network. This results in the flooding of the higher marsh from the creeks, with velocity pulses as a consequence. In the model, pulses would not be present without vegetation (Figure 4).

Where and how flow pulses in the creeks originate, is variable with location. In the Scheldt estuary (The Netherlands) flow pulses are only present at over-marsh flows and absent during under-marsh tides. They occurred only at the high marsh, as water exchange via the marsh margin plays an important role at the low marsh (Temmerman et al., 2005b). At a salt marsh in Fundy (Canada) no tidal flow pulses were observed, only small pulses generated by the changes in channel gradients. These creeks did not have any levees, so the water exceeded the marsh margin and the creeks at nearly the same time (Davidson-Arnott et al., 2002). So levees also play a role in the presence of pulses.

The velocity pulses promote the remobilization of the deposited sediment in the creeks during neap tides and probably even erosion of the creek itself (Reed, 1988; Stoddart et al., 1989). So velocity pulses lead to a higher SSC in the creek and give opportunities for the transportation of the sediment to the marsh surface. It is so that even the peak of SSC can coincide with the velocity pulses in the creeks (Reed, 1999).

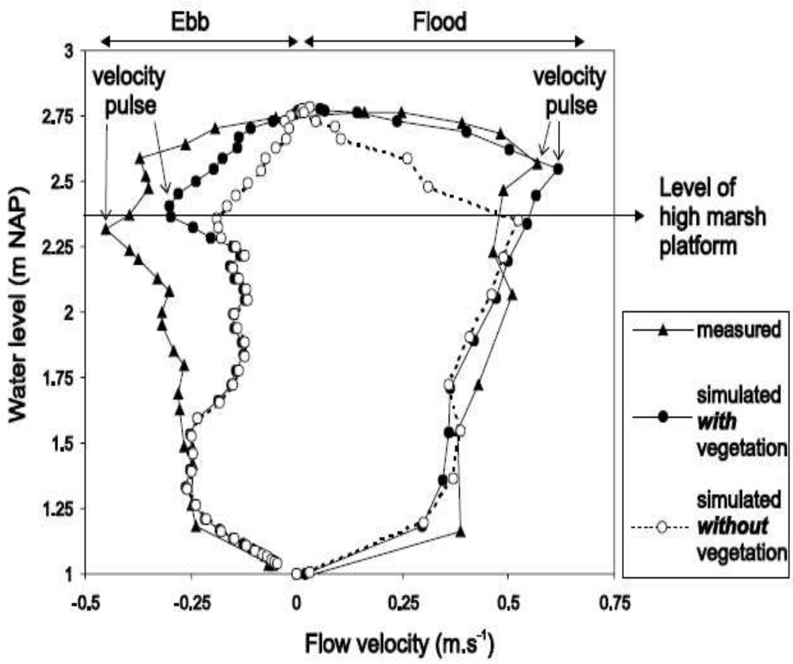

Figure 4. Water level and flow velocities of simulations with and without vegetation and field measurements over one tidal cycle at the Scheldt estuary (Holland) (Temmerman et al., 2005a)

Elevation

In combination with tidal range, the elevation of a salt marsh determines the duration and frequency of inundation. Many studies show that sedimentation rates decrease with increasing surface elevation (e.g. Temmerman et al., 2005a; Christiansen et al., 2000; Stoddart et al., 1989). This explains the decline of sedimentation rate with the aging of marshes (Pethick, 1981 and French, 1991 in French and Spencer, 1993).

Elevation affects not just inundation time during a tidal cycle, but the water depth too. Subsequently, this influences the wave activity as waves break sooner in lower water depth. Deposition can not occur in the vicinity of breaking waves, so sedimentation only occurs below this point and above it where all the wave energy is dissipated (Figure 5) (van Proosdij et al., 2006).

The study by Davidson-Arnott et al. (2002) shows that the relationship between elevation and sedimentation is not that straightforward. At a macrotidal marsh in Canada, the highest sedimentation rate occurs at the middle marsh and not the low marsh, because the great water depth during spring tides enables waves to inhibit deposition and promote erosion.

