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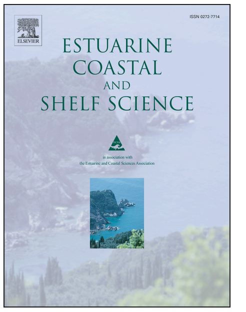

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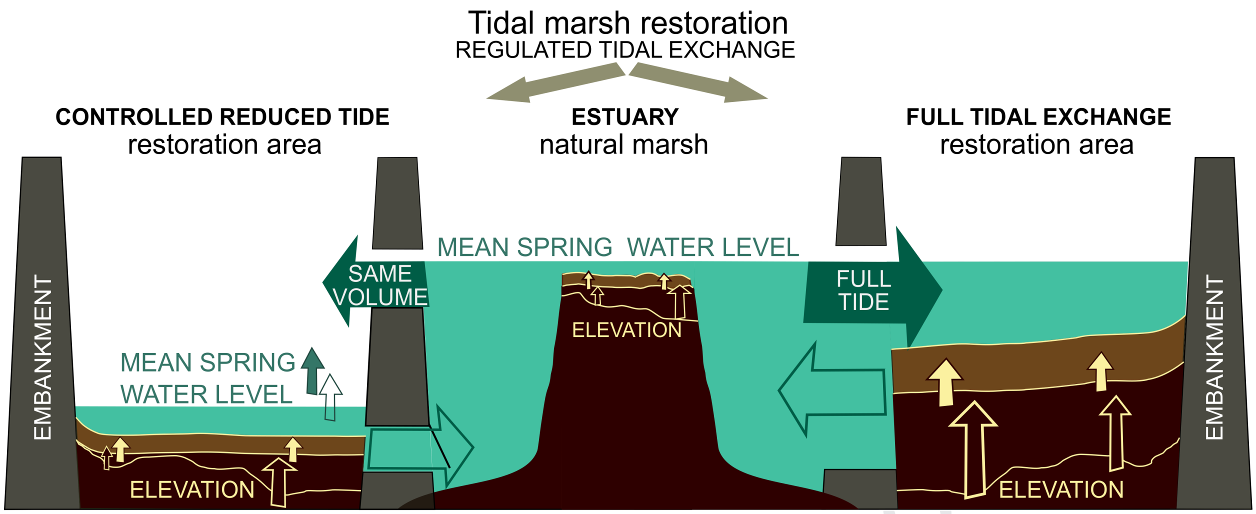
Tidal marsh restoration
REGULATED TIDAL EXCHANGE
CONTROLLED REDUCED TIDE
restoration area
ESTUARY
natural marsh
FULL TIDAL EXCHANGE
restoration area
MEAN SPRING WATER LEVEL
SAME VOLUME
FULL TIDE
MEAN SPRING WATER LEVEL
EMBANKMENT
ELEVATION
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TITLE:

Effects of tidal re-introduction design on sedimentation rates in previously embanked tidal marshes

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[1]Abbreviations

[1] CRT; Controlled Reduced Tide, FTE; Full Tidal Exchange, MR; Managed Realignment, RTE; Regulated Tidal Exchange, MHW; Mean high water, MSHW; mean spring high water, MNHW; mean neap high water, MSLW; mean spring low water, MNLW; mean neap low water, SETs; surface elevation tables, MS; marker sticks, DEMs; Digital elevation models, TIN; triangulated interpolation, SPM; Suspended particulate matter, LME; linear mixed effects, AIC; Akaike information criteria, AR1; Autoregressive process with lag 1, FF; flooding frequency, HP; hydroperiod, WD; water depth, ∆E ; Elevation change.

Abstract

Due to an increasing appreciation of the highly valuable ecosystem services of tidal marshes, an increasing number of projects are being implemented to re-introduce tides on formerly embanked land using a variety of 'soft' engineering techniques. However, the ecological development of the recreated tidal marshes largely depends on the design of the project, as this determines the hydro-geomorphological evolution. In this study we compare the hydro-geomorphological development in two marsh restoration projects in the Scheldt estuary (Belgium), one with a controlled reduced tidal exchange (CRT) and one with a full tidal exchange (FTE) between the marsh and adjacent estuary, based on ten years (CRT) and five years (FTE) of data on sedimentation/erosion rates, sediment properties and tidal characteristics. The results clearly show that the CRT technique strongly reduces the input of sediments, whereas larger water depths in the FTE led to extremely high sedimentation rates of 60 to 400 cm yr^{-1} in the first 2.5 months. The rapidly accreting sediments in the FTE consolidated much less than in the CRT and this poor sediment consolidation may have contributed to slower vegetation and benthos colonization in the FTE.

This comparison of two different tidal systems can serve as an example to show the effect of different techniques to re-introduce tides on the creation of tidal marshes on low-lying areas. Depending on the tidal marsh development goals, different hydrologic regimes and thereby different sedimentation rates may be desired. For example, when the objective is to contribute to estuarine flood risk mitigation by creating and maintaining a high water buffering capacity in restored tidal marshes, a CRT system with low sedimentation rates is preferred. However, when the objective is to build up soil elevation, for example as an adaptation to sea level rise, the FTE technique as studied here could be a good way to trap sediments.

1. Introduction

In the past centuries, urbanization, industrialization and agriculture led worldwide to large scale embankments of coastal and estuarine tidal habitat. Current trends in sea level rise and coastal squeeze constitute further threat to these habitats (Kirwan and Megonigal, 2013). The high ecological and socioeconomic value of tidal habitat is increasingly acknowledged (Barbier et al., 2011). As a result, tides are being or have been re-introduced in an increasing number of sites around the world over the last decades (ABPmer, 2019). In the case of historically embanked areas, tidal habitat is created by establishing tidal exchange between the formerly embanked land and adjacent sea or estuary with the objective to create ecosystems with similar ecosystem structures and functions as natural tidal marshes and mudflats.

In general, we can differentiate between two ways to introduce the tide in embanked areas: managed realignment (MR) and regulated tidal exchange (RTE). MR is the relocation of sea or river defenses more landward after which (part of) the old seawall or riverside dike is breached (French, 2006). RTE is a more controlled way to introduce the tide behind permanent sea or river defenses. RTE systems use engineered water control structures, such as culverts, tide gates, spillways or sluices to allow tidal exchange (ABP, 1998). The advantage of RTE systems over dike breaching is that the tide can be regulated according to the desired land use of the area (such as mosquito control, fish passage, habitat creation, flood storage).

Most restoration efforts along the North Atlantic coast of North America and in Australia include restoring tidal flow by placement of culverts or removing/opening tide gates (Bakker and Piersma, 2006; Fell et al., 2000; Haines, 2013; Reiner, 2012; Sinicrope et al., 1990; Smith and Medeiros, 2013; Warren et al., 2002; Winning and Saintilan, 2009). Furthermore, reinstating the tide has been realized using self-regulating tide gates (SRT) in US tidal marshes (Connecticut, (Giannico and Souder, 2005; Roman et al., 1984; Rozsa, 1995, 2012); Rhode Island (DiQuinzio et al., 2002); Massachusetts,(Reiner, 2012); Oregon, Washington state, (Giannico and Souder, 2005), Maine (Adamowicz and O'Brien, 2012) and Australia (Glamore, 2012; Russell et al., 2012). These SRTs are tide gates with a buoyant lid which remains open most of the time, allowing tidal inflow at defined heights during rising tide and outflow during ebb tide. Also in Europe RTE systems are increasingly used to re-introduce tides on formerly embanked tidal marshes (ABPmer, 2019; Goeldner, 1999; Rupp-Armstrong and Nicholls, 2007). Mostly culverts and sluices have been used to control tidal exchange (ABP, 1998; ABPmer, 2019; Lamberth and Haycock, 2003; Ridgway and Williams, 2011; Wolters et al., 2005). An SRT pilot study that started in 2004 at Goosemoor (UK) resulted in the desired intertidal habitat restoration, after which SRTs were also implemented at Lymington, Seaton and South Efford (UK)(Masselink et al., 2017; Ridgway and Williams, 2011; White, 2014; Williams, 2009; Wolters et al., 2005). In Belgium a new technique was introduced in 2006, creating a controlled reduced tide (CRT) on relatively low-lying land (Cox et al., 2006). The implementation of high inlet culverts, which are adjustable in height, and a low outlet culvert results in a comparable tidal inundation regime inside the low-lying restoration area as on the higher natural tidal marshes in the estuary (Beauchard et al., 2011; Maris et al., 2007; Oosterlee et al., 2017) (more details are given in section Methods).

