WP5 Measures

Basic analysis reports

Measure nr° 13. Lippenbroek: Flood Control Area with Controlled Reduced Tide (FCA-CRT)

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1 Description of measure

- Measure Category: Hydrology/Morphology; and Biology/Ecology
- Estuary: Scheldt
- Salinity zone: Limnic
- Pressure: Gross change in morphology and hydrographic regime
- Status: Implemented (since 2006)
- River km: Scheldt-km 115-129, TIDE-km 31-45
- Country: Belgium
- Specific location: Sea Scheldt (Zeeschelde), Flanders, at the left bank of the Scheldt near Driegoten, Hamme
- Responsible authority: Waterwegen en Zeekanaal NV
- Costs: 1,000,000 €
- Cost category: 1,000,000 – 5,000,000 €

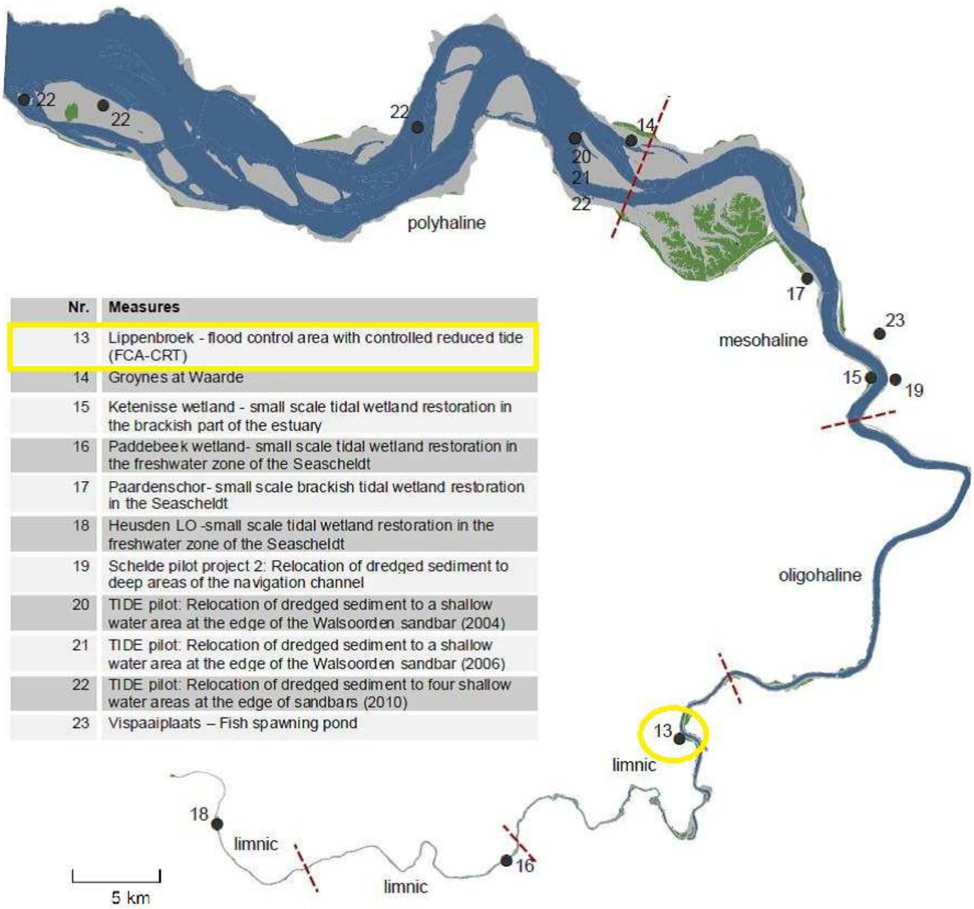


Figure 1. Location of the FCA-CRT Lippenbroek

Figure 2. Air view of FCA-CRT Lippenbroek

1.1 Measure description

GENERAL INTRO

The worldwide extent and abundance of intertidal habitat has greatly decreased, primarily due to human alteration of estuarine habitats. Impacts include construction of embankments or weirs, harbour expansion, deviation of freshwater inflow and conversion of tidal marsh for agricultural uses and urban and industrial development. The remaining habitat is often degraded by strong anthropogenic pollution or changing hydrodynamics. Loss of valuable habitat results in loss of associated function, such as estuarine biogeochemistry (C, N and P transformations and buffering of estuarine silica concentrations), energy dissipation (control tidal currents and waves) and mitigation of floods (protecting landward sea defences from scour and erosion).