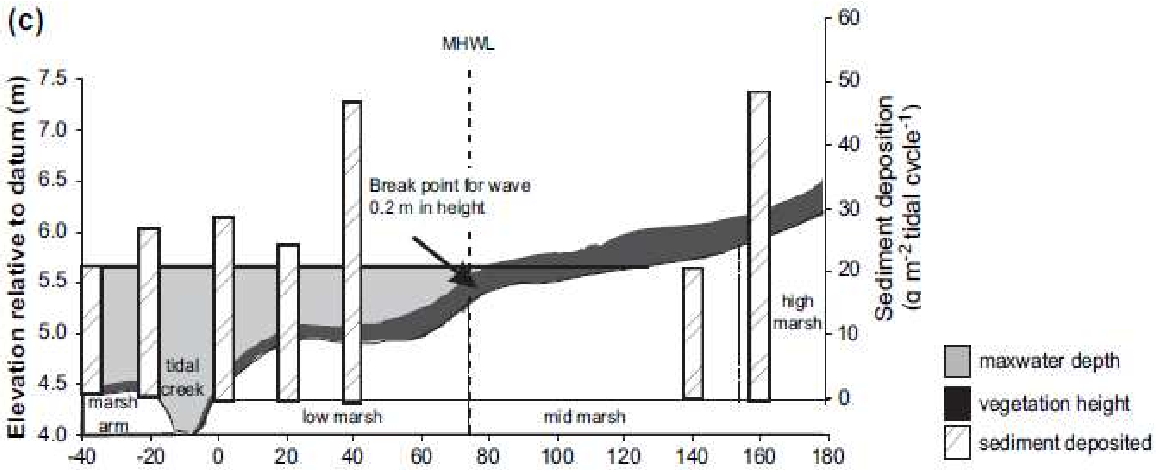

Figure 5. Sediment deposition during one tidal cycle in relation to topography, maximum water depth, vegetation height and the breakpoint for waves at low water level in the Bay of Fundy, Canada (Van Proosdij et al., 2006).

Vegetation

Flow velocity

Mean flow speeds in vegetated areas are generally 2.5 to 3 times lower than adjacent unvegetated areas (Leonard and Reed, 2002). The velocity decreases with distance from the marsh edge, so with increasing distance across the vegetation (Leonard and Luther, 1995; Christiansen et al, 2000). The biggest decrease in flow velocity is at the vegetation boundary between the creek and the marsh surface (Christiansen et al., 2000). This rapid reduction is found at the same place with computer models (Temmerman et al., 2005a). Measurements in *Juncus roemerianus* and *Spartina alterniflora* patches show that flow speeds are in both canopies inversely related to stem density (Leonard and Luther, 1995). Field records from Möller et al. (1999) show that wave height is four times more reduced over a salt-marsh surface than over a sand flat. Also the wave energy is significantly more dissipated.

Vegetation changes the water speed not only horizontally, but also vertically. Leonard and Luther (1995) made vertical speed profiles in open water and in canopies of different plant species. The velocity of the water is not uniform with height (Figure 6). In open water without obstruction, the time-averaged flow speed is proportional to the logarithm of the height above the ground (Allen, 2000). Vegetation reduces the flow speed and causes a 'kink' in the profile at the height where the canopy density is highest. This is consistent with data from Christiansen et al. (2000) and Leonard and Reed (2002).

Within *Juncus roemerianus* and *Spartina alterniflora* stands, water speed is generally lowest at 7 to 12 cm above the marsh surface where leaves start to emerge from the sheath. The kink is sharper with increasing vegetation density (Figure 6) (Leonard and Luther, 1995). Different species with different morphology lead to different speed profiles. Complex or variable species architecture results in more variable profiles for different flooding events (Leonard and Reed, 2002).

For shorter species who are often completely submerged during tidal flows, another profile is observed (Figure 7). Here the kink is absent. The water can be divided in two flow zones: the lower zone within the canopy which shows low velocities and the upper zone which is free from obstruction. Flow speed in the canopy is reduced relative to the velocity above, and at the top of the vegetation a drop in flow speed can be observed (Leonard and Luther, 1995; Leonard and Reed, 2002). In the denser part of the vegetation the velocity is nearly constant or increases slightly linear, above the canopy a logarithmic profile develops (Neumeier and Ciavola, 2004).

The effect of submerged and unsubmerged canopies on sedimentation is investigated with 3D computer models by Temmerman (2005a). When the water level is below canopy height, there will be more difference in flow velocity between vegetated areas and unvegetated areas. This will lead to much deposition in vegetated areas and less in barren places. When the vegetation is submerged, more large-scale sheet flow occurs, resulting in more homogeneous sedimentation patterns.