The main physical processes determining development and sustainability of tidal habitats are tides and sedimentation, which in their turn determine geomorphology, hydrodynamics and ecological development therein (Teal and Weinstein, 2002). For this reason, site elevation relative to the tidal frame determines the suitability of a site for tidal habitat creation, as it relates to the frequency, duration and depth of tidal inundations (Pethick, 2002). However, the elevation of many of these embanked areas is low compared to the estuarine tidal frame, because they were cut off from tidal supply and deposition of sediments for a certain amount of time. Moreover, in many cases subsidence occurred due to de-watering of the sediments, oxidizing of organic contents and compaction because of agricultural machinery (e.g. Sloey and Hester (2016); Teal and Weinstein (2002)). Tidal introduction to relatively low sites would result in high flooding frequencies, duration and depths, and hence the creation of bare mudflats or even open water instead of vegetated tidal marshes, which most often are the objective. Consequently, many embanked sites are not suitable for marsh restoration when exposed to full tidal exchange, because of their low elevation relative to the tidal frame. A common practice in the US is to raise the site elevation by depositing dredged material prior to dike breaching (Teal and Weinstein, 2002; Williams and Orr, 2002; Wolters et al., 2005). Another way to increase surface elevation prior to dike breaching is by introducing a regulated tide since tidal flooding will result in sedimentation (Abbotts hall; Dixon et al. (1998)).

In this study we compared the hydro-geomorphological functioning (i.e. surface elevation changes, evolution of tidal inundation regime and soil properties) of two differently designed tidal re-introduction systems along the Scheldt estuary (Belgium). Both systems consisted of initially low-lying formerly embanked land where tidal marsh habitat creation was the objective. The first study site uses large simple culverts for full tidal exchange (full tidal exchange; FTE), whereas in the second study site a controlled reduced tide (CRT) was introduced. The intention of a CRT is to combine tidal marsh habitat formation and flood water storage in the CRT area. This requires keeping sedimentation as low as possible in order to maintain storage capacity.

We analyzed more than four years of data on hydrology, elevation change and additional sediment properties in the CRT and FTE area after tidal introduction. This gives us the opportunity to study different techniques for tidal re-introduction on previously embanked tidal marshes and its consequent changes in surface elevation change and sediment characteristics. We expect that the introduction of a full tide (FTE) on low-lying land will result in higher flooding frequencies, longer hydroperiods and larger water depths during flooding compared to a reduced tide (CRT). Consequently, we expect that the large tidal prism will lead to high elevation change rates. These effects are known to occur in tidal marshes, although never documented for full versus restricted tidal exchange between tidal marshes and the adjacent estuary. As plant colonization can only happen from a suitable site elevation and hence flooding frequency and duration (French, 2001), the development of tidal marshes on relatively low-lying land using a full tidal exchange will take more time than using a controlled reduced tide.

2. Methods

2.1 Study area

Our first study site, Lippenbroek, is located in the freshwater tidal reaches of the Scheldt estuary, Belgium (51°05'10"N; 4°10'20"E; Fig. 1A) with a tidal range of 5.4 m. This formerly embanked land of approximately 8 ha that was transformed into a flood control area (FCA) with a controlled reduced tide (FCA-CRT) in March 2006. CRT is a form of regulated tidal exchange and realized by high inlet culverts (three in this case) and low outlet culvert (one in this case) in the riverside dike (Fig. 1B, left). The level of the inlet culverts is adjustable by use of cross beams; the current heights of beams are at 0.95, 0.75 and 0.55 m below mean high water level (MHW) in the three culverts respectively. In this way the estuarine tidal range of 5.4 m is reduced, creating comparable tidal inundation frequency and depths within the low-lying CRT as on the adjacent higher natural tidal marshes, thereby maintaining spring-neap variation in inundation depths and frequencies but with a prolonged flooding duration. A detailed description of the CRT 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); Oosterlee et al. (2017); Vandenbruwaene et al. (2011); Vandenbruwaene et al. (2012).

Our second study site, Burchtse Weel, was designed to create approximately 13 ha of intertidal habitat in the brackish part of the Scheldt estuary (51°12'23''N; 4°21'30"E; Fig. 1A) with a tidal range of 5.3 m. The area was subjected to tidal influence in January 2011. The tide enters and leaves through a large simple culvert system with several channels in the riverside dike (Fig. 1B, right). The base of the channels is at mean low water level in the estuary, whereas the top of the channels is vertically and independently adjustable in height but kept unchanged during the time of research at 2.3 m under mean high water level. An old, but still functioning, relatively small tidal gate is located in the east of the area in the riverside dike through which water can leave the area as well. A small local river (Laarbeek) flows into a water reservoir north-east from the restoration area, which is connected to the intertidal area through gravitational valves. Because of a technical defect in the riverside dike, the FTE area was closed for construction works between July 15th 2011 and March 21st 2013. Water levels in the FTE area were slightly subjected to the estuarine tide during closing time and fluctuated between 1.7 and 2.5 m TAW (Belgian ordnance level) in 2011 and 1.0 and 1.6 m TAW in 2012 and until opening in 2013.

In the CRT area eight measuring locations were stratified randomly selected based on a reasonable spreading of initial elevation relative to local mean high water level (Fig. S1). These eight locations are classified as low (CRT4, 5, 6), mid (CRT1, 2, 3) and high sites (CRT7, 10). In 2010 extra measuring sites in the CRT (CRT9, 10, 11) were installed on the mudflats, since all other measuring sites were vegetated. Also, three natural reference measuring sites were selected at the adjacent natural marsh (NAT) (one mid (NAT1) and two high sites (NAT2, 3), following the same criteria as above). No nearby natural tidal marshes have low elevations and could therefore not be monitored. In the FTE area, initially three locations (SET1 (low), SET2 (mid), SET3 (high)) were selected in the field based on elevation and accessibility. Additionally, during closing time in 2012 eight other measuring locations (MS1-MS8) were selected in order to include locations in deeper, less accessible parts of the area.

2.2 Field measurements and data analyses

2.2.1 Water levels & hydrological parameters

Water levels in the CRT area were recorded every five minutes and corrected for atmospheric pressure using pressure data loggers (Schlumberger Water Services, type DIVER) at the eight locations in the FCA-CRT. 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 sensor. Water levels in the FTE area were recorded every minute at a location next to the inlet and outlet of the FTE by a private company *Macq, traffic and locomotion* using a hydrostatic pressure transmitter (Vegawell, Vega n.v.).

Based on these tidal water level time series, hydrological variables were calculated using R software (R version 3.2.0, R-package Tides (Cox, 2014), including flooding frequency (FF; number of inundating tides as a percentage of the total number of tides), water depth (WD; average water depth during inundation of one tidal cycle), and hydroperiod (HP; relative average inundation time as a percentage of the time of an inundating semi-diurnal tidal cycle (12h25)). These tidal characteristics were calculated over time periods of spring-neap tidal cycles using specific elevation of a measuring site at that moment. Storm tides with water levels higher than 1.25 m above mean high tide were not considered for the calculations of FF, WD and HP because these tides do not reflect daily tidal functioning, but exceptional storm events. Moreover, mean spring high water (MSHW), mean mid high water (MHW), mean neap high water (MNHW), mean spring low water (MSLW), mean mid low water (MLW) and mean neap low water (MNLW) were calculated over spring-neap cycles. These mean water levels were based on tidal data series that were recorded in the main creek of the CRT area close to the inlet culverts, in the FTE area at the culverts and in the estuary near the CRT and FTE areas. Changes in mean water levels were calculated as the slope of a linear regression of the water levels as a function of time over nine years (2006-2015) in the CRT and over five years (2011-2016) in the FTE area.

2.2.2 Soil elevation change at fixed locations

Field data on elevation change were collected at 11 CRT locations and 11 FTE locations (as described above; Fig. S1). In the CRT area elevation change (ΔE) was measured every two months using surface elevation tables (SETs) (Cahoon et al., 2002; Nolte et al., 2013), since the start of tidal inundation in March 2006. In the FTE area ΔE was measured every two weeks using SETs, from April 2011 until closing in July 2011. After reopening in July 2013 ΔE was measured every two months using SETs and marker sticks (MS). A SET consists of a benchmark pole that is put into the ground until it reaches stable subsoil. Benchmarks reach a depth of 4-6 meters deep, into the thick quaternary clay layer in the FTE area, and 10-15 m deep in the CRT area into a thick Pleistocene sand layer. Elevation change is the result of all subsurface and surface processes (sedimentation, erosion, auto-compaction, accumulation and decay of organic matter) that occur between the marsh surface and the bottom of the benchmark pole (Cahoon et al., 1995). Marker sticks were placed at eight lower locations in March 2012 and consist of a tube with measuring tape, attached to a deep benchmark. After March 2014 sedimentation gradually resulted in the burial of the lowest marker sticks, after which they could not be measured anymore.

Rates of short term ΔE were computed by calculation of the slope between two successive measurements.