Throughout the world, tidal marshes are restored to obtain natural protection against recurring storm surges and to preserve the goods and services these habitats provide. Managed realignment is a technique that consists of the removal or breaching of dikes to restore tidal influence. Elevation is a key factor in planning of managed realignment and for suitable site selection as it relates directly to frequency, height and duration of tidal inundation, which are the main factors in sedimentation patterns and vegetation development. Agricultural sites adjacent to estuaries have often lowered in elevation as a result of compaction. This typically leaves them below the levels of contemporary marshes within the same system, which have often increased in height with sedimentation (Temmerman et al. 2003). The difference in elevation rules out many sites for potential realignment, since this would result in entirely flooding of the site every tide and would thus result in development of completely non-vegetated intertidal mudflats, of which it is not certain if and how fast they could evolve to a vegetated marsh system.

An alternative solution is the installation of a restricted tidal exchange. This has the advantage of lowering the tidal wave in the site to an acceptable level, but the technique cuts out spring-neap tide variation needed for optimal habitat diversification.

Another solution is the installation of sites under controlled reduced tide (CRT). This could offer opportunities for tidal marsh restoration in combination with safety measures.

INTRO SCHELDT ESTUARY

To protect the Sea Scheldt (Zeeschelde) for storm surges and in general for sea level rise, the Sigmaplan was developed. Initially the focus was restricted to flood reduction for which Flood Control Areas (FCA) were developed. European, international and national legislations like the Water Frame Directive (WFD), Habitat and Bird Directive (HD/BD), that dictate a ‘no net loss’ policy and the development of a ‘sound ecosystem’, had led to the development of the actualised Sigmaplan. The actualised Sigmaplan is the Flemish management plan for flood prevention that also has to reach the nature objectives in the Belgian part of the Scheldt estuary. The expansion of intertidal wetlands is part of the strategy to control flood risk. The new combined focus on both security and nature had led to the new concept of Flood Control Area with Controlled Reduced Tide (FCA-CRT), areas with a safety function but, with a special sluice system, also attributable to the restoration of important estuarine functions. The long term objective for the Scheldt estuary is the development of several thousands of ha of tidal restoration projects, of which ca. 1000 ha with the CRT technique. Eventually (by 2030) new CRT habitat will comprise 36% of tidal freshwater marshes along the Scheldt.

However, before implementation on a large scale, as the basal hypotheses whether this technique could successfully restore freshwater tidal marsh habitat on a lowered rural site, had to be checked. A research strategy was developed in three stages with increasing complexity. First, two mesocosmos experiments were executed to study the growth of Reed and the behaviour of heavy metals in soils and flood water in relation to flood frequencies and different soil textures. Lastly, a pilot project for a Flood Control Area with Controlled Reduced Tide (FCA-CRT) was developed in Lippenbroek. The main objective was to study the ecosystem functioning of the FCA-CRT. This pilot project will indicate if sustainable ecological structures and functions could develop in a FCA-CRT which are qualitatively and quantitatively similar to outer-dike intertidal habitat.

Pilot project LIPPENBROEK

Lippenbroek is an area of 10ha (8ha without counting the dike surface) with the aim to combine water storage during extreme high tides and estuarine wetland restoration. It is the first FCA-CRT in the world that is functional and acts as a pilot project in terms of habitat development for other flood control areas to come (eg. Kruibeke-Bazel-Rupelmonde). By creating the correct conditions (primarily a correct tidal regime), the aim is to develop a sustainable freshwater tidal marsh habitat on a lowered rural site with nature itself as the primary steering factor.

Lippenbroek concerns a low polder area, separated from the estuary by a lowered overflow dike with sluice system (high inlet culverts (Figure 3), low outlet valves) to introduce a wide range of inundation frequencies in this embanked site to restore estuarine functions and habitat (Figure 4 & Figure 5). Only with extremely high water, the water flows over the low dike to (partially) fill the FCA. The area is separated with a high dike (Sigma dike) from the hinterland for safety against flooding. This technique allows implementation of a restricted tidal regime with neap and spring tides.

Figure 3. Left: Inlet culvert construction (as seen from within the pilot restoration site), consisting of three inlet culverts, each 1 m wide, with adjustable thresholds at different heights. Right: Close-up of the inlet culverts at spring tide flooding (as seen from within the pilot restoration site).