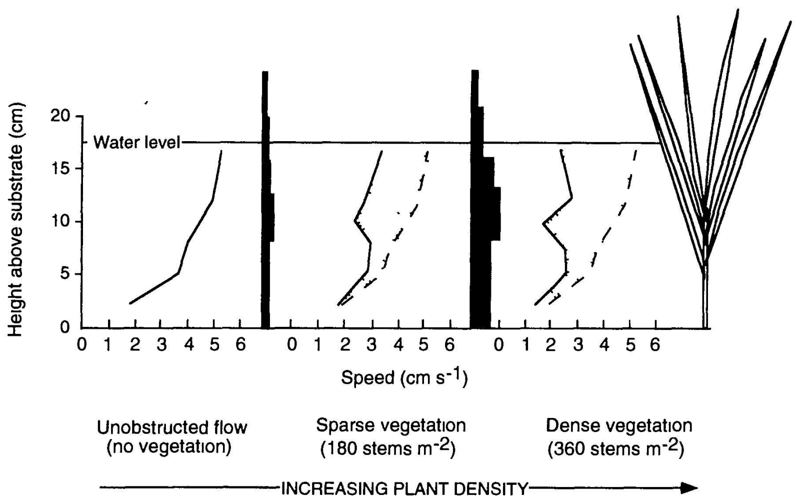

Figure 6. Three vertical speed profiles in a *Spartina alterniflora* canopy (black line) compared to unobstructed flow (stippled line) at different stem densities. The black bars indicate the relative distribution of plant material (Leonard and Luther, 1995).

Turbulence intensity

When water encounters a solid object or surface, friction arises. This friction is restricted to a layer of water around that object: the boundary layer. Outside the boundary layer no friction stress exists (Dyer, 1994). When seawater moves across a marsh platform, the vegetation will create much flow resistance besides the ground surface friction. That results in a turbulent boundary layer (Allen, 2000).

Turbulence is a chaotic flow with complicated, dynamic streamlike patterns that leads to the formation of eddies: swirling of a fluid. Eddies are characterized by their ability to change abruptly in size, shape and velocity. It is the opposite of laminar flow, when the streamlines of the water are parallel (Dyer, 1994). Turbulence is a very important factor in the transport and distribution of sediments in water (French et al, 1993 in Leonard and Luther, 1995). Turbulence leads to mixing of the water column, with dissolved and suspended particles in the water becoming more uniformly spread (Dyer, 1994).

Turbulence is inversely related to distance from the creek (Figure 8) (Leonard and Luther, 1995; Christiansen et al., 2000). During flooding tides, the turbulent kinetic energy is exponentially reduced in the vegetation. At a distance of 15 metres from the creek only 1% of the initial energy is left. This suggests that the turbulence originates from the creeks and that vegetation reduces it by the inhibition of larger turbulent eddies and the breaking down of existing eddies into smaller ones (Leonard and Luther, 1995; Christiansen, 2000). The greatest reduction in turbulent energy was between the creek and the vegetation boundary where it can be decreased with a factor five (Christiansen et al., 2000).

Turbulence intensities also decrease with increasing stem density (Leonard and Luther, 1995). Further, the rate of turbulence reduction seems to be related with plant type. With the same stem density, *Spartina alterniflora* is a more effective dissipater of turbulence intensity than *Juncus roemerianus* (Leonard and Luther, 1995). In contrast to reducing turbulence, vegetation can also generate small eddies around stems in some circumstances. This can promote erosion at the microscale of plant stems (Leonard and Luther, 1995).

As with flow speed, turbulence intensities are not vertically uniform but influenced by plant architecture and density. At the height where the mean velocity is mostly reduced, the turbulence intensity is mostly dissipated, too. Plants can also cause turbulence. At regions where plants have large interstem distances and the largest stem diameters are at 3 cm height, maximum turbulence production occurs (Leonard and Luther, 1995). In a *Spartina alterniflora* vegetation, most turbulence is in the horizontal plane and not in the vertical plane. This results in more horizontal flow of water rather than vertical mixing, which is beneficial to the transport of particles to the marsh interior (Leonard and Reed, 2002).

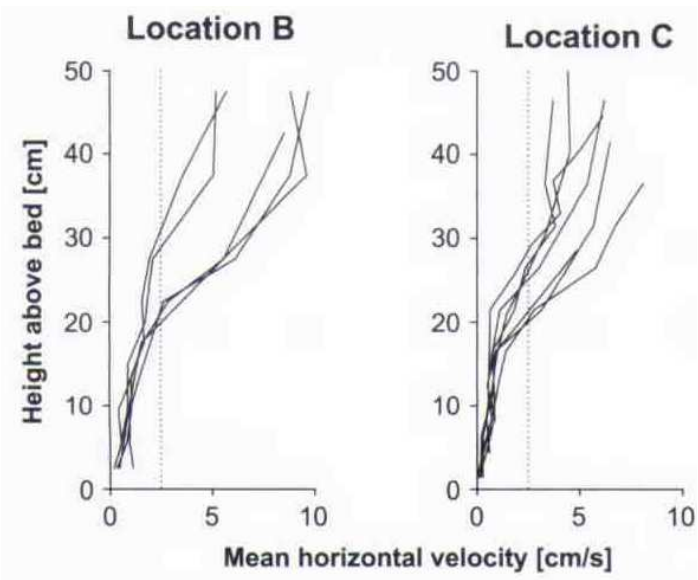

Figure 7. Vertical speed profiles in and above a submerged *Spartina maritima* canopy at two locations. The height of the vegetation was around 20 cm (Neumeier and Ciavola, 2004).