2.2.3 Elevation change over the total area

Deposited sediment volumes were computed as differences between two successive Digital elevation models (DEMs). Therefore, topographic surveys of the whole CRT area were conducted on a grid of 10x10m before flooding in February 2006 (T0) using a dGPS (Trimble R4 GNSS, accuracy ± 2 cm) and subsequently in December 2008 (T3), December 2009 (T4), April

2012 (T6), and April 2015 (T9) using a total station (Sokkia, SET510k, accuracy 1-3 mm). During all surveys elevations were measured relative to a fixed vertical control benchmark located at the sluice of the CRT. DEMs of the platform for T0, T3, T4, T6, and T9 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. LiDAR data of the FTE area was obtained from the Flemish government, department Mobility and Public works. Flights took place on 18/3/2010, 20/3/2014, 17/4/2015 and 10/3/2016, and data was corrected for vegetation. Digital elevation models (DEMs) were created using ArcMap 10.2, using TIN. The DEMs have a grid size of 1 m and vertical resolution of 1 cm. No LiDAR data were available for places with permanent water. The elevation of grid cells on the locations with permanent water at the time of LiDAR measurements in 2010 were derived from construction plans of the contractor.

2.2.4 Soil properties

In June 2013, sediment cores were taken in the FTE area at sites SET2, MS5 and MS7 (resp. high, mid, low locations), using acrylic cylinders (1 m x 0.056 m Ø). Five transparent tubes were carefully pushed into the mud until 2% compaction was measured, which coincides with a core depth of 0.6 m for low, 0.45 m for mid and 0.25 m for high sites. In May 2014, cores of the CRT sediment were taken up to a depth of 0.5 m at locations CRT3, 4 and 8, (resp.mid, low and high locations) and up to a depth of 1.5 m of the natural marsh sediment at locations NAT1 and NAT3 using a gouge (Ø 10cm, to minimize compaction during coring). Core samples were divided into subsamples of 10 cm depth intervals. After determination of wet weight, samples were dried for at least 72 h at 105°C for determination of dry bulk density and organic matter content (loss on ignition at 550°C for 5 hours). Moisture content is expressed as %weight loss per sample volume.

Additionally, in spring 2014, spring 2015 and spring 2016 soil samples were taken for grain size analyses at all eleven CRT sites, all accessible FTE sites (SET1, SET2, SET3 and MS3), three reference sites close to the CRT area and two reference sites close to the FTE area. Reference sites were distributed within a comparable range of flooding frequencies as in the restoration areas. For grain size analyses mixed samples were taken at each site, based on 10 to 15 cores of 15 cm deep, using a gouge (Ø 1 cm). Samples were pretreated by addition of H_2O_2 and HCl followed by heating (4h; 550°C; Heiri et al. (2001)) to remove organic matter content and were dispersed using ultrasound. Grain sizes were determined using laser diffraction (Mastersizer 2000 Malvern). Clay/silt/sand fractions were calculated using Wentworth classification (clay: <4 µm, silt: 4-63 µm, sand: >63 µm). For bulk densities six samples were taken at the three CRT sites (CRT3, 4, 8) and each accessible site in the FTE with rings of an exact volume of 100 cm^3 (Eijkelkamp). After collection, these samples were dried for at least 72 h at 105 °C after which dry bulk density was determined.

2.2.5 Suspended matter concentrations

Water samples were taken monthly in winter and every two weeks in summer in the upper part of the water column in the middle of the estuary over the study period of 10 years (2006-2016), as part of a long-term monitoring program for the Scheldt estuary (Maris and Meire, 2016). Suspended matter (SPM) was determined gravimetrically after filtration on pre-combusted Whatman GF/F filters. Monthly averaged SPM concentrations were calculated for the sampling location just next to the CRT; for the location next to the FTE, SPM concentrations from sampling locations 3.5 km upstream and 3.5 km downstream of the FTE were averaged.

Measurements over a transect from the main channel of the estuary to the inlet of the CRT were performed by Flanders Hydraulics and described in Maris and Meire (2016).

2.2.6 Tidal channel formation

Data on tidal channel formation in the CRT was collected by repeated (yearly) topographic surveying of the channel network (thalweg profile and selected cross-sectional profiles) and analyzed as described in detail in Oosterlee et al. (2017). For the FTE, yearly DEMs (1 by 1m resolution, as mentioned in 2.2.3) calculated from LIDAR images were used to locate tidal channels (which was possible because of the nearly absence of vegetation). The used definition of a newly formed channel is an incision of 10 cm over a 2 m radius, at least 10m in length. Slope calculations using ArcMap 10.2, Spatial Analyst, were used to manually locate the presence (slope > 5°) of a creek following a similar procedure as in Fagherazzi et al. (1999).

2.3 Computations and statistical analyses

Computations and statistical analyses were performed using R software, version 3.5.0.(R Core Team, 2018). To determine the relation between tidal descriptors, data were log-transformed to reduce heteroscedasticity, after which linear regressions were fitted. Selection of linear or higher order polynomial regression was based on the Akaike information criteria (AIC), where the best fit was represented by the lowest AIC and the model with additional terms had a significant p-value for the extra sum of squares test compared to the reduced model. We used the R-package nlme (Pinheiro et al., 2018) to perform linear mixed effects (LME) analyses of the relationship between flooding frequency (FF) and hydroperiod (HP). As fixed effects, we entered all FF terms of the 3rd degree polynomial regression and FF*site as an interaction term into the model. Subsite was included as a random intercept and we added an AR1 correlation structure to account for pseudoreplication. The high heteroscedasticity of only the CRT made it impossible to compare CRT and FTE & natural marsh for the relation between hydroperiod and mean water depth. LME analyses of the relationship between HP and ΔE was performed, with HP as fixed effect, HP*site as an interaction term, subsite as random intercept and an AR1 correlation structure to account for pseudoreplication. Evolution of sediment volumes over time were tested to be changing over time or not by fitting a linear or second order polynomial regression. Model selection was based on the same criteria as mentioned before.

3. Results

3.1 Tidal characteristics

Comparison of a spring tide - neap tide cycle in the FTE area and the estuary does not show large differences (Fig. 2a-c). Only small differences in the lower part of the tidal curve close to the moments of low water level were observed, since water levels in the FTE area cannot drop below the base level of the culvert system. Although there seems to be a slight delay for the water to enter and leave the FTE area during higher tides (Fig. 2c), the timing and duration of high and low water remains unchanged compared to those in the estuary. This means that the tide in the FTE area and the tide in the estuary are highly comparable. For this reason, relations between inundation frequency, hydroperiod and mean water depth (Fig. 3a, b) were determined for the FTE and natural marsh together. Contrary to the FTE, the CRT is characterized by reduced tidal amplitude and a prolonged hydroperiod (Fig. 2d-f and Fig. 3a, b). In both systems the variation in spring tide – neap tide, important for the development of different tidal habitats, is not impeded (Fig. 2a, d).

Site elevation of the FTE area is positioned very low in the tidal frame with the average elevation of 4.3 m below mean high water level (Fig. 2a), whereas the relative position of the CRT platform within the tidal frame is close to mean high water level and comparable to that of the platform of natural low tidal marshes close to the CRT (Oosterlee et al., 2017). Most of the natural tidal marshes along the Scheldt estuary adjacent to the CRT are natural high tidal marshes, with an elevation above mean high water level (Fig. 2d). The relatively low site elevation of the FTE area results in frequent flooding (>80%) of all the FTE measuring sites (Fig. 3a), whereas in the CRT a much wider range of flooding frequencies (20-93%) is present. Furthermore, relatively low site elevation results in relatively high water depths in the FTE (0.3m to >3 m) and CRT (0-0.8m) as compared to the natural marsh (0-0.4 m; Fig. 3b).

Hydroperiods (HP) were in general approximately two times larger for CRT sites with a comparable flooding frequency (FF) to sites in the FTE area or estuary (Fig. 3a). However, HP and FF were highly related for both CRT and FTE/estuary together. These log-linear relationships were significantly different (F-test, $F(3,2865)=174.54$, $p<0.0001$, table S1) regarding the intercept, fixed effects and fixed effects interaction with site (table S2).

. Moreover, the reduced tide clearly resulted in smaller water depths on CRT sites with a comparable hydroperiod to those of the FTE & natural tidal marshes (Fig. 3b). However, water depths at high sites (low hydroperiod) were reduced by roughly 15% where at low sites the hydroperiod was reduced by roughly 80% compared to FTE & tidal natural marshes.

3.2 Short term elevation change

Elevation change (ΔE) rates between subsequent measurements in the FTE area were highly variable over time and space (Fig. 4a). Enormous ΔE rates of more than 60 cm over 2 months were measured in the FTE area in the first months (note that rates rapidly decreased over time), with the highest rates at the lowest sites and the lowest rates at the highest sites (Fig. 4a). Reopening of the culverts after more than 1.5 years resulted again in extremely high ΔE rates (Fig 4b). ΔE rates decreased rapidly over time as the elevation of sites increased. The large range of initial elevations of the measuring sites in the FTE (3.58 to 0.58 m below MHWL in March 2013) determined the large range of ΔE rates at that moment (between 0.26 and 1.04 m in 2 months). Note that after March 2014 sedimentation gradually resulted in the disappearance of the lowest marker sticks, after which they could not be measured anymore. This means that in 2016 only the five highest measuring sites could be measured.

