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AUTHORS:

Lotte Oosterlee[1*]

Cox, Tom, J.S. [1]

Wouter Vandenbruwaene[2]

Tom Maris[1]

Stijn Temmerman[1]

Patrick Meire[1]

TITLE:

Tidal marsh restoration design affects feedbacks between inundation and elevation change

AFFILIATIONS:

*Corresponding author

Contact information: e-mail: lotte.oosterlee@uantwerpen.be, tel.: +32 (0)3 3658706

[1] University of Antwerp, Ecosystem Management Research Group, Universiteitsplein 1C, BE-2610 Wilrijk, Belgium

[2] Flanders Hydraulics, Berchemlei 115, BE-2140 Antwerp, Belgium

ABSTRACT

Tidal marsh restoration or creation on formerly embanked land is increasingly executed along estuaries and coasts in Europe and the USA, either by restoring complete or reduced tidal exchange. Ecosystem functioning and services are largely affected by the hydro-geomorphologic development of these areas. For natural marshes, the latter is known to be steered by feedbacks between tidal inundation and sediment accretion, allowing marshes to reach and maintain an equilibrium elevation relative to mean sea level, and steering ecological succession towards a climax state. However, for marsh restoration sites, these feedbacks may be disturbed depending on the restoration design. This was investigated by comparing the inundation-elevation change feedbacks in a natural versus restoration site with reduced tidal exchange in the Scheldt estuary (Belgium).

This study analyses long term (15 years) datasets on elevation change and tidal inundation properties to disentangle the different mechanisms behind this elevation-inundation feedback. Moreover, subsequent changes in sediment properties that may affect this feedback were explored. We found in the restoration area with reduced tidal exchange a different elevation-inundation feedback than on natural marshes, i.e. a positive feedback on initially high sites (i.e. sediment accretion leads to increasing inundation, hence causing accelerating sediment accretion rates) and a gradual silting up of the whole area. Furthermore, there is evidence for the presence of a relict consolidated sediment layer. Consequently, shallow subsidence is less likely to occur.

Although short term ecological development of the tidal marsh was not impeded, long term habitat development may be different by the disturbed hydro-geomorphological interactions. Potential consequences for ecosystem functioning and services are discussed. Ecosystem trajectories may be controlled or changed by adaptive management, and suggestions for improved management are made.

KEYWORDS:

tidal marsh restoration, hydro-geomorphology, biogeochemistry, Controlled Reduced Tide (CRT), habitat creation, adaptive management

Introduction

Determining the success of tidal marsh restoration requires understanding of the main drivers of the delivery of ecosystem services provided by restored versus natural tidal marshes. Especially because tidal marsh restoration projects have been increasingly implemented over the last decades, it is important to gain more insight in their hydro-geomorphological functioning and the way this affects the ecosystem functioning and services. The restoration and creation of tidal marshes on formerly embanked land is realized by (re-)establishing tidal exchange between the restoration site and the adjacent estuary or sea, after which it is assumed that the associated structures and functions of these habitats will return. Within the framework of nature conservation policies (Department of Fisheries and Oceans 1986; European Commission 2011; Madsen et al. 2011; USACE and USEPA 2008) the ultimate objective of these restored areas is to obtain an ecological functioning that equals that of natural marshes (Crooks et al. 2001; European Commission 2011; Zedler 1996).

In Northwest-Europe alone, about 12,500 ha of intertidal habitat are being (re-)created on formerly embanked land, of which 75% by so-called managed realignment (especially the older projects) and 25% by regulated tidal exchange (ABPmer 2016; Wolters et al. 2005). Managed realignment encompasses landward relocation of sea defenses after which the old embankment is breached to allow full tidal exchange. In contrast, regulated tidal exchange relates to the controlled exchange of water to an area behind permanent sea or river defenses. The exchange of water occurs then through engineered structures in the embankment, such as sluices or culverts, (ABP 1998; Maris et al. 2007). One form of regulated tidal exchange is a controlled reduced tide (CRT) (Beauchard et al. 2011; Cox et al. 2006; Maris et al. 2007). By use of a CRT a reduced tidal amplitude is realized and therefore particularly applicable for intertidal marsh development in historically embanked areas that have nowadays a lower elevation than remaining natural marshes (due to soil subsidence and the historical stop in sedimentation). In this study we evaluate the functioning of a CRT marsh in terms of tidal characteristics and geomorphology compared to an adjacent natural marsh.

A key issue determining success of regeneration of intertidal habitats on formerly embanked land is their position within the tidal frame (Pethick 2002), determining the frequency, duration and depth of tidal inundations. Sediments supplied by tidal flooding are deposited on tidal marshes, resulting in long-term sediment accretion and elevation changes that drive the long-term evolution of the intertidal habitat development (e.g. succession) (Olff et al. 1997; Struyf et al. 2009).

In natural tidal systems an inverse relation (i.e. negative feedback) between increasing elevation (due to sedimentation) and decreasing tidal flooding and hence decreasing sedimentation rates exists. Topographic differences are reduced as a consequence of this negative elevation-inundation feedback mechanism. In the end the marsh platform evolves towards an equilibrium elevation high in the tidal frame (Allen 1990; French 1993; Pethick 1981; Temmerman et al. 2004). This feedback enables marshes to adapt to sea level rise through increased sediment accretion rates with increased tidal flooding, e.g. resulting from sea level rise (Kirwan et al. 2010; Schuerch et al. 2013). However, in a CRT area the volume of water entering the area is determined by the dimensions of the inlet culvert, and not by the site elevation relative to the tidal frame (Cox et al. 2006). For this reason we hypothesize that in a CRT the elevation-inundation feedback differs over time as follows: when the spatial topographic differences are reduced because of the negative feedback mechanism described above, the flooding water volumes are spatially redistributed over the area. It is expected that this will lead to more frequent, deeper and longer flooding and consequently an increase of sedimentation rates on initially high sites. Hence our hypothesis is that eventually this positive feedback mechanism between elevation and inundation will result in ongoing, spatially uniform sedimentation rates and rise of the mean high water level in the CRT area.