Deposition

The decrease in mean flow speed and turbulence leads to the reduction of vertical mixing and the ability to maintain particles of a given size in suspension. This promotes deposition (Christiansen et al., 2000). Leonard and Reed (2002) measured suspended sediment concentrations within the canopy and above the canopy. The SSC turned out to decrease twice as much in the vegetation than higher in the water column. This indicates that vegetation really enhances the deposition of sediment.

Because of the abrupt change from an unvegetated to a vegetated area at the border of the creek and the marsh platform, flow velocities and turbulence are mostly reduced at this place. As a result, the sedimentation rate is high next to the creek and decreases quickly due to progressive sediment deposition to the interior of the marsh (Figure 9) (Reed et al., 1999; French and Spencer, 1993; Neubauer et al, 2001; Temmerman et al., 2005a).

Not only the SSC decreases quickly from the creek margin to the marsh interior (Reed, 1999) but also the size of the deposited grains drop (Christiansen et al., 2000). This leads to a decrease in the amount of inorganic as well as the amount of organic sediment with distance from the creek. The organic fraction is finer and more easily transported (French et al., 1995 in Reed et al., 1999). So the relative amount of organic matter increases with distance from the creek (Reed, 1999; French and Spencer, 1993).

The high sedimentation rates adjacent to the creek lead, on the long term, to the development of levees with basins behind it. If that were the only mechanism, levees would continually grow higher and higher. Obviously, this is not true, because elevation decreases the sedimentation rate. By this feedback mechanism levee growth ends in an equilibrium elevation (Temmerman et al., 2004). Not just vegetation affects levee formation. Both suspended sediment concentration and grain size play a role in the development of levees and basins. In the absence of coarse sediment, the settling velocity is lower and no levees will originate (Davidson-Arnott et al., 2002; Temmerman et al., 2004).

Vegetation is not the only factor affecting the spatial distribution of deposition. The creeks, the marsh edge and marsh elevation determine the flow paths of the water with the suspended sediment (Temmerman et al., 2005b), and influence the spatial variation in sedimentation as well. So are elevation, distance from the marsh edge, and distance from the creeks negatively correlated with sedimentation rate (Esselink et al., 1998; Temmerman et al., 2003a). The importance of creeks on the spatial pattern of sedimentation and the effect of small topography changes, is highest on the high marsh. At the low marsh, sheet flow from the marsh margin will be slowed down by vegetation and most of the sediment will be settled out before it reaches the high marsh (Temmerman 2005b). Exceptions are possible: at the salt marsh of Allen Creek there was no significant relation between deposition rate and distance from the creek (van Proosdij et al, 2007).

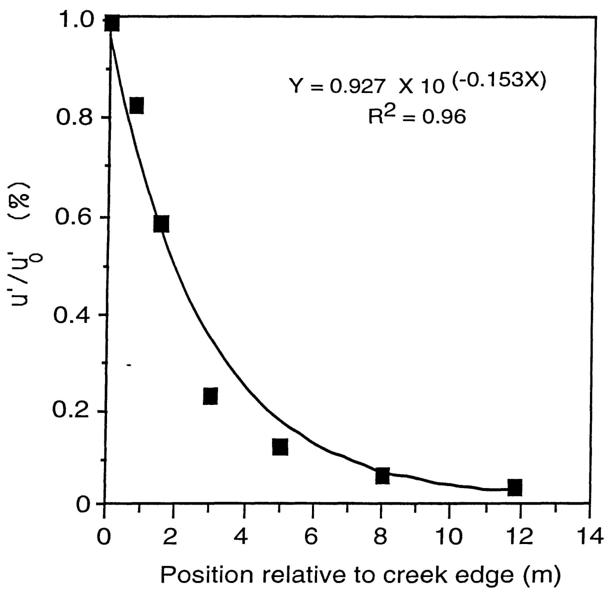

Figure 8. The turbulence intensity (u'/u'_0) decreases exponentially with increasing distance from creek. Values of marsh interior (u') have been normalized against creek edge values (u'_0) (Leonard and Luther, 1995)