ΔE rates were also highly variable over time and space in the CRT area, but they are of a different order of magnitude than in the FTE area, with ΔE rates ranging from -0.45 to 3.65 cm per 2 months during the first year and -0.3 to 2.17 cm per 2 months during the tenth year (Fig. 4b).

In 2010 extra measuring sites in the CRT were installed on the mudflats, since all other measuring sites were vegetated. At these bare sites erosion was observed at times, whereas only accretion was measured on the vegetated sites.

When the evolution of total site elevation relative to the tidal frame is studied, flattening of both areas can clearly be observed (Fig. 5). In absolute numbers this means that the range between the 5th and 95th percentiles of the elevation data in the FTE area decreased with 2.81m over approximately five years. In the CRT area this range decreased from 63 cm at the beginning of the project to 48 cm after nine years. Mean elevation of the total FTE area increased with 3.65 m in five years, which coincides with 53% of the tidal frame. For the CRT area the mean elevation increased with 0.22 m over nine years, which corresponds to 0.68% of the tidal frame. The elevation changes in the CRT correspond with a net annual rate of sediment volume accumulation of approximately 212 m^3 $ha^{-1}yr^{-1}$ (calculated over nine years, creek erosion included), whereas the rate of volume change of freshly deposited sediment in the FTE area is about 25 times larger with 5441 m^3 $ha^{-1}yr^{-1}$ (calculated over five years, creeks included).

In contrast to the CRT area, where the rate of sediment volume change within the total CRT area does not significantly change over time, a decrease of the rate of sediment volume change is observed in the FTE (Fig. S2).

3.3 Explanatory variables for observed elevation changes

3.3.1 Tidal characteristics

We correlated ΔE rates observed in the FTE area, natural tidal marshes and CRT area to hydroperiod and mean water depth (Fig. 6) by LME analyses. Although locations with a similar flooding frequency had a larger hydroperiod in the CRT area than in the FTE area or natural tidal marshes, ΔE rates were distinctly lower in the CRT area for locations with a similar hydroperiod. Plotting ΔE rates against hydroperiod shows a significantly different correlation for these parameters between CRT and FTE (Fig. 6a; F-test, $F(1,2003)= 158.19$, $p<0.01$, table S3), regarding the intercept, fixed effect and fixed effect interaction with site (table S4). Plotting ΔE rates against mean water depth shows a positive relation, but no significantly different relation between all three areas (Fig. 6b). This means that for all areas the water depth determined the elevation change rates.

3.3.2 Soil properties

Within a few months the extremely high ΔE rates were the result of rapid deposition of poorly consolidated mud (Fig. 7). Relatively low dry bulk densities (DBD) down to 0.27 g cm^{-3} were measured in the top 5 cm of the low and mid FTE sites (Fig. 7), three months after reopening of the culverts in 2013. For both sites DBDs increased with depth to values that were comparable to DBDs measured in the CRT area at the low and mid sites. After one year after reopening of the FTE area we observed an increase of DBD of the top layer at SET2 from 0.4 g cm^{-3} in 2013 to 0.51 g cm^{-3} in 2014, which continued over the next years to 0.58 g cm^{-3} in 2016 (Fig. S3). Also, at the other (high) FTE measuring sites we observed an increase of DBD over time (Fig. S3). Unfortunately, the lowest sites (MS1, MS2 and MS4 to MS8) were unmeasurable after 2013, because the marker sticks were not visible anymore due to high sedimentation. DBDs of top 5 cm of the newly deposited sediments in the FTE area are comparable to those in the CRT area in 2014, 2015 and 2016 (Fig. S3). In both areas higher values were found close to a creek (locations “creek edge” in the FTE area and “CRT8” in the CRT area). Moisture contents of the FTE and CRT sediments were comparable and highest for those with lowest DBD and decreased with depth. Organic content of the sediments was ~4.5% in the FTE and two to three times higher in the CRT area.

Deposited sediments consisted of mostly silts with a mean grain size of ~18 µm in the FTE area and ~36 µm in the CRT area (Fig. S4). Reference sites in the estuary at the same locations as the restoration areas contained more sandy sediments than in the CRT and FTE areas (Fig. S4).

3.3.3 Suspended particulate matter

As the two restoration areas are located in different parts of the estuary, possible differences in suspended particulate matter (SPM) concentrations should be taken into account to explain the observed differences in ΔE rates. Measured mean SPM concentrations between 2006 and 2015 did not significantly differ between the location in the Scheldt estuary next to the CRT (133 mg l^{-1}) and next to the FTE (89 mg l^{-1}; Two-sample T-Test after correction for seasonality, t=-0.186, df=212, p=0.852, fig. S5). Observed SPM concentrations in the Scheldt estuary were highly variable in time and space. The estuarine turbidity maximum zone can be found around the CRT in summer and around the FTE in winter. SPM measurements over a transect from the main channel in the estuary to the CRT inlet show a reduction of SPM concentrations towards the CRT culverts (Maris and Meire, 2016).

3.4 Tidal channel formation

In the CRT pre-existing ditches were initially functioning as tidal channels and new tidal channels preferentially developed in low areas of the CRT, as has been reported already in detail by Vandenbruwaene et al. (2012) and Oosterlee et al. (2017). In the FTE no channel initiation was observed in the first half-year (Fig. 8A), when ΔE rates were extremely high (Fig. 4A) and sediment consolidation poor. During the closing period the FTE area was under marginal tidal influence (tidal range 0.6 – 0.8 m), but water inside the FTE area could still drain towards the estuary through the outlet culvert. During this period small drainage channels of 10-40 cm depth were formed in the deposited sediments, through which subsurface drainage occurred (Fig. 8B and Fig. S6). After re-opening the small drainage channels remained functional and the tidal channel network developed further over time (Fig. 8C-E).

4. Discussion

4.1 Elevation changes

The two study areas showed very different elevation change rates. ΔE rates of half a meter per 2 months in the FTE area are excessively high and never documented before in any tidal restoration area (ABPmer, 2019). ΔE rates as measured in the CRT area are also being considered relatively high (> several cm per year), however, not uncommon in managed realignment sites in the UK ((e.g. Tollesbury: 2.3 cm yr^{-1}(Garbutt et al., 2006); Orplands: 2.5 cm yr^{-1}, (French, 2006); Northey Island: up to 4.9 cm $yr^{-}1$, (ABP, 1998); Paull Holme strays: 10 cm yr^{-1} (Clapp, 2009); Chowder Ness: up to 20 cm yr^{-1} (Wallingford, 2013)). Higher ΔE rates in the FTE compared to the CRT are in line with our expectations. Despite the temporal variability in short-term ΔE rates, long-term ΔE rates in the CRT were significantly decreasing over time for the initially low sites, whereas there is a significant increase of ΔE rates for the initially high sites (Oosterlee et al. (2017).

4.2 Effect of tidal re-introduction design on the tide

The tide in the FTE is nearly identical to the one in the estuary, except for a slight delay in time during ebb and flood tide, probably caused by the height of the culverts, being over 2 m below MHWL. Besides this marginal difference in tide, the dimensions of the culverts are large enough to assure a quasi-full tidal exchange, with complete flooding and nearly complete drainage of the area over semi-diurnal tidal cycles. As long as the FTE culverts are not adapted in size, the area is broadly comparable to a managed realignment (MR) site realized by breaching the dike on a level of approximately mean low water level. However, the main difference to MR is the possibility to control tidal influence.

The strongly reduced tidal amplitude in the CRT area results in differences in the relation between flooding frequency, hydroperiod and water depth compared to FTE and natural tidal marshes (Fig. 3). The most explicit difference is a prolonged hydroperiod in the CRT, which is caused by the design of the CRT; the CRT area can only drain as soon as the water in the estuary is below the level of the outlet culvert (app. 4 m below MHWL, while estuarine mean tidal range is 5.40 m). This means that the CRT area can drain only for a relatively short time, not long enough to let all the water out. In this way water remains in the tidal channels during spring low tide (Fig. S1). The fact that for both study sites the spring–neap tidal variation is maintained, theoretically allows habitat development over the whole tidal range.

Our data on hydrological parameters and ΔE rates support the hypothesis that low-lying areas such as our FTE study area flood more frequently, deeper and longer, resulting in higher ΔE rates, compared to the CRT. In general, previous studies have demonstrated that sediment deposition in tidal marshes is typically higher at lower elevations within the tidal range where hydroperiod is longer and therefore time for sediment settling is longer (Cahoon and Reed, 1995; Leonard, 1997). However, studies on sedimentation rates that specifically focus on the effects of full versus restricted tidal exchange between tidal marshes and the adjacent estuary, are lacking to our knowledge. Based on the data of Fig. 6 we can conclude that not hydroperiod, but water depth is a very important explaining hydrological factor for the extremely high elevation change rates in the FTE area compared to those in the CRT area and natural tidal marshes. Implementing a reduced tide on a relatively low site as in the CRT area creates a situation where the marsh surface platform is subjected to limited water depths. The FTE area was also initially positioned very low within the tidal frame but subject to full tidal exchange resulting in on average 4.3 m of water depth on the platform during flooding, whereas this was initially 0.11 m on average for the CRT area. Consequently, the larger the water depth is on a site, the more suspended matter is supplied and deposited on that site.