Besides this disturbed feedback mechanism between elevation change and inundation, the CRT sediments may also develop different properties as compared to natural marshes, potentially affecting elevation change. In managed realignment sites in the UK, for example, agricultural use of the previously reclaimed land resulted in (irreversible) changes of the sediment properties, including the collapse of pore space, oxidation of organic matter and clay shrinkage (Spencer et al. 2008). Organic matter decomposition and auto-compaction may result in subsidence of the marsh platform (Allen 1990; Cahoon et al. 1995; Callaway et al. 1996; D'Alpaos et al. 2007; Morris et al. 2002; Neubauer 2008) and thus affects elevation change and hydrology of a marsh system. After de-embankment the old sediments are buried by fresh estuarine sediments. However, the changes of physicochemical sediment properties of the relict soils are known to affect restoration trajectories and success (Crooks et al. 2001; French 2006; Spencer et al. 2008). It is expected that in the CRT area a consolidated relict soil layer may be present and affect elevation change and thus habitat formation. Yet, we first need to demonstrate which changes of sediment properties (dry bulk density, moisture content, organic matter and grain size) occurred after flooding and how they affect elevation change within the CRT area.

The introduction of a reduced tide on former agricultural land resulted in the formation of typical freshwater estuarine habitats (Beauchard et al. 2011; Jacobs et al. 2009). However, as the elevation-inundation feedback in a CRT area is hypothesized to change over time, the long term development is less clear. The hypothesized difference of hydro-geomorphological functioning of a CRT area compared to natural marshes is expected to have an important impact on ecological functioning and the delivery of ecosystem services of a CRT area. Different habitat succession and climax state of a CRT marsh may be a result of increased flooding at high sites and continuing flooding in the whole CRT area. Sediment related ecosystem services such as nutrient and carbon burial may be positively influenced because of continuing sedimentation, although flood water storage potential will decrease with increasing elevation. For this reason a better understanding of the underlying geomorphological and hydrological processes that are primarily driving the development of this area is essential.

In a previous study based on the first four years of elevation change measurements in the studied CRT area, no significant differences in the elevation-inundation feedback were found between the CRT area and the adjacent natural marshes (Vandenbruwaene et al. 2011). In this study five more years of data show new insights in the hydro-geomorphological interactions within the CRT area. The objectives of the study are to examine (1) the temporal evolution of rates of elevation change, (2) the subsequent changes in tidal characteristics (tidal flooding frequency, depth and duration) over time, (3) the subsequent changes in sediment properties affecting elevation change (dry bulk density, organic matter content (LOI), grain size and moisture content) and the role of subsidence in the CRT and an adjacent natural freshwater marsh.

Methods

Study area:

Our study site Lippenbroek of approximately 8 ha is located in the freshwater reaches of the Scheldt estuary, Belgium (51°05’10”N; 4°10’20”E; fig. 1A). This site is part of the alluvial floodplain and was embanked and used as agricultural land for the last centuries. Recently, since March 2006, it was transformed into a flood control area (FCA) with a controlled reduced tide (CRT). CRT is a form of regulated tidal exchange and realized by elevated inlet culverts and low outlet culverts in the riverside dike (fig. 1C). In this way the mean estuarine tidal range of 5.40 m is reduced to ca. 1.30 m (fig. 1D), creating a comparable spring tide-neap tide variation in tidal water levels within the CRT area as on the adjacent natural marshes, but with a prolonged flooding duration (fig. 1D). A detailed description of the CRT area and previous research on the design, hydrological and geomorphological functioning can be found in Beauchard et al. (2011); Cox et al. (2006); Maris et al. (2007); Vandenbruwaene et al. (2011), Vandenbruwaene et al. (2012). Our research area is the first FCA in combination with a CRT and serves as a pilot project for much larger FCA-CRTs (in total ca. 1600 ha) that are currently becoming operational elsewhere in the estuary (Meire et al. 2014; Meire et al. 2005)).

Based on initial elevation relative to local mean high water level (MHW) eight measuring locations were selected in the CRT area using a stratified random approach: these eight locations were classified into low elevation sites (40% to 20% of the tidal range below MHW; site 4, 5, 6), mid (20% to 0% of the tidal range below MHW; site 1, 2, 3) and high elevation sites (0 to 20% of the tidal range above MHW; site 7 and 8). Additionally, three natural reference sites were selected at the adjacent natural marsh (NAT) (one mid and two high sites, following the same criteria as above) (fig. 1B). No nearby natural marshes have low sites and could therefore not be monitored.

Field measurements and data analyses

Surface elevation change and accretion rates at fixed locations

Field data on rates of elevation change and sediment accretion were collected at the eight measuring locations within the CRT marsh and three on the adjacent natural marsh since March 2006 (fig. 1). Elevation change was measured every two months using surface elevation tables (SETs) (Cahoon et al. 2002; Nolte et al. 2013).

Vertical accretion rates were measured yearly in winter by kaolin marker horizons (MHs) (0.3x0.3 m) (Cahoon and Turner 1989), established upon the marsh surface in February 2006, just before the introduction of the reduced tidal regime. By comparing MH data to SET data of the same location the effect of shallow subsidence can be determined as the difference between the SET measurements (including shallow subsidence over the 10 to 15 m depth of the rods) and the MH measurements (excluding this subsidence) (Cahoon et al. 1995).

Rates of elevation change and accretion were calculated by simple linear regression through the origin of elevation and accretion as a function of time or by differentiation of the 2^{nd} order polynomial regression. Selection of linear or 2^{nd} order polynomial regression was based on the Aikaike information criteria (AIC), where the best fit is represented by the lowest AIC.

Elevation change over the total area

Topographic surveys of the whole CRT area were conducted on a grid of 10x10m before flooding using a dGPS (Trimble R4 GNSS, vertical accuracy ± 2 cm) and subsequently after approximately 3, 4, 6 and 9 years using a total station (Sokkia, SET510k, vertical accuracy 1-3 mm). During all surveys elevations were measured relative to a fixed vertical control benchmark located at the culvert system of the CRT area. Digital elevation models (DEMs) of the platform were created using ArcMap 10.2, 3D Analyst, using triangulated interpolation (TIN). The DEMs have a grid size of 1 m and vertical resolution of 1 cm. Mean elevation change rate was calculated as the slope of a linear regression over elevations as a function of time. For this purpose only elevations of the tidal marshes and flats were used, and elevations of the two main creeks were excluded. Deposited sediment volumes were computed as volume differences between two successive DEMs.