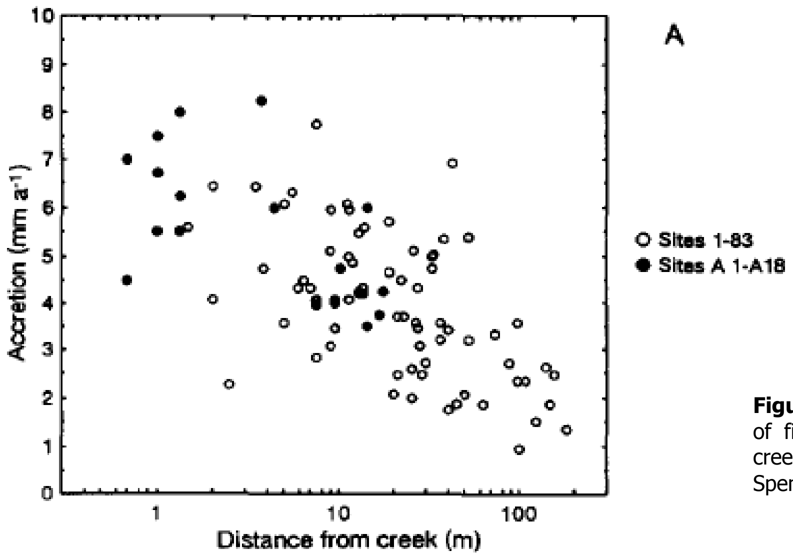

Figure 9. The mean annual accretion of five years with distance from the creek at Norfolk, U.K. (French and Spencer, 1993).

Resuspension and erosion

The decreased flow speed and turbulence also inhibits erosion (Christiansen et al., 2000). Besides, the roots of the vegetation stabilize the deposited substrate (van Eerdt, 1985; Boorman, 1999). Christiansen et al. (2000) indeed did not find any evidence that sediment was remobilized after deposition in the vegetation canopy. Their measured shear stresses were not big enough to be able to remobilize the sediment. And during peak tides when resuspension was mostly expected, there was no increase in SSC. Grain size analysis also indicated that no remobilization of the sediment had taken place. Brown (1998) measured sediment erosion at barren areas at Skefflingen Marsh (U.K.) while in the vegetated areas the elevation remained the same, indicating that the plants stabilized and protected the substrate. Vegetation also freezes the network structure of the creeks; creeks can undergo only minor lateral changes after the establishment of plants (Marani et al., 2003). Although this data prove that vegetation inhibits resuspension and erosion, these processes do take place. Boorman (1999) noticed that annual rates of deposition are much lower than short-term rates. From this he concluded that after initial deposition recirculation of the sediment occurs (Boorman, 1999 and Boorman, 2001 in Boorman, 2003).

Temmerman et al. (2007) showed with aerial photographs and computer models that the erosion-reducing function of vegetation only occurs at small scales in the vegetation patch itself. The obstructed flow within the vegetation results in enhanced flow speed between the patches, and there erosion will take place. At the long term, vegetation patches will lead to development of creek networks. Brown (1998) noticed this process in the field. It suggests that higher vegetation densities lead to higher creek densities. This is contrary to the general idea that vegetation freezes the pattern of the creek network and the creek density.

Differences between species

After the different effects of species on mean flow speed and turbulence, the final effectiveness of sediment trapping differs between species. *Salicornia spp* seem to be an ineffective sediment trap while *Atriplex portulacoides* efficiently baffles the water flow because of the strong stems and high leave density, even during winter (French, 1985 in Stoddart et al., 1989).

Silva et al. (2009) explain different sedimentation rates in areas of different plant species by the plant capacity of trapping sediment. Patches of *Spartina maritima* had on average a higher sedimentation rate than *Sarcocornia perennis subsp. perennis*. This is likely to be a result of the stoloniferous rhizome system which develops as a net during the growing season. Low sedimentation rates were measured in the vegetation of *Sarcocornia perennis subsp. perennis*, a species which develops a weaker rhizome system than *Spartina maritima* and traps less sediment. Hughes (2001) also mentions the greater ability of *Spartina* in trapping sediment compared to *Salicornia sp*.

Temmerman et al. (2003a) did not find different sediment trap capacities between salt-marsh communities (e.g. *Puccinellia maritima, Atriplex portulacoïdes*) and freshwater marsh communities (e.g. *Phragmites australis, Salix spp*). Vegetation characteristics really differed between these two locations, but that did not result in a different spatial sedimentation pattern. They conclude that salt-marsh vegetation does have an effect on sedimentation by promoting deposition, but that the different communities at the same elevation do not differ in effectiveness of sediment trapping.