4.3 Elevation-inundation feedbacks

The observations in this FTE are according to the elevation-inundation feedback typically found in natural tidal marsh systems (Allen, 1990; French, 1993; Pethick, 1981; Temmerman et al., 2004): The lower in the tidal frame, the more frequently, longer and deeper sites are inundated, resulting in high sedimentation rates for relatively low sites. These high rates, in turn, lead to an increase in platform elevation, causing less tidal inundation and decreasing sedimentation rates on the initially low sites. Sedimentation continues until elevation equilibrium close to mean high spring tide water level. Since the FTE area is subjected to nearly the same tide as in the estuary, this feedback is also expected to be present in the FTE and is indeed observed for example at the five lowest sites where elevation change rates decrease over time (Fig. 4a) or when looking at the total area volume changes over time (Fig. S2).

For most CRT sites with an initially low elevation we observed the above described natural inundation – elevation feedback in the first years. However, over a period of ten years we found an increase of ΔE rates for the initially high CRT-sites, indicating a deviation of the above-described process (Oosterlee et al., 2017). This different elevation-inundation-feedback is a result of the way a CRT is designed. The volume of water coming into the CRT area is determined by the dimensions of the inlet culvert, and this volume is spatially distributed over the whole CRT. In practical terms this means that when lower parts of the CRT silt up, the water and its suspended sediments are redistributed over the area, leading to less frequent, less deep, and shorter flooding and hence lower sedimentation rates on the initially lower sites. In addition, initially high sites will, after a certain period, flood more frequently, deeper and longer, leading to an increase of sedimentation rates and hence ΔE rates (Fig. 4b). This also implies that the spatially averaged ΔE rate in the CRT will go on at a constant rate over time, which is indeed observed as the total area sediment volume changes are not changing with time in the CRT (Fig. S2).

4.4 Effect of culvert design on SPM

Observed SPM concentrations in the Scheldt estuary are highly variable in time and space, as earlier found by Maris and Meire (2016); Van Damme et al. (2005). The estuarine turbidity maximum zone is positioned between the two research areas, depending on the season, resulting in higher average SPM concentrations in the estuary at the location of the CRT. But even though SPM concentrations in the estuary are higher at the location of the CRT area (133 mg l^{-1}) than at the FTE area (89 mg l^{-1}), other factors may affect SPM concentrations of the incoming water, such as the location and elevation of the inlet culverts.

Firstly, between the main channel of the Scheldt estuary and the culverts of the CRT area there is a small, shallower connecting channel of ~80 m length (Fig. S1). Measurements over a transect from the main channel into this connecting channel show lower flow velocities as compared to the main estuarine channel, and thereby a reduction of SPM concentrations towards the CRT culverts (Maris and Meire, 2016). In contrast to the CRT area, the FTE area is directly connected to the main channel of the estuary. Secondly, the inlet culverts of the CRT are placed high within the tidal frame. In this way, only the upperpart of the water column can enter the CRT, whereas almost the full tidal range of the water column enters the FTE (Fig. 2). In case of a vertical gradient of SPM in the water column, less SPM would enter the high-positioned inlet culverts. However, no data is available to determine if vertical mixing is occurring in the connecting channel in front of the CRT.

4.5 Blessing in disguise: effect of closing on tidal habitat evolution

Creeks are essential for the drainage of the area, consolidation of the sediment (Harvey et al., 1987) and aeration and biogeochemical cycling (Wilson and Gardner, 2006). In 2011 no tidal channel formation was observed, only a sloping mud mass (Fig. 8 and Fig. S6A-B). An explanation may be that the poorly consolidated sediment was too ‘fluid’ to sustain the formation of tidal channels. The banks of forming channels would easily collapse, if formed at all (as illustrated by fig. S7 showing that deep footsteps immediately closed behind people ‘wading’ through the mud), hence hindering the formation of channels. Further, we assume that the hindered channel formation also hinders the subsurface drainage of the sediment, hence further sustaining the poorly consolidated sediment conditions. Thus, a potential feedback mechanism may have been present between poor channel development and poor sediment consolidation. During the partial closure of the FTE area from July 15th 2011 to March 21st, when tidal range was strongly reduced to 0.6 – 0.8 m, the sediment could start to consolidate by drying and subsurface drainage towards the outlet sluice that remained open. During that period, also channels started to form (Fig. 8 and Fig. S6).

During the initial period with full tidal exchange, all remnant vegetation located more than 1 m below MHWL died off. Additionally, only few invertebrates were able to colonize the mud in 2011 (Maris et al., 2017; Schoeters, 2012). However, during the closing period small drainage channels were formed (Fig. S6C) and their draining function was maintained after reopening (Fig. 8C-E; Fig. S6D). An increase of dry bulk densities from 2014 to 2016 (Fig. S3) supports an improvement of subsurface sediment drainage towards these creeks. Also densities of benthic invertebrates increased after re-opening of the FTE with an explosive increase of densities in autumn 2014 (Maris et al., 2017).

Despite the initially excessive elevation change rates it seems the area evolved towards a potentially ecological valuable intertidal system within less than 5 years. However, the CRT area developed even faster in this direction (Beauchard et al., 2013a, b; Beauchard et al., 2014; Jacobs et al., 2009; Vandenbruwaene et al., 2012).

4.6 Implications for tidal habitat restoration

Our results bring up new ideas for tidal habitat restoration. Former agricultural low-lying sites often have low permeable or even impermeable, heavily compacted top soils (due to former use of agricultural machinery, soil drainage, etc.), which may seriously limit the colonization of vegetation or benthic invertebrates because of very poor drainage of the fresh tidal sediment deposits on top of this low permeable soil (Tempest et al., 2015; Van Putte et al., 2019). Allowing the FTE area to fill with a thick layer of estuarine deposited sediments, followed by a period without tidal exchange and subsurface drainage of the deposited sediment, will most probably result in suitable sediment conditions for tidal marsh creation. Thus, the advantage of an FTE, as shown in this study, over de-embankment (managed realignment) is that low-lying areas can be raised to a preferred elevation for tidal flat or marsh development in a controlled way, followed by a temporal closure of the culvert to allow sediment drainage (which is usually not possible when dikes are breached). In the FTE mudflat habitats will build up soil elevation by sediment accretion and will evolve towards tidal marshes, whereas with the CRT technique, adaptive management supports changing the hydrological regime in a way to promote creation of tidal flats or tidal marshes, depending on the restoration goals.

5. Conclusions

This comparison between two differently designed tidal re-introduction sites in the Scheldt estuary can serve as an example to show the effect of different tidal re-introduction techniques on the creation of intertidal habitat on low-lying areas. The CRT was designed with the intention to reduce sedimentation rates, since its main function is water storage during storm tides (Maris et al., 2007). High sedimentation rates are therefore undesirable. This study shows that the CRT technique indeed strongly reduces the input of sediments into the study area by a decrease of tidal volume flooding the area and a decrease of SPM concentrations due to the location and elevation of the inlet culverts. The CRT system results in relatively low ΔE rates compared to the FTE case. Elevation change rates in the FTE area are of an order of magnitude higher than those in the CRT. For these regulated tidal exchange systems, it seems that the larger the water depth, the more suspended matter is supplied and deposited on a site. In this way the water depth, and not hydroperiod, is the main explaining factor for the extremely high elevation change rates in the FTE area compared to those in the CRT.

High sedimentation rates are not necessarily negative in the perspective of tidal marsh restoration; the FTE technique can be used as a controlled way of increasing surface elevation with natural coastal or estuarine sediments prior to dike breaching, in this way potentially (partially) by-passing the problems of reduction of vertical soil water movement by formerly compacted agricultural soils. On the other hand, the CRT technique allows adaptive management which supports changing the hydrological regime in a way to promote creation of tidal flats or tidal marshes, depending on the restoration goals.

Literature research about the effect of the introduction of different forms of RTE on hydro-geomorphological interactions to compare our results with was unfruitful. Unfortunately, most of the time, monitoring of RTE restoration projects covers vegetation, benthic invertebrates, fish and birds, whereas important aspects of hydrodynamics and geomorphology are not monitored. In some cases, it seems that these aspects are measured, however, not being published in peer-reviewed literature. We would like to urge the necessity for sharing experiences in tidal restoration practices for better understanding and more efficient ways of working.