Sediment properties

In May 2014, cores up to a depth of 0.5 m of the CRT sediment were taken at locations 3, 4 and 8 and up to a depth of 1.5 m of the natural marsh sediment at locations 1 and 3, using a gouge (Ø 10cm, to minimize compaction during coring), divided in subsamples of 10 cm. After determination of wet weight, weighted subsamples were used for determination of dry bulk density (after drying for 72 h at 105°C), grain size distributions (Mastersizer 2000 laser diffraction, Malvern) and organic matter content (loss on ignition at 550 °C for 5 hours). Samples for grain size analysis were pretreated by heating after addition of H_2O_2 and HCl to remove organic matter content and dispersed using ultrasound. Moisture content is expressed as %weight loss per sample volume.

Channel erosion

Channel morphology was measured almost annually since March 2006. Initially elevation points along the length profiles (thalwegs) of the channels were measured with an interdistance of respectively 10 m. Also elevation points were measured every 0.25 m along 6 cross-sections along the channels (two ditches) that pre-existed in the area before the introduction of tide in 2006. Additionally 6 cross-sections and all thalwegs of newly formed channels (interdistance 2-5m) were measured. A newly formed channel was defined as such when it incised the surface by more than 0.1 m over a minimum distance of 2 m. The volume of sediments eroded in the existing and newly formed channels was calculated as described in Vandenbruwaene et al. (2012).

Water levels & hydrological parameters

Water levels in the CRT area were recorded every 5 minutes and corrected for atmospheric pressure using pressure data loggers (Schlumberger Water Services, type DIVER) at the 8 locations. Water levels in the estuary at a location close to the CRT area were recorded with the same frequency by Flanders Hydraulics Research using a radar sonde. Based on these pressure sensor data the following tidal characteristics where computed: flooding frequency (number of inundating tides as a percentage of the total number of tides), water depth (average water depth during inundation of one tidal cycle), hydroperiod (average inundation time during inundation of one tidal cycle) and dry time (average dry time per tidal cycle) were calculated, using R software (R version 3.2.0, R-package Tides (Cox 2014). Tidal characteristics were calculated over time periods of a spring tide-neap tide cycle using specific elevation of a measuring site at that moment. These descriptors were then averaged over three month periods (meteorological seasons). Storm tides were defined as water levels higher than 6.6 m TAW (Belgian ordnance level) in the Scheldt at the location of the pilotage in Antwerp, based on the Flemish criterion. Storm tides were not taken into account for the calculations of flooding frequency, water depth, hydroperiod and dry time, because these storm tides do not reflect daily tidal functioning, but temporary events with wind setup of the tidal water levels. Moreover, mean water levels were calculated for high and low water during spring, intermediate and neap tides over spring tide-neap tide cycles. This was based on tidal data series that were recorded in the main creek of the CRT area close to the inlet culverts and in the estuary. Mean water levels were calculated as the slope of a linear regression of the water levels over nine years as a function of time.

Computations and statistical analyses were performed using R software, version 3.2.0. (R Core team 2014).

Results

Elevation change, accretion rates and shallow subsidence

Comparison of subsequent DEMs over the nine year study period showed a clear overall elevation increase (fig. 2). Concomitantly, the area flattened: an increase of mean elevation was observed and the range of present elevations decreased (fig. 2). The total area of high marsh, with an elevation between mean spring high water and mean mid high water decreased with approximately 15%. Additionally, the area of low marsh, with elevations between mean neap high water and mean high water, increased with the same percentage. Elevation change of the individual locations lies within the range of the DEM elevations over time; the mean elevation change rate (2.35 cm yr^{-1}) of the marsh platform is comparable to the elevation change rates of the mid sites (fig. 2).

A considerable within-site variation of rates of elevation change in the CRT was observed (table 1). The range of this variation decreased over time. Most of this variation can be ascribed to the differences in initial elevation between the sites, with the highest elevation change rates observed in the lowest areas for both CRT area as natural marsh (table 1 and figure 2). Elevation change rates for the mid and high elevations in the CRT area were comparable to their natural reference in the estuary.

The marker horizon measurements showed accretion rates similar to elevation change rates for most sites. Subsidence was found to be considerable at only one CRT site (site 8) and the high natural sites. No significant subsidence of the inner CRT platform was observed. On the contrary, it seems that subsidence increasingly occurred within the natural marshes in the direction towards the river. In the natural marsh subsidence varied from 0 to 7.5 cm after 9 years. Similar subsidence rates were found to occur on the creek edge in the CRT (site 8).

Sediment volumes

Platform elevation changes and channel erosion both contribute to net sediment volume changes of a CRT area and therefore affect redistribution of water volumes and high water levels within the CRT site. Over the past nine years 17500 m^3 of sediment accumulated on the platform (on a total platform surface area of 7.8 ha). Over the same period creek erosion was relatively small and amounted to 2000 m^3 (on a total creek surface area of approximately 0.5 ha in 2015). Thus, the net annual rate of sediment accumulation in the whole area was approximately 1650 m^3 per year. Evolution of platform sedimentation and channel erosion volumes over time is shown in fig. 3. These rates of total volume changes did not significantly decline over time.

Sediment properties

Physical sediment properties (table 2) revealed a clear difference between two sediment layers in the CRT area, based on dry bulk density and moisture content. The old agricultural soil was more compacted and lower in moisture content, overlain by newly deposited, wetter and less dense sediments. Moisture contents of the new sediments in the CRT area decreased with depth, and subsequently declined greatly in the relict agricultural soil (table 2 and fig. 4).Dry bulk densities and moisture contents in the natural marsh sediments stayed more or less stable with depth. Dry bulk densities of the newly deposited sediments at all eight CRT sites were similar, except for site 8 (additional measurements, not shown) and comparable to those of the natural references.

In general, dry bulk densities seem to be inversely related to moisture content and organic matter content in both CRT area and natural marsh. Whereas mean moisture content and LOI were comparable in the top and deeper layers of the natural marsh (table 2), the newly deposited sediment in the CRT area contained more water and organic matter than the old relict CRT sediments, except for site 8. Additional cores in the top 5 cm of natural sediments showed moisture contents varying from 45 to 65%, while for the CRT sediments they varied between 60 and 80%.

The top sediments of both CRT and natural marsh had comparable clay contents (<2 μm) varying from 5 to 9%. Sand contents (>63μm) of the fresh CRT sediments were very low with 2 to 4 %, except for site 8 where 20% of the sediment consists of sand. Mean grain size was relatively uniform with depth at all CRT and natural sites, except again for the site 8, where mean grain size was highly variable and smallest at a depth of 15 cm. This layer contained about 10% less sand than the other layers.