Also, there seems to be no clear relation between canopy height and sedimentation rate (Boorman et al., 1998). Such a relationship is only found in relatively short vegetation, because with the increase in height, vegetation is more easily flattened by the water flow. In contrast, short vegetation (around 5 cm) can be a good sediment trapper because of its stiffness.

Positive feedback mechanism of sedimentation

Vegetation can only establish on a salt marsh when intertidal flats have reached an elevation that seawater only reaches it for a maximum of six hours a day (Van Duin et al., 1996 in Boorman, 1999). Further sedimentation has a positive effect on plants. Laboratory experiments showed that *Salicornia europaea* and *Aster tripolium* in general grew better when sediment was added. Even if the deposition rate was made much higher than it would have been under natural circumstances, the plants did not show negative effects during the experimentation time of two months (Boorman et al., 2001).

Laboratory experiments with *Puccinellia maritima* gave similar results. *Puccinellia maritima* was stimulated in growth performance with a burial depth of 4mm/month, However, burial depths of 8 mm/month effected the growth negatively while 12 mm/month resulted in increased mortality. The range of burial tolerance fits quite well with the accretion rates in his habitat (Langlois et al., 2001).

Seasons

Seasons do not only influence the SSC but also the vegetation, causing the dieback of annuals in winter. That moment of minimum flow resistance corresponds with the storm season (Allen, 2000). So, the highest sedimentation rates are expected during the summer, when high plant densities promote deposition and prevent erosion mostly. Neubauer et al. (2001) did indeed measure highest sedimentation rates during the growing season at the creek bank of a tidal freshwater marsh in Virginia. Deposition rates were relatively constant throughout the year at the sites in the marsh interior. At a salt marsh in Florida, mean deposition rates were as well at the levees as in the marsh interior higher during summer than during winter (Leonard et al., 1995).

However, Silva et al. (2009) found at all their four locations on two different salt marshes in Portugal the highest accretion rates in winter. They suggest that this is caused by much higher rates of suspended sediment during winter storms, leading to higher accretion rates. This situation has been proven to be true at a salt marsh in a Southern California estuary (Cahoon et al., 1996). At that location nearly no sedimentation occurred at normal tides, but only with episodical floodings induced by storms. However, in this estuary, the river plays a dominant role in sediment availability. Storms mobilize much sediment which can be deposited on the marshes because of the high water levels resulting from the high flow discharge of the river.

More studies reveal that storms can play an important role on sedimentation rate. On a marsh in Louisiana winter storms have an important role in the temporal variation of deposition. Winter cold fronts mobilize sediment en transport it with flooding water on the marsh (Reed, 1989). French and Spencer (1993) found large mismatches at some locations on the high marsh between short-term and annual sedimentation rates, indicating that the highest surfaces only receive sediment during storms. From the salt marsh Peazemerlannen (The Netherlands) it is concluded that much of the sediment is not regularly deposited but mainly during storm tides (Bakker et al., 2002). Davidson-Arnott et al. (2002) even conclude that on the salt marsh they studied, wind is the most important factor controlling spatial variation.

However, it is not true that the effect of plants is negligible at the sites where storms dominate in controlling the seasonal variation of sedimentation rate. Vegetation does play a role in dissipating wave energy during storms and so supports deposition. Based on their data, Neumeier and Siavola (2004) come with two conceptual models:

1. Normal weather: the low sedimentation rate is dependent on elevation and creek proximity. There is only moderate sediment trapping by the vegetation.
2. During storms: vegetation protects the marsh against erosion. In addition, the trapping capacities of the plants are more effective with the elevated SSC.

A study at Skefflingen in the U.K. (Brown, 1998) reveals a pattern of deposition and erosion that can probably explain the contrasting findings of seasonal variation in sedimentation rate by a spatial factor: elevation. At this marsh a net result of sedimentation and erosion leads to a profile in which the upper and middle marsh continue to be elevated, while the lower marsh experiences more variation with cycles of accretion and erosion. This was shown by an increase in sediment level between March and June followed by erosion in the subsequent winter on the bare areas at the marsh edge. In contrast, at the higher elevation accretion also happened in the winter. However, like many other studies, the research period of 18 months is too short to conclude that the observed pattern really is a seasonal one, or that it is just a result of unusual winter events.

Synthesis

In general, most studies agree about the influence of the discussed factors on sediment deposition, although for many some exceptions are observed. However, studies about the seasonal pattern of SSC in the water gave very contrasting results. Studies in South Carolina found highest SSC during summer (Gardner et al., 1989; Murphy and Voulgaris, 2004). But in Belgium, the Netherlands and the U.K. the SSC is found to be at its maximum in winter (Chen et al., 2005; Fettweis et al., 1998; Temmerman et al., 2003b; French, 1989 in French and Spencer, 1993). Taking into account the locations of the studied salt marshes, the different results are probably due to the environments with different processes in the water going on.