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CAPTIONS

Figure 1 (A) Location of the study areas within the Scheldt estuary. **(B)** Operating principle of a full tidal exchange system (FTE; right) and controlled reduced tide system (CRT; left), illustrated for an average tide and spring tide (top), neap tide (bottom) during ebb (black arrow) and flood (blue arrow).

Figure 2 Comparative graphs of tidal water level time series. For a spring-neap tidal cycle in **(A)** the full tidal exchange system (FTE) and the estuary and **(D)** the controlled reduced tidal system (CRT) and the estuary and for two tidal cycles in the estuary and the FTE during spring tide **(B)** and neap tide **(C)** and in the estuary and CRT area during spring tide **(E)** and neap tide **(F)**. Mean high water levels (MHW) in the FTE and CRT area and in the estuary at the locations of the FTE and CRT areas are indicated by a blue line. Black dotted lines show the base level of the culverts (i.e. outlet culvert in case of the CRT). Boxplots of initial surface elevation of the natural marshes within the estuary adjacent to the CRT area, and within the FTE area and CRT area are shown at the left side; boxplots represent quartiles with whiskers at 5^{th} and 95^{th} percentiles, mean elevations indicated by diamonds.

Figure 3 (A) Relation between hydroperiod per tidal cycle and flooding frequencies and **(B)** relation between mean water depth per tidal cycle and hydroperiod for eight locations in the CRT, three locations in the natural marsh, and 11 locations in the FTE area. Single dots represent hydrological descriptors per spring-neap tidal cycle.

Figure 4 (A) Rate of elevation for 11 measuring sites in the FTE area over five years. Between 15 July 2011 and 21 March 2013, the culverts were closed, indicated by vertical dashed lines. **(B)** Rate of elevation changes for 11 measuring sites in the CRT over time. Black lines represent a random low, intermediate and high measuring site for each research area, grey lines the rest of the sites.

Figure 5 Evolution of platform elevation over time for the whole CRT and FTE area (for both creeks excluded), expressed relative to local mean high water level (MHWL) and tidal range, based on DEMS. Elevations are expressed as percentage of the local total tidal frame within the study areas. Boxplots represent total area elevation divided in quartiles with whiskers at 5^{th} and 95^{th} percentile, mean elevations area indicated by diamonds.

Figure 6 Relation between elevation change and hydroperiod per tidal cycle (HP; **(A)**) and mean water depth per tidal cycle (mWD; **(B)**) for eight locations on the CRT marsh (open dots; dashed line), three locations on the natural tidal marsh (grey squares), and for 11 locations in the FTE area (black dots; black line). Dots represent average values per spring-neap cycle.

Figure 7 Vertical sediment profiles showing mean (n=3 for CRT and NAT, n=5 for FTE) sediment properties collected at the FTE sites SET2(high), MS5 (mid) and MS7 (low) (full circles), the CRT marsh sites CRT3 (mid), CRT4 (low) and CRT8 (high) (open circles), the natural marsh sites NAT1 and NAT3 (open squares), expressed relative to surface elevation at the start of tidal introduction in the CRT and FTE areas (i.e. FTE: January 2011, CRT&NAT: March 2006). Error bars show standard error.

Figure 8 Digital elevation models of the FTE area shown for five years based on LiDAR data. White areas inside the FTE area correspond to no data.

SUPPLEMENTARY DATA

Figure S1 The two study areas, shown with the initial topography in 2006 (CRT) and 2011 (FTE) before introduction of tidal flooding, with indications of the measuring locations in the CRT area (CRT1 to CRT11), the adjacent natural tidal marshes (NAT1 to NAT3) and FTE area (SET1-SET3 and marker sticks (MS) 1 to 8).

Figure S2 Evolution of sediment volumes deposited over time for the whole CRT and FTE area, based on DEMS.

Figure S3 Average dry bulk densities (n=6) at five FTE sites and three CRT sites, taken in spring 2014, 2015, and 2016.

Figure S4 Shepard sediment classification with grain size distributions of 15 cm deep, newly deposited mixed sediment samples of the CRT marsh (eight sites), FTE area (four sites) and natural marsh sediments close to the CRT (three sites) and FTE area (two sites), using Wentworth classification (clay: <4 µm, silt: 4-63 µm, sand: >63 µm

Figure S5 SPM concentrations measured between 2006 and 2015 at the location in the Scheldt estuary next to the CRT and FTE areas. Boxplots represent quartiles with whiskers at 5^{th} and 95^{th} percentiles, mean SPM concentrations indicated by diamonds.

Figure S6 Photographical representation of the evolution of the FTE area over time at measuring site MS7, taken from the dike closest to this site. The blue dot represents the location of the measuring stick. Photo **S6A** was taken by S. Temmerman, **S6B-D** by L. Oosterlee.

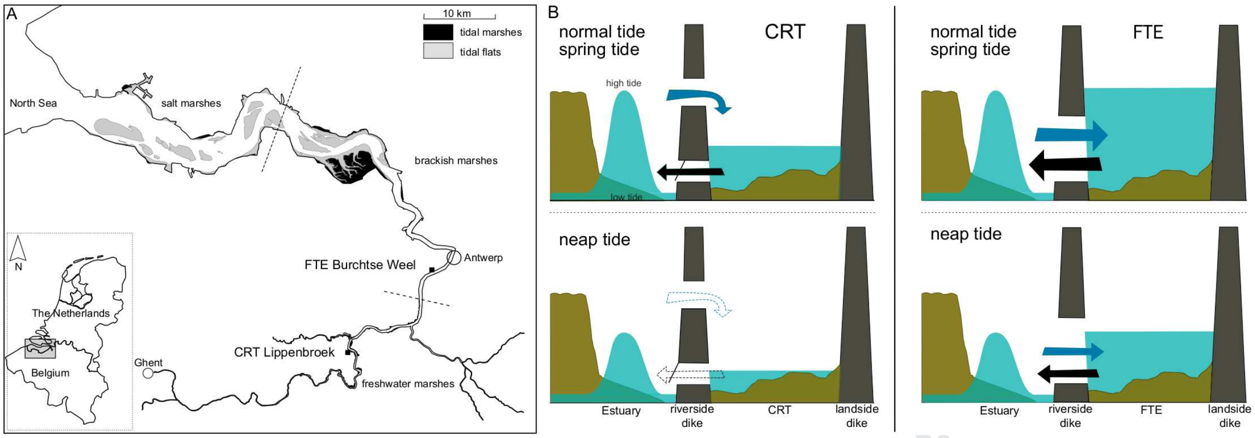
Figure S7 Photograph of people wading through the mud on 6 April 2011. Deep footsteps immediately closed behind there wading people. The photo was taken by S. Temmerman.

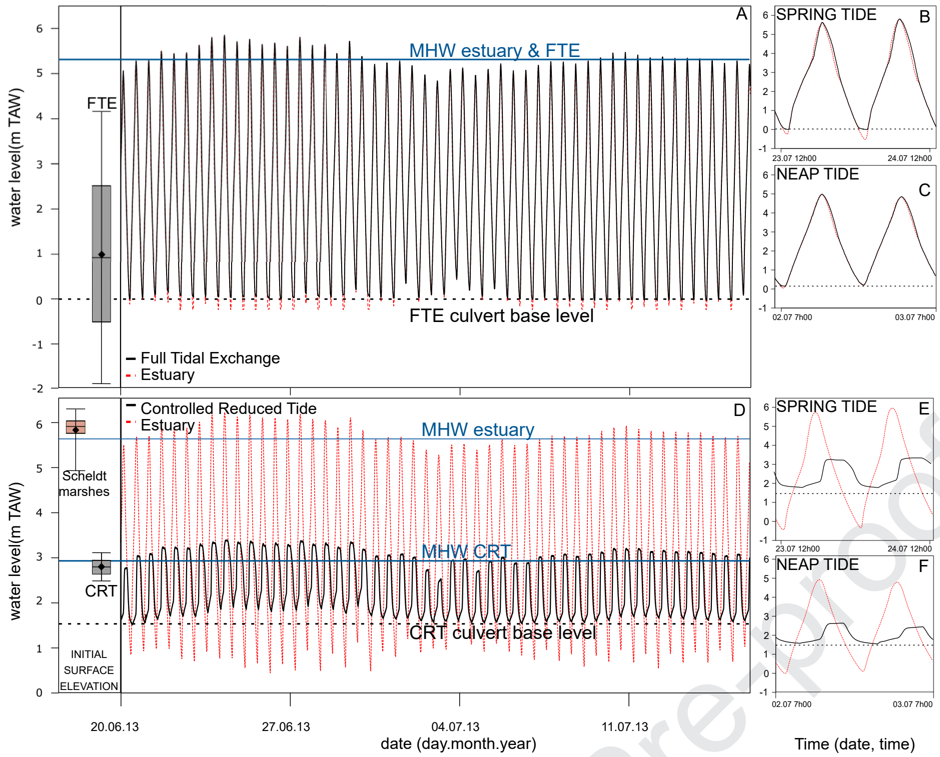
Table S1 T-table lme analyses of ln(hydroperiod ~ flooding frequency (FF) with fixed effect estimates, their approximate standard errors, the denominator degrees of freedom, the ratios between the estimates and their standard errors (t-value), and the associated p-value from a t distribution. Rows correspond to the different fixed effects.