Tidal characteristics

We could clearly observe a trend of convergence of the tidal characteristics over time: the low sites showed a significant decline in flooding frequency as well as a decline in water depth and hydroperiod and an increase in dry time (table 3 and fig. 5). An opposite response was measured on the high sites; flooding frequency and hydroperiod increased significantly over the past nine years, and dry time decreased, although water depths did not change significantly. Whereas high parts of the CRT were subjected to a similar hydroperiod as the natural reference at the start, after nine years a large difference was observed (fig. 5). Tidal characteristics changed significantly over nine years in accordance with changes in elevation. The different hydroperiods and dry periods for site 1 and 2 (table 3) indicated poor drainage, occurring locally.

Calculations on tidal series showed a significant decrease in low water levels in the Scheldt estuary, whereas low water levels in the CRT area increased (table 4). Concerning high water levels in the estuary only those for neap tide increased significantly. A rise of high water levels in the CRT was observed (i.e. 21.5 cm over nine years), which was at least double the rise in low water levels (i.e. 8 cm over nine years). The rise in high water levels could be ascribed to a relatively higher rise in mean mid high water levels and in a lesser extent to mean neap high water and mean spring high water levels.

Discussion

Feedbacks between elevation and inundation

Sediment accretion and elevation change rates are, among others, influenced by position in the tidal frame and hence by tidal inundation frequency, depth and duration (Allen 2000; Pethick 1981; Temmerman et al. 2003). Typical for natural marshes is the feedback mechanism where the higher the marsh platform is located within the tidal frame, the less it is inundated and the smaller elevation change rates become (fig.6), as described in many studies (e.g. (Allen 2000; Leonard 1997; Temmerman et al. 2003). In accordance to this negative elevation-inundation feedback, in the first years we observed the same elevation change patterns in the CRT and natural marsh. Relatively high rates were measured at the lowest CRT sites, which are in the same order of magnitude as historical elevation change rates in young freshwater marshes in the Scheldt (Temmerman et al. 2004). These rates are also comparable to other managed realignment sites in the UK (e.g. Tollesbury: 2.3 cm yr^{-1}(Garbutt et al. 2006); Northey Island: up to 4.9 cm yr^{-}1,(ABP 1998); Orplands: 2.5 cm yr^{-1}, (French 2006); Paull Holme strays: 10 cm yr^{-1} (Clapp 2009); Chowder Ness: up to 20 cm yr^{-1} (Pendle 2013)).

Our data strongly imply a disturbed elevation-inundation feedback mechanism in the CRT marsh than on the natural marshes. After approximately six years we found that elevation change rates started increasing for the initially high CRT sites (table 1), which coincides with our hypothesized positive feedback mechanism (fig.6). This result agrees well with the modeling of Vandenbruwaene et al. (2011) where within nine years high sites were predicted to increase in elevation change rate. Additionally, an increase of flooding frequency and hydroperiod at the high sites (table 3) strongly indicates the presence of the positive elevation-inundation feedback. An increasing deviance from the natural reference for the high sites over time for all four hydrological descriptors suggests the same. This positive elevation-inundation feedback is a result of the design of a CRT area: the dimensions of the inlet culvert determine the volume of water coming into the CRT area, and this volume is spatially distributed over the whole CRT area. This means that when lower parts of the CRT area silt up, the water and its suspended sediments are redistributed over the whole area, leading to the observed higher flooding frequency of the initially high sites, and an increase in elevation change rates (fig. 6).

Sedimentation will continue, and so will the mean high water levels. This increase of mean elevation occurs at the same rate as the rise of mean spring high water, as would be expected because the mean spring high water is rising as a result of sedimentation within the CRT area; mean spring high water can be used as a proxy for spatially-averaged platform changes within the CRT area, assuming the whole area is inundated during spring tide. Additionally, the increase in low water levels can be ascribed to the evolution that larger parts of the platform are inundated over time; consequently the water takes longer to drain from the sediments, not fast enough to drain the whole area before the next tide enters. This hypothesis is also supported by the higher increase in low waters during spring tides than during intermediate tides and neap tides; spring high water floods the whole area and drainage during subsequent low water takes longer, whereas mean and neap high waters only flood the channels and not the complete platform.

Volumes of deposited sediment can be computed from the rise in mean spring high water: a rate of 2.28 cm yr^{-1} would correspond to 16830 m^3 of sediment deposited after nine years which is in the same order of magnitude as the calculated 17500 m^3 of sediment based on the time series of DEMs (fig. 3). By simply assuming that this sedimentation rate would continue in the long term, this would mean that the area would be filled up to the level of the inlet culverts by approximately 82 years after introduction of the tide.

Shallow subsidence

It is generally known that elevation of tidal marshes increases with inorganic sediment deposition and organic matter accumulation, while it decreases by belowground processes, including decomposition of organic material, auto-compaction of the sediments and erosion (Allen, 1995; Callaway et al., 1996; Cahoon et al., 1995; D'Alpaos et al., 2007; Morris et al., 2002; Neubauer, 2008). Auto-compaction of the deeper sediment layers does not seem to occur in the CRT marsh (table 1), which was expected since this area was embanked at least 200 years ago (De Ferraris, 1965), after which it was drained and cultivated and therefore well consolidated. Only on a well-draining creek edge (site 8) subsidence seems to be present. Also in the adjacent natural marshes we observed subsidence (table 1), which is increasing with decreasing distance to the river. This suggests the role of increasing sediment drainage and possibly lateral sediment movement towards the river (see e.g. Mariotti et al. (2016).

Physical sediment properties

Agricultural use prior to marsh restoration resulted in changes of the subsurface sediment (fig. 4). Onto this heavily altered, compacted soil, new freshwater estuarine sediments accumulated since tidal flooding was introduced in 2006. It seems that the newly deposited sediments are quite homogeneous over the whole CRT area. Their physical properties are very similar to those of the natural sediments. It may be that more sandy material was deposited close to the inlet and creek, which, in combination with good drainage and consequently oxidation of organic compounds, may have resulted in compaction (higher dry bulk density; table 2 and fig. 4).

The bulk densities of the relict agricultural CRT soil are lower than known from other managed realignment (MR) studies; often values above 1.0 g cm^{-3} were measured elsewhere. These different bulk densities cannot be explained by organic matter contents, which are similar in the CRT (table 2) and MR sites, but may be explained by their higher sand contents (>10%) and consequently lower porosity (Burden et al. 2013; Clapp 2009; French 2006; Kadiri et al. 2011; Tempest et al. 2015).