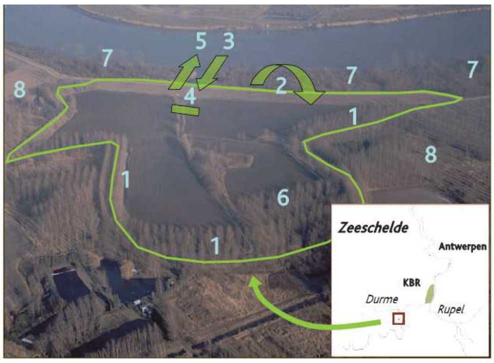


Figure 4. Overview of Lippenbroek and situation in the estuary. KBR is the planned FCA Kruibeke-Bazel-Rupelmonde, where in Kruibeke the CRT-concept will be applied at large scale (ca. 180ha). The picture visualises Lippenbroek before construction, with agricultural activities and a popular plant (6). The construction consists of a high ring dike (1), a low flood dike (2), an inlet sluice (3) and a pool with sample bridge (4). Arrow (5) indicates the existing outlet sluice, (7) are the marshes of the 'De Plaat'. The landuse in the adjacent polders (8) is currently mainly agriculture or popular plants. (Maris et al. 2008a)

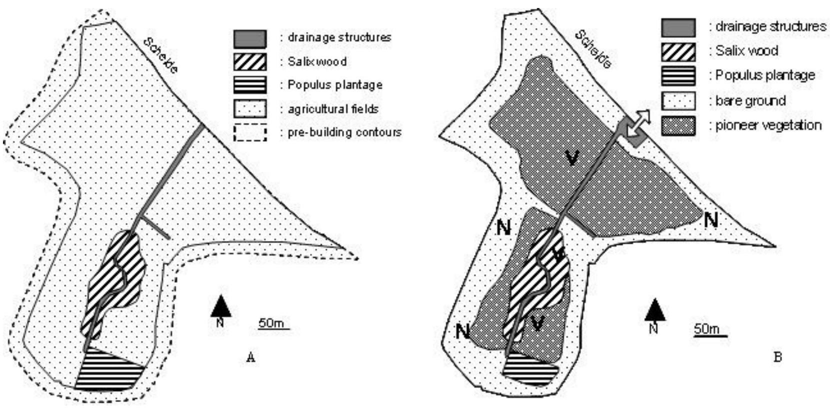


Figure 5. Schematic overview of the study site before (A) and after construction (B). Sampling locations with ("V") and without ("nV") initial vegetation are shown in B. The central creek is shown in grey; the white arrow indicates the culverts' location.

Concept FCA-CRT

The development of intertidal wetlands (mudflats and marshes) in a FCA-polder, which normally only floods once or twice a year at storm tide, needs a sluice system that enables the exchange of Scheldt water at a daily basis. Mudflats will develop in parts of the polder that are flooded daily with Scheldt water, marshes on the other hand flooded only at neap tide. For the development of a diverse wetland ecosystem, differentiation in flooding frequency on the polder surface is essential and has to be similar to natural wetland areas.

A special sluice technique allows implementation of a restricted tidal regime with neap and spring tides, by the use of high inlet culverts and low outlet valves. Important, an inlet culvert which only lets in the top of the tidal wave is created. Consequently, water flows gravitationally out to a lower exit culvert when water levels in the river have again decreased (Figure 6). The site elevation and river tidal regime are thus detached. Fine-tuning of inlet culvert level permits installation of a tidal regime with a pronounced spring-neap variation. This aspect is of tremendous importance to restore the full range of intertidal habitats and has until now been lacking completely from other tidally restricted systems.

When a site has a pronounced topography, or an extended ditch system, the water volumes needed to create a tidal gradient are much bigger. This would theoretically lead to more culverts at mean high water neap level, but the problem can also be solved by adding some culverts with lower thresholds (Figure 7). Such a configuration permits bigger water volumes to enter every tide without increasing the number of culverts, which saves up on the building costs. Off course, in the latter case, precise fine tuning will be required according to the desired flooded surfaces at neap, average and spring high waters (Figure 7). Therefore, calculation of surface/volume relationships of the site and discharge estimates of the culverts is needed. After a few test runs and fine-tuning of the inlet sluice sill level, a reduced tidal regime was introduced from March 2006 on.