Also from the maximum flow speed during a tidal cycle, no uniform conclusion is possible. According to some authors the flow velocity of the water is highest during high tide (Pye, 1994; Bouma et al., 2005; Temmerman et al., 2005b), while others show that the maximum flow speed is during low tide (Christiansen et al., 2000; Davidson-Arnott et al., 2002; Stoddart et al., 1989). Some explanations they give for their findings depend on the location, such as landscape slope and tidal range. It is likely that the moment of maximum flow speed of the water during a tidal cycle depends on the local conditions of the salt marsh.

Another point of discussion is the overall effect of the seasons on sedimentation rate. Neubauer et al. (2001) and Leonard et al. (1995) found the highest sedimentation rates during summer, which can be explained by the combination of maximum vegetation cover and low storm frequencies. But other studies conclude that the winter gives highest deposition rates as a result of storms mobilizing and transporting sediment (Cahoon et al., 1996; French and Spencer, 1993; Reed, 1989; Silva et al., 2009). Neumeier and Siavola (2004) think that sediment trapping by vegetation during storms is more effective, while Brown (1998) shows that marsh elevation can play an important role. Apparently, the overall effect of the winter season is dependent on the size and frequency of the storms, the elevation and the vegetation cover, resulting in a variable overall effect for different locations.

About which factor(s), controlling spatial and temporal variation in sedimentation rate, is the most important, the conclusions are divers. According to Temmerman et al. (2005b), elevation and the distance from the marsh edge and the creeks are the most dominant influences causing spatial variation. But Davidson-Arnott et al. (2002) conclude wind is the factor controlling the sedimentation pattern. Murphy and Voulgaris (2004) investigated the effect of rainfall and found an average effect of 25% increase in the SSC, while most other studies do not mention this factor at all. These diverse views on the controls of sedimentation rate can be explained by the impossibility to investigate all factors with one study. So papers will always be focused on one side of the whole process. Interactions between most of the factors make it even more difficult to estimate the relative importance of the factors and to get a good overview.

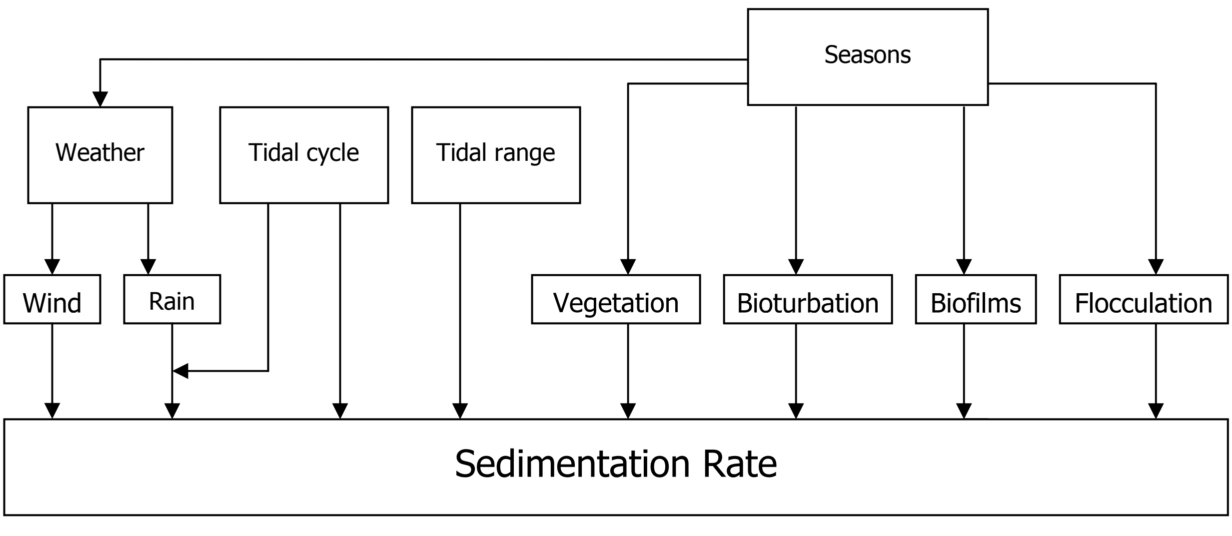

Figure 10. The main factors leading to temporal variation in the sedimentation rate on salt marshes.