Table S2 Type III tests of fixed effects, with numDF =the numerator degrees of freedom, denDF = denominator degrees of freedom, F-values, and P-values for Wald tests for the terms in the model and combination of model terms.

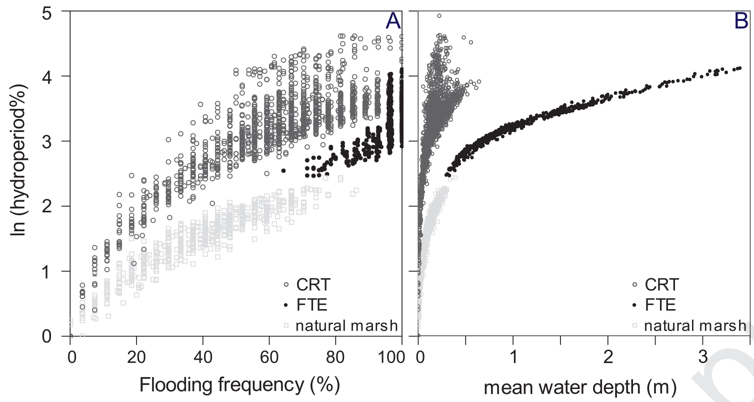
Table S3 T-table lme analyses of elevation change ~ Hydroperiod (HP) with fixed effect estimates, their approximate standard errors, the denominator degrees of freedom, the ratios between the estimates and their standard errors (t-value), and the associated p-value from a t distribution. Rows correspond to the different fixed effects.

Table S4 Type III tests of fixed effects, with numDF =the numerator degrees of freedom, denDF = denominator degrees of freedom, F-values, and P-values for Wald tests for the terms in the model and combination of model terms.

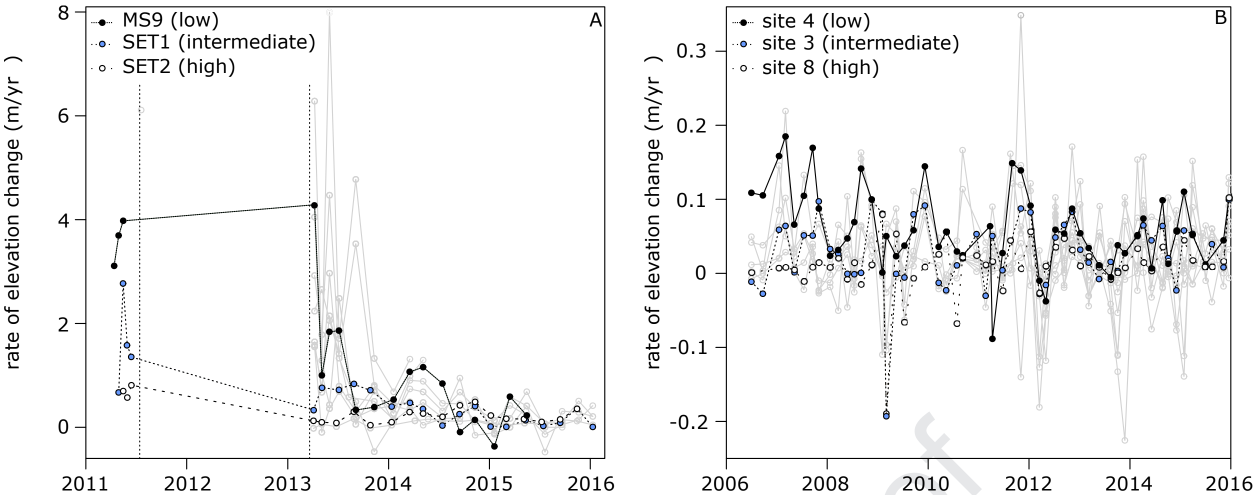

A
10 km
tidal marshes
tidal flats
North Sea
salt marshes
brackish marshes
Antwerp
FTE Burchtse Weel
N
The Netherlands
Belgium
Ghent
CRT Lippenbroek
freshwater marshes
B
normal tide
spring tide
CRT
high tide
low tide
neap tide
Estuary
riverside dike
CRT
landside dike
normal tide
spring tide
FTE
neap tide
Estuary
riverside dike
FTE
landside dike

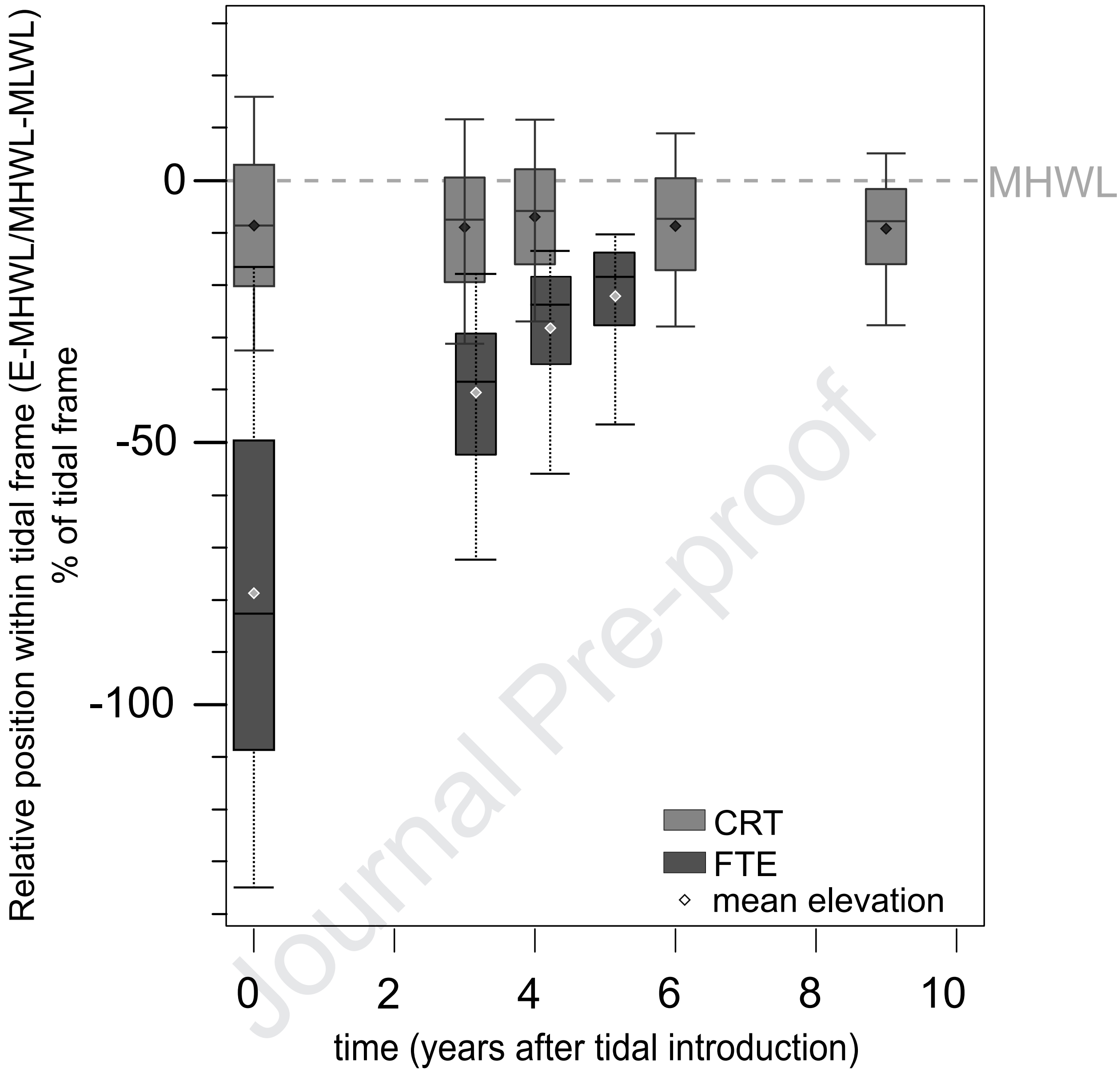


water level(m TAW)
FTE
MHW estuary & FTE
FTE culvert base level
Full Tidal Exchange
Estuary
A
SPRING TIDE
B
23.07 12h00
24.07 12h00
NEAP TIDE
C
02.07 7h00
03.07 7h00
Controlled Reduced Tide
Estuary
MHW estuary
MHW CRT
CRT culvert base level
Scheldt marshes
CRT
INITIAL SURFACE ELEVATION
D
SPRING TIDE
E
NEAP TIDE
F
20.06.13
27.06.13
04.07.13
11.07.13
date (day.month.year)
Time (date, time)