Moisture content of the new sediments in the CRT area decreases with depth, and subsequently declines greatly in the relict agricultural soil. This suggests that more compacted sediments cause differences in hydrological properties, such as water storage and soil water movement. It is known that the compacted layer may create an aquaclude (Crooks et al. 2002), resulting in oversaturated surface sediment conditions and limiting vertical movement of pore water (Spencer et al. 2008; Ursino et al. 2004). This seems to be partly the case in the CRT area: the high moisture contents found in the top sediment of the CRT area cannot only be attributed to longer hydroperiods, since the high sites also show high moisture content when not flooded for several tides (data not shown). Yet, tidal data series indicate lowering of the water table between tides within the CRT sediments by a few centimeters under platform elevation, and deeper drainage during neap tides, creating aerated top soil conditions. Moreover, the observation of a moisture gradient from the top layer of freshly deposited (new) sediment to deeper new sediments suggests some drainage, lateral or vertical. It appears that this relatively poor sediment drainage did not inhibit vegetation or benthos colonization in this freshwater CRT area (Beauchard et al. 2011; Jacobs et al. 2009).

Future geomorphologic evolution

The relative importance of different geomorphological processes may change over time, determining elevation change of the CRT area and evolution of current habitats in the CRT area.

Based on our findings we can conclude that subsidence of the former agricultural soil is, until now, not an important process controlling the mean elevation change of the inner marsh platform in the CRT area. As the relict agricultural soil is highly compacted and organic matter contents are relatively low, future subsidence is less likely to occur. Consolidation of the new sediments is expected to be inhibited because of the waterlogged conditions created by the underlying old compacted agricultural sediment layer.

Both distance to the sediment source, e.g. the inlet culverts of the CRT area, and distance to tidal channels are important for the delivery of suspended sediments. They both played a minor role in explaining spatial variations in elevation change rate until now (Vandenbruwaene et al. 2011). Instead, spatial variation in surface elevation was the most important controlling factor. However, when topographic differences become small, it is expected that both distance to creeks and inlet will become more important factors determining spatial sedimentation patterns and hence elevation change. The relative importance of these different influencing factors may be different in areas that are larger than our relatively small research area.

Creek erosion occurred at the same pace and may continue for the next years, until an equilibrium is reached with tidal discharges going through the creeks. Creek erosion could have an impact on the inundation regime over time, as it contributes to an increase in water storage volume and thereby lowering inundation frequency and height on the marsh platform. However, until now the total creek erosion volume was from a much lower order of magnitude than the total sedimentation volume on the marsh platform (fig. 3) and hence the impact of creek erosion on the inundation regime is of much less importance than the platform sedimentation at this moment. This is supported by the fact that we actually observed the positive sedimentation-inundation feedback on initially high sites, meaning the creeks do not store enough water to reduce inundation at high sites. We expect that creek erosion rates will not accelerate and hence will not affect the future inundation regime.

Consequences for habitat development

In natural marshes habitat succession is primarily driven by elevation of the marsh platform and hence flooding frequency, depth and duration. A platform at equilibrium level with the estuarine mean high water level has evolved towards a climax state (Olff et al. 1997; Struyf et al. 2009). We can clearly observe this situation along the Scheldt estuary where most of the lower and intermediate tidal marshes, with pioneer or reed vegetation, are scarce and mostly high marsh with willow brook forest exists (Struyf et al. 2009; Vandenbruwaene et al. 2011). The observed positive elevation-inundation feedback in the CRT area is expected to affect habitat development. An increase of inundation frequency on the initially higher areas within the CRT area is expected to inhibit habitat succession or even cause reversed habitat succession at these locations. Over time the marsh is expected to turn into a climax state, however, this stage may be different from the climax state of natural marshes, because of the extended flooding duration in the CRT area compared to natural marshes.

Extended flooding duration in combination with the presence of a consolidated layer in the CRT marsh may cause waterlogged conditions under the surface layer of the newly deposited sediment. These conditions may affect fertility and germination of seeds and so favor the growth of clonal species able to adapt to anaerobic circumstances, such as typical wetland macrophytes (e.g. common reed (*Phragmites australis*), broadleaf cattail (*Typha latifolia*), great manna grass (*Glyceria maxima*)) (Vartapetian and Jackson 1997). This is in agreement with the negative redox potentials of the newly deposited sediment measured by Beauchard et al. (2014) and the high and dense cover of these clonal plants (unpublished data) in the CRT area.

Adaptive management

Despite different hydro-geomorphological functioning, an advantage of reduced tidal exchange (here CRT) over full tidal exchange (e.g. managed realignment) is that the culvert dimensions and thereby the tidal volume entering the CRT area can be adapted according to the desired restoration goals. Firstly, a trade-off between flood water storage and sediment related ecosystem services such as carbon sequestration or nutrient burial have to be made. Secondly, also habitat trajectories can be changed to reach a desired outcome. Allowing more tidal water volume into the CRT area may create more pioneer habitat and mudflat whereas less tidal water volume may result in more high marsh.

For a CRT area with the function of tidal marsh development and flood water storage it is recommended that initially water volumes are large, resulting relatively fast in the formation of estuarine soil, creating a pioneer environment for fauna and flora. After this, the height of the lower inlet culverts can be altered in a way that less water enters the CRT area during neap tide and intermediate tides. When the incoming tidal volume during intermediate tide equals the creek volume, the CRT marsh wil not be flooded during most of the tides. Additionally the height of the highest inlet culverts can be adapted in order that the CRT marsh platform will be flooded during spring tide. In this way tidal characteristics for high marshes are created, sedimentation rates will be reduced, hence assuring enough water storage capacity.

Conclusions

This study provides the first long term comparison of the hydro-geomorphological interactions within a restored marsh with controlled reduced tide (CRT) and natural tidal marshes. Firstly, the design of a CRT area leads to a disturbed elevation-inundation feedback than on natural marshes, i.e. a positive elevation-inundation feedback on initially high sites and a gradual silting up of the whole area. The effects of this feedback can be mitigated by adaptive management, depending on the desired restoration goals. Our results should be taken into account during the evaluation of large marsh restoration projects and setting the succes criteria for these projects. For example, along the Scheldt estuary about 1600 ha of restored CRT marshes will be implemented within the near future.

Secondly, there is evidence for a compacted agricultural soil. For this reason subsidence less likely to occur in the CRT area. This layer causes a reduction of vertical soil water movement.