Moreover, the timescales over which the data are gathered range from some single tidal cycles to years. The choice for a study period determines to a large extent on which sedimentation factors the focus lies. When the research is done in a few weeks or months, it is impossible to investigate the role of storms. Besides, local variation may also play a major role. The effect of factors may possibly change dramatically at different salt marshes, as noticed by the effect of the seasons on the SSC.

Obviously more research is needed about the effects of the seasons on the SSC and the final sedimentation rate. It would be interesting to know what elements cause the exceptions of the general effects of the factors. This information will give a better understanding of the processes. Furthermore is it remarkable that hardly any research has been done yet about the effects of trawling fishery and dredging on the sedimentation rate of salt marshes. These activities are likely to increase the SSC directly by disturbing the sea floor. Also indirect effects are expected: with the destruction of the seagrass beds and mussel banks, their capacity to catch sediment out of the water will disappear too.

Showing a complete picture of the factors influencing sedimentation rate is impossible. Not just because of the inconsistencies about some factors and the poor understanding of some factors. But especially the amount of factors and the interactions between them and the sedimentation rate itself, makes it hard to give a complete picture on the overall process. But from the studies so far, a qualitative overview of the most important factors on the sedimentation rate of salt marshes will be given.

The spatial variation in sediment deposition is mostly controlled by the following factors: elevation of the marsh surface, distance from the marsh edge, distance from the creeks and vegetation. The main factors controlling the temporal variation are the weather, the tidal cycle, the tidal range and the seasons (Figure 10). The factors differ in the time scale they act, ranging from hours like the weather and the tidal cycle till the year with its seasons.

By integrating the process of sedimentation, time and space are actually not inseparable. They are really closely intertwined because temporal factors affect spatial factors, such as the seasons, influence the weather and the vegetation (Allen, 2000). Interactions between only spatial factors can also result in temporal variation; vegetation influences the creek network but the creeks also affects the vegetation (Temmerman et al., 2005a). Therefore figure 11 shows a general picture of the overall factors controlling spatial and temporal variation in the sedimentation rate on salt marshes.

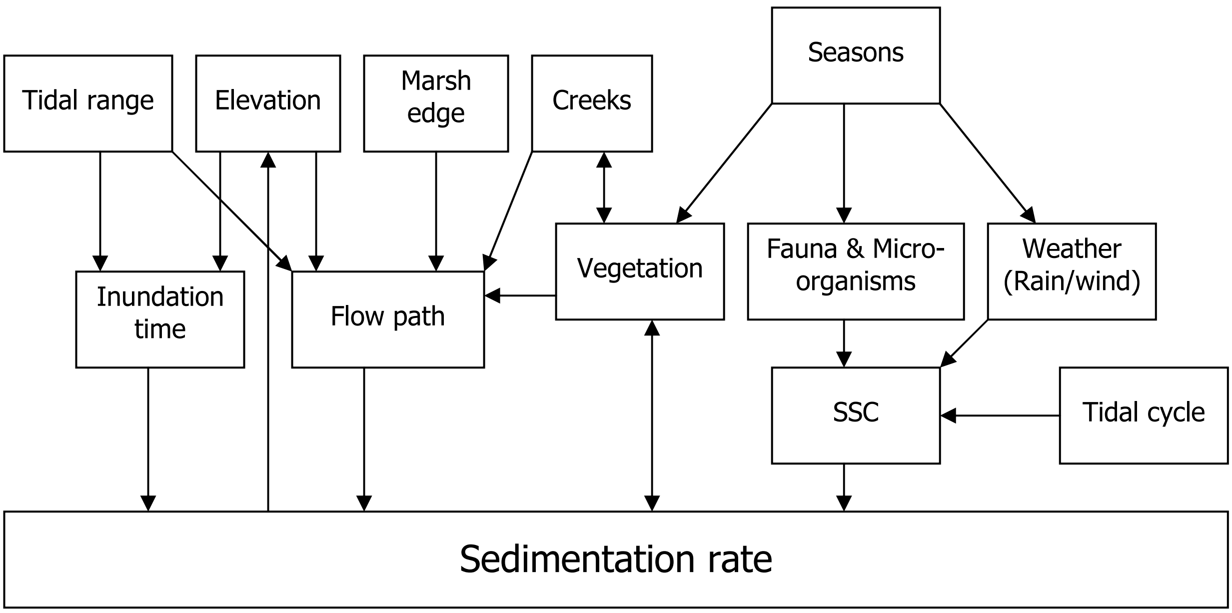

Figure 11. The main factors determining the spatial and temporal variation in the sedimentation rate on salt marshes.

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