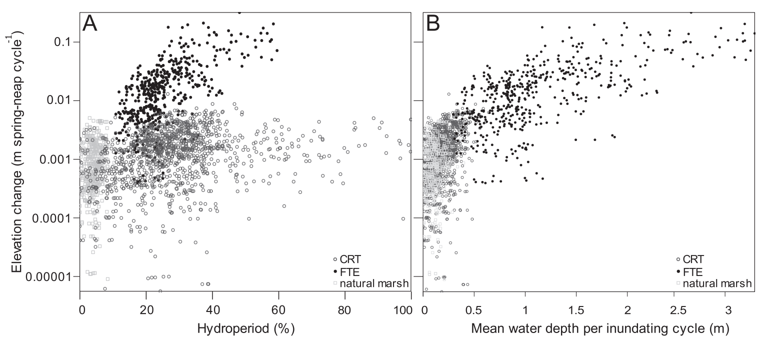


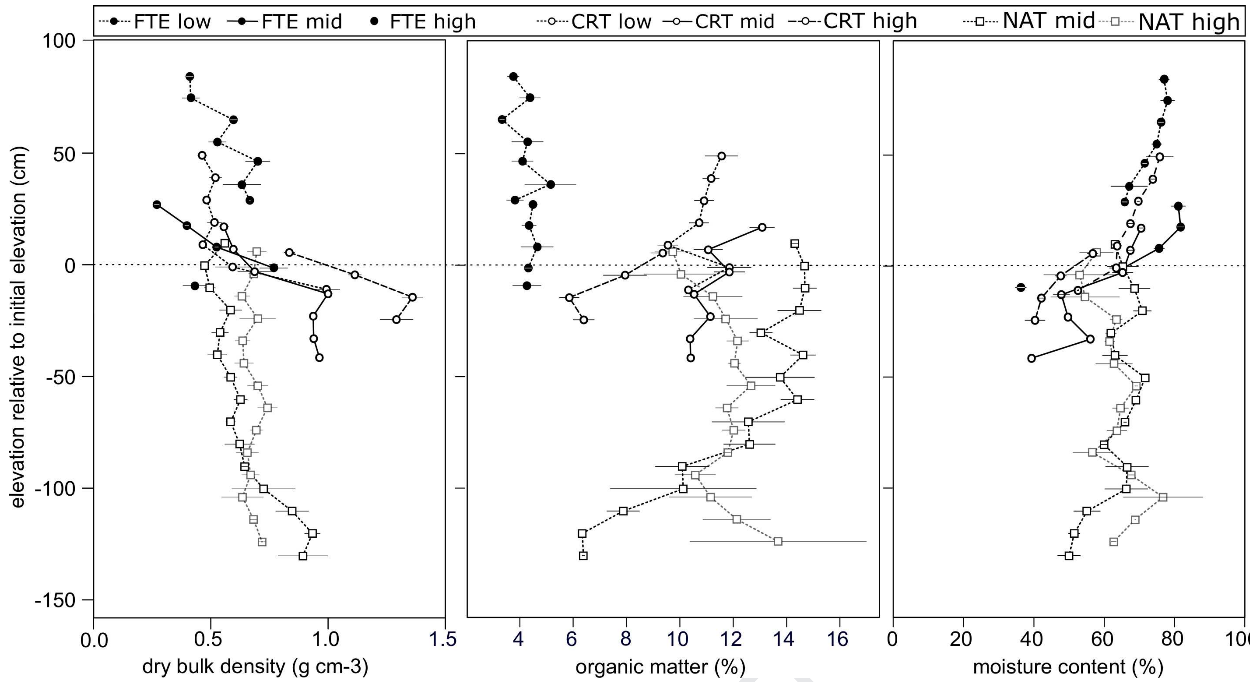
A
B
ln (hydroperiod%)
Flooding frequency (%)
mean water depth (m)
CRT
FTE
natural marsh
CRT
FTE
natural marsh

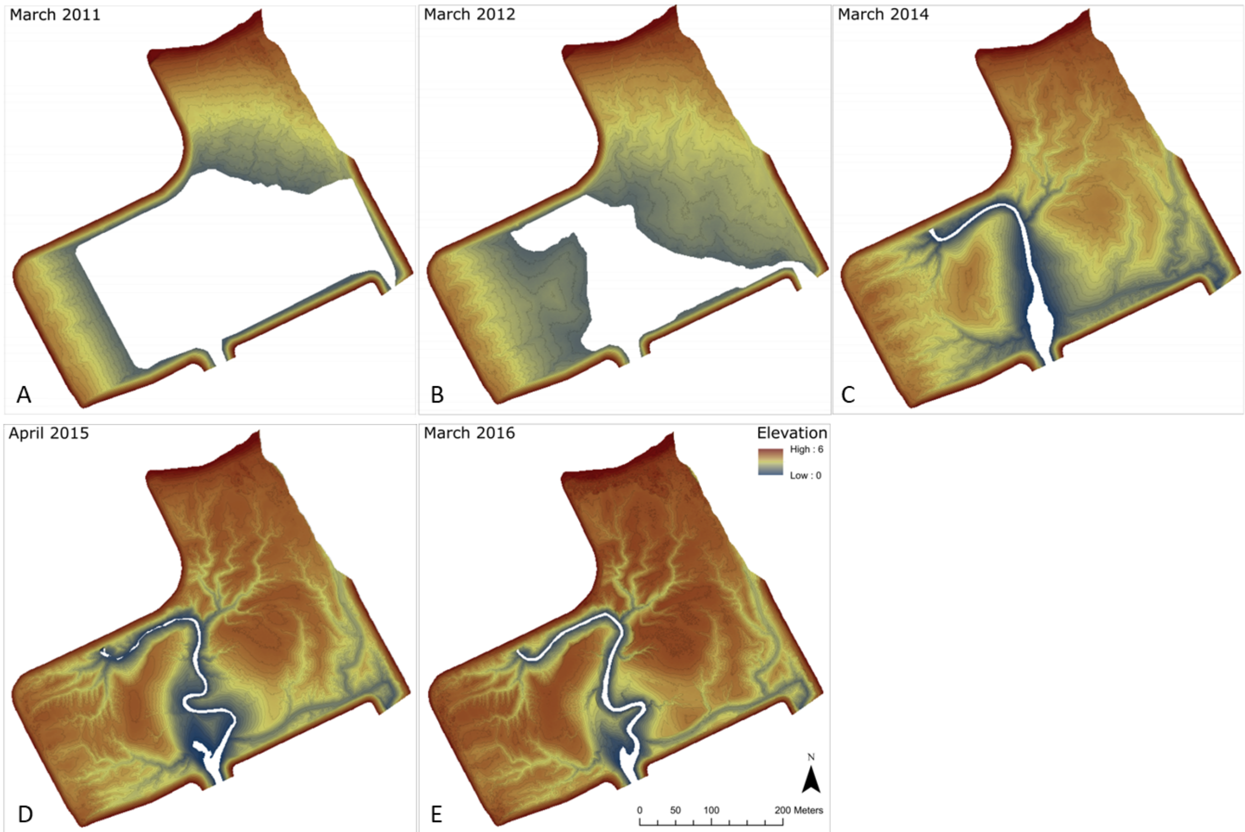

A
MS9 (low)
SET1 (intermediate)
SET2 (high)
rate of elevation change (m/yr)
0
2
4
6
8
2011
2012
2013
2014
2015
2016
B
site 4 (low)
site 3 (intermediate)
site 8 (high)
rate of elevation change (m/yr)
-0.2
-0.1
0
0.1
0.2
0.3
2006
2008
2010
2012
2014
2016



Relative position within tidal frame (E-MHWL/MHWL-MLWL)
% of tidal frame
0
-50
-100
MHWL
CRT
FTE
mean elevation
0
2
4
6
8
10
time (years after tidal introduction)


A
B
Elevation change (m spring-neap cycle^{-1})
0.1
0.01
0.001
0.0001
0.00001
CRT
FTE
natural marsh
0
20
40
60
80
100
Hydroperiod (%)
0
0.5
1
1.5
2
2.5
3
Mean water depth per inundating cycle (m)


FTE low
FTE mid
FTE high
CRT low
CRT mid
CRT high
NAT mid
NAT high
elevation relative to initial elevation (cm)
dry bulk density (g cm-3)
organic matter (%)
moisture content (%)


March 2011
March 2012
March 2014
A
B
C
April 2015
March 2016
Elevation
High : 6
Low : 0
D
E
N
0 50 100 200 Meters

Highlights:

- Tidal re-introduction using controlled reduced tide strongly reduces input of sediments
- Full tidal exchange in low-lying areas results in high sedimentation rates
- Controlled reduced tide is defined by extended flooding and reduced tidal amplitude
- Full tidal exchange results in exact copy of natural tide in restoration area