The differences in hydro-geomorphological interactions, tidal characteristics and sediment properties do not seem to have impeded short term development of a tidal freshwater marsh with typical flora and fauna species (Beauchard et al. 2013a; Beauchard et al. 2013b; Jacobs et al. 2009), but may affect long term habitat development and delivery of ecosystem services. Further research is now required to explore subsurface waterflow and drainage in marsh restoration areas with a relict consolidated sediment layer and its effect on biogeochemistry and biota and the implications for ecosystem services.

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FIGURE CAPTIONS

Fig 1 a) Location of our study area (Lippenbroek) within the Scheldt estuary. b) Our study area, shown with the initial topography in 2006 before introduction of tidal flooding, with indications of the study sites in the CRT area (numbers 1 to 8) and the adjacent natural marsh (site NAT1 to site NAT3). c) Operating principle of a CRT, illustrated for a mean tide and spring tide (top), and neap tide (bottom) during ebb (black arrow) and flood (blue arrow).d) Comparative time series of water levels for two spring-neap cycles in the estuary (top graph) and the CRT (lower graph) with an indication of the range of platform elevations in the natural reference marsh in the estuary (REF platform) and the restored marsh in the CRT area (CRT platform). For the estuary only water levels above 4 m TAW (i.e. Belgian ordnance level) are shown

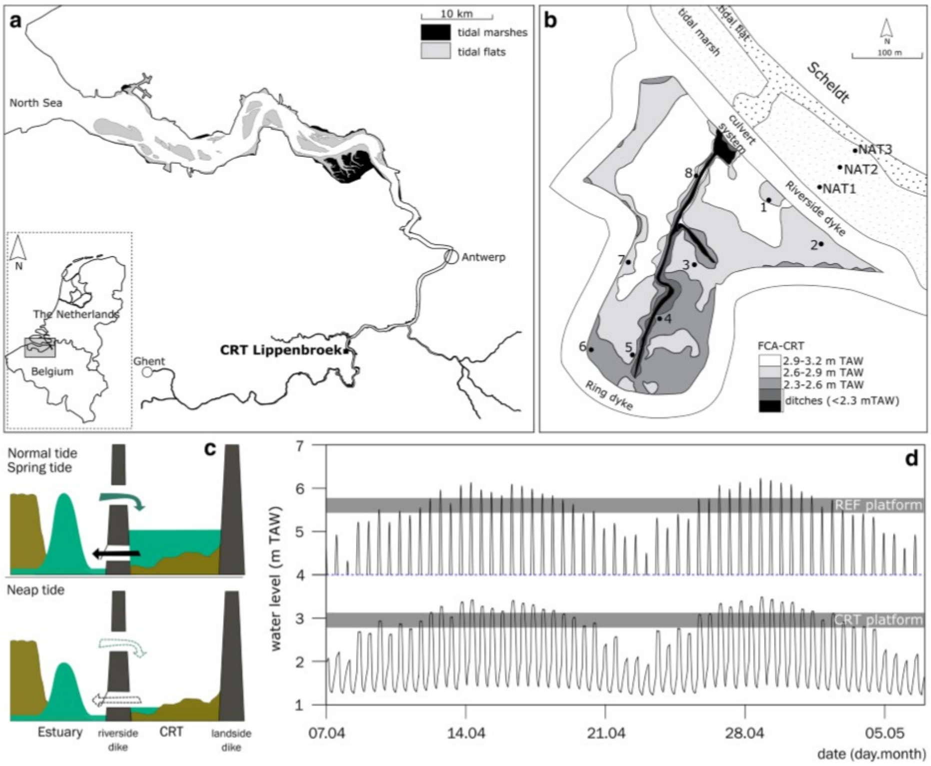

Fig 2 Black and grey lines show elevation changes over time at all eight CRT sites. Boxplots represent quartiles with whiskers at 5th and 95th percentile, and mean elevations of the CRT marsh platform, based on DEMs. Yellow dashed lines show changes of mean high water during neap tide (MNHW), intermediate tide (MHW) and spring tide (MSHW) over time within the CRT area

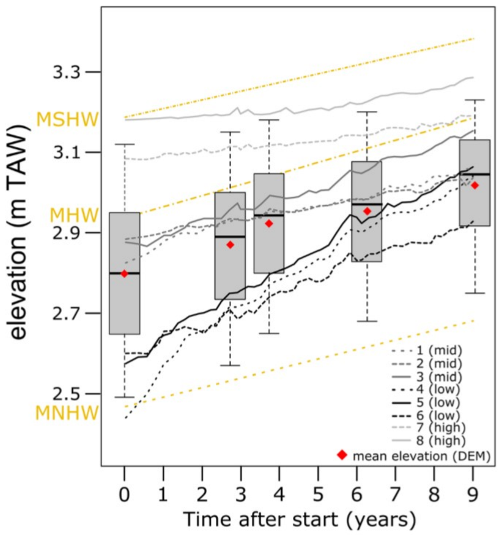

Fig 3 Evolution in time of gross sediment volumes induced by the sedimentation of platform in the CRT area and the eroded sediment volumes in the CRT channels

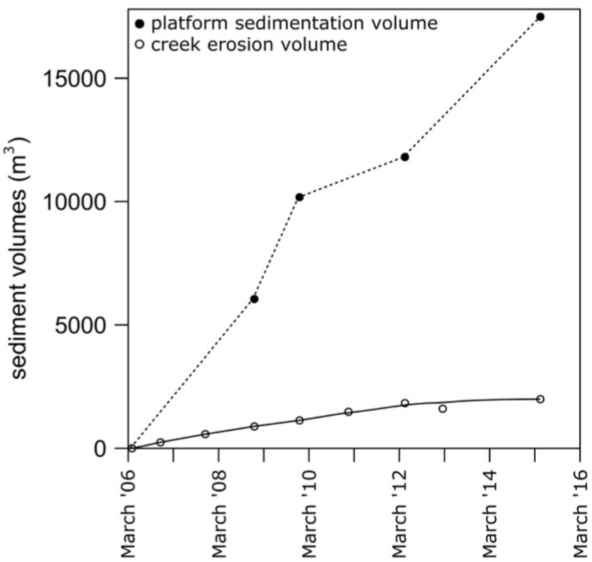

Fig 4 Vertical sediment profiles showing mean (n=3) sediment properties collected at natural marsh sites 1 and 3 and the CRT marsh sites 3, 4 and 8 (for respectively low, mid and high elevation) expressed relative to surface elevation of March 2006 (red dotted line; i.e. the start of tidal introduction in the CRT area). Error bars show standard error

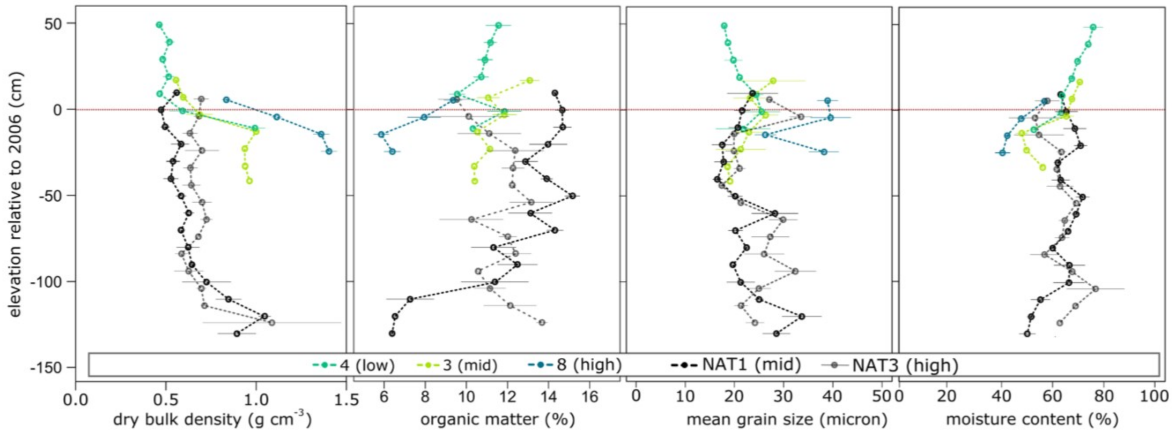

Fig 5 Evolution of hydrological descriptors in flooding frequency, mean water depth, mean hydroperiod per inundating tidal cycle and average dry time between two subsequent tides per spring - neap cycle for three representative locations in the CRT (site 4, 3 and 8 for respectively low, mid and high elevation) and one high site in the natural marsh (site 3, in yellow). Values are averaged per season. Straight lines show linear regressions, error bars show the standard error

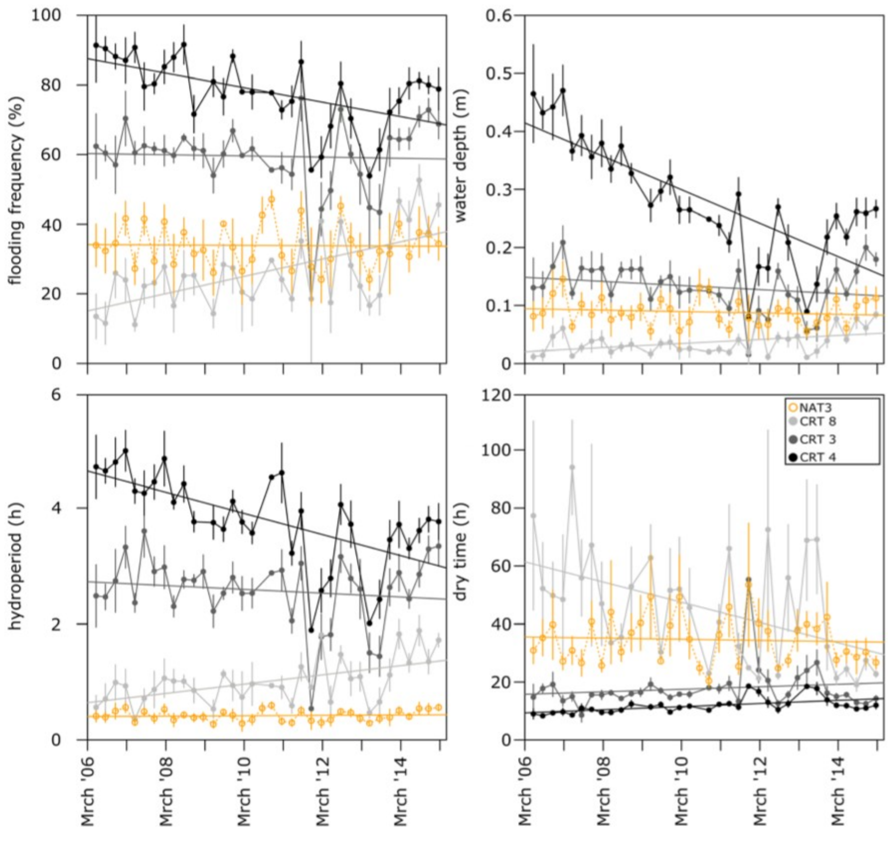

Fig 6 Schematic presentation of the elevation-inundation feedback in natural marshes (left sides of figs. a and b) and the CRT marsh (right sides of figs. a and b) over time. Initially low areas silt up faster than higher ones, in both natural marshes as the CRT area. Consequently, in the natural marsh, this increase in elevation leads to a reduction of inundation and elevation change over time. However, in the CRT area initially high areas in the CRT area become more inundated as a result of flattening of topography and the increase in elevation becomes faster over time. Continuation of sedimentation in the CRT results in a rise of the mean spring water level. The length of vertical yellow arrows is indicative for the rates of elevation increase. Full yellow arrows indicate elevation change in that particular year; empty arrows (in B) indicate previous elevation change.

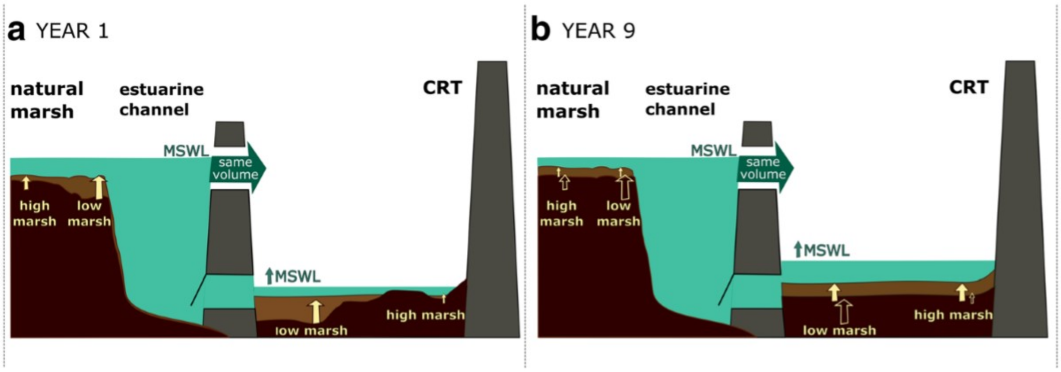

TABLE CAPTIONS

Table 1 Changes in elevation change (ΔE) and accretion rates for all CRT sites and reference sites (NAT). Elevation change and accretion rates in 2006 and 2015 were computed as the slope of a linear regression through the origin of elevation and accretion as a function of time or as the slope of the gradient of the polynomial regression at that time. The choice of models was determined by the lowest AIC. Significance level: *:<0.05, **:<0.01, ***:<0.001. Accretion rate > elevation change rate indicate subsidence. NA = no data available.

Site	ΔE rate (cm year^{-1}) in 2006	Difference in ΔE rate (cm year^{-1}) between 2006 and 2015		Accretion rate (cm year^{-1}) in 2006	Difference in accretion rate (cm year^{-1}) between 2006 and 2015	
1 (mid)	3.5	−1.0	***	NA	NA	
2 (mid)	1.6	0.0	***	1.4	0.0	***
3 (mid)	2.5	+0.5	***	2.6	+ 0.4	***
4 (low)	10.0	−3.7	***	9.5	− 2.6	***
5 (low)	6.4	−1.1	***	NA	NA	
6 (low)	3.7	0.0	***	3.1	0.8	***
7 (high)	0.7	+0.4	***	0.4	+ 0.5	***
8 (high)	0.1	+0.9	***	0.8	+ 0.8	***
NAT1 (mid)	1.8	−0.3	***	1.6	0.0	***
NAT2 (high)	0.7	+0.1	*	1.2	− 0.2	**
NAT3 (high)	0.9	−0.6	***	1.9	− 0.6	***

Table 2 Sediment profile data for sediment cores derived from the CRT marsh (site 3, 4 and 8) and natural marsh (NAT1 and NAT3). Horizon '0-10 cm' consists of the top 10 cm of the newly deposited sediment (n=3) in both CRT and natural marsh. Horizon 'relict' consists of 30 cm of the relict agricultural sediment (n=9) in the CRT. Horizon '10-100 cm' consists of the lower 10 to 100 cm of the natural marsh sediment. Numbers in bold show average values, followed by standard errors. MGS=volume based mean grain size (D4,3); LOI=loss on ignition.

Site	Sediment horizon	MGS (μm)		LOI (%)		Dry bulk density (g cm^{-3})		Moisture content % (volumetric)	
3 (mid)	0–10 cm	**27.8**	± 6.53	**13.1**	± 0.46	**0.56**	± 0.02	**70.5**	± 0.5
3 (mid)	relict	**23.8**	± 2.81	**11.1**	± 0.37	**0.86**	± 0.07	**54.9**	± 3.5
4 (low)	0–10 cm	**17.9**	± 0.37	**11.6**	± 0.61	**0.46**	± 0.02	**75.8**	± 3.8
4 (low)	relict	**21.7**	± 3.19	**10.3**	± 0.13	**0.99**	± 0.06	**52.6**	± 0.2
8 (high)	0–10 cm	**38.9**	± 2.09	**9.4**	± 0.44	**0.84**	± 0.02	**56.8**	± 1.5
8 (high)	relict	**34.7**	± 2.58	**7.0**	± 0.47	**1.24**	± 0.04	**44.0**	± 1.3
NAT1 (mid)	0–10 cm	**23.7**	± 1.30	**14.3**	± 0.15	**0.56**	± 0.02	**63.1**	± 0.9
NAT1 (mid)	10–100 cm	**19.9**	± 1.11	**14.6**	± 0.30	**0.51**	± 0.02	**68.6**	± 2.3
NAT3 (high)	0–10 cm	**27.1**	± 0.70	**9.7**	± 0.67	**0.70**	± 0.04	**57.8**	± 4.7
NAT3 (high)	10–100 cm	**24.3**	± 2.87	**11.4**	± 0.84	**0.67**	± 0.03	**57.0**	± 4.9

Table 3 Rates of changes in hydrological descriptors per tidal cycle calculated over 9 years as the slopes of linear regressions shown in Figure 5 for all eight CRT sites and three natural reference sites (NAT). Significance level: *:<0.05, **:<0.01, ***:<0.001, ns=not significant.

Site	Δ flooding frequency (%)		Δ water depth per tidal cycle (cm)		Δ hydroperiod per t idal cycle (min)		Δ dry time between two subsequent tides (min)	
1 (mid)	− 0.2	ns	0	ns	20	**	54	ns
2 (mid)	0.4	ns	0.4	ns	25	***	51	ns
3 (mid)	− 0.2	ns	− 0.4	ns	− 2	ns	26	ns
4 (low)	− 2.1	***	− 2.9	***	− 11	***	32	***
5 (low)	− 1.3	*	− 2.1	***	− 10	***	27	*
6 (low)	− 0.7	ns	− 1.1	**	− 14	***	23	***
7 (high)	1.9	*	4.4	*	10	*	− 85	ns
8 (high)	2.5	***	3.4	**	5	***	− 209	**
NAT1 (mid)	− 0.8	*	− 0.8	***	− 1	*	24	ns
NAT2 (high)	− 0.8	ns	− 0.3	*	0	ns	35	ns
NAT3 (high)	− 0.1	ns	− 0.1	ns	0	ns	− 12	ns

Table 4 Mean changes in water levels (cm yr^{-1}), calculated as the slope of a linear regression over water levels during neap, mid or spring tide as a function of time over 9 years. HW=high water, LW = low water. For "difference estuary-CRT" the difference between every low water or high water in the estuary and CRT was used. Significance level: *:<0.05, **:<0.01, ***:<0.001.

	CRT		Estuary		Difference estuary—CRT	
	LW	HW	LW	HW	LW	HW
Neap (N)	0.28**	2.14***	− 1.28***	0.86*	− 1.5***	− 1.6***
Mid (M)	0.89***	2.69***	− 1.04***	ns	− 2.77***	− 2.39***
Spring (S)	1.03***	2.04***	− 1.65***	ns	− 2.61***	− 2.28***
					Negative values correspond to increases in water levels in CRT compared to the estuary	