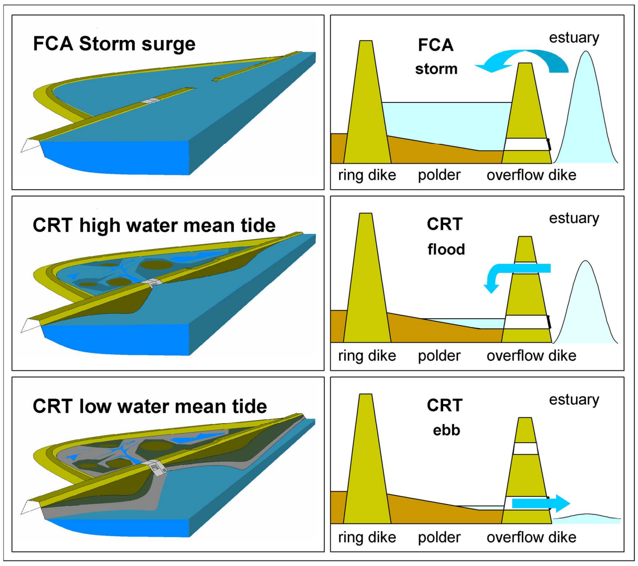


Figure 6. Functioning of a Flood Control Area (FCA) with Controlled Reduced Tide (CRT) at storm surge (upper panels), at high water mean tide (central panels) and at low water mean tide (lower panels). Inflow phase initiates when rising river level exceeds the inlet threshold, and continues throughout the rising and falling of the tide until the level drops back to this threshold. Outstream begins water pressure opens the outlet culvert, and continues until the river level rises again to close the valve. (Maris et al. 2008a, Maris et al. 2008b)

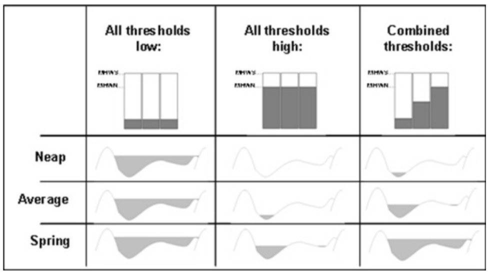


Figure 7. Threshold configuration has to be tuned for optimal tidal flooding gradient (Maris et al.).

1.2 Monitoring

The monitoring of Lippenbroek is still in progress. A large monitoring programme was installed to investigate whether sustainable ecological structures and functions can develop, that are quantitatively and qualitatively similar to these of the outer-dike mudflats and marshes. 9 research entities are working together within a joint spatial-temporal monitoring setup. The spatial-temporal monitoring was setup for processes (tidal cycling, nutrient processing (N, P, Si, O), and sedimentation) and structures (tidal marsh topography, -vegetation, and -fauna).

The UA - ECOBE group coordinates all research. The monitoring is part of the OMES-programme (to monitor environmental effects of Sigmaplan) when it concerns tidal characteristics, water and mass balances, basic water quality, heavy metals, sedimentation, geomorphological development of ditches, vegetation (incl. phytoplankton and -benthos), zooplankton, light climate, and primary production. Research of fauna (zoobenthos, birds, and fish) is conducted outside OMES.

On ten randomly chosen monitoring sites, 9 plots (2 x 2m) for different sampling purposes are designated (Figure 8). This approach guarantees maximal comparability of different parameters, and minimises mutual interference of destructive and non-destructive measurement techniques. Vegetation, benthos, sedimentation and soil properties (e.g. compaction, granulometry, nutrients, and pollutants) are recorded in detail. At three reference sites on the adjacent marsh, the same parameters are being recorded (Figure 8).

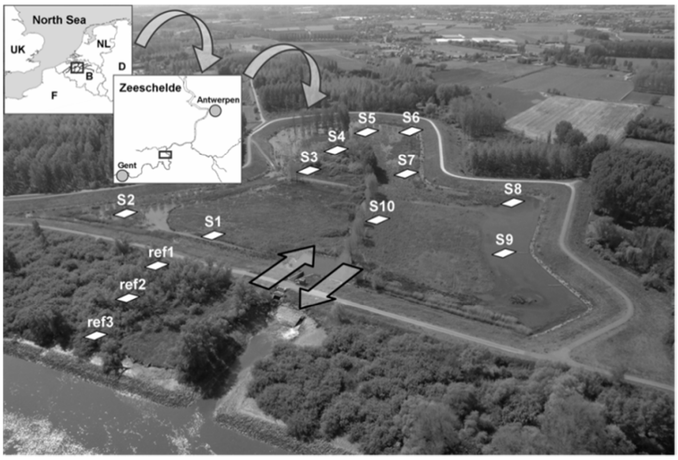


Figure 8. Situation and aerial view of the CRT pilot site and Scheldt estuary. Monitoring sites (S1 to S10) and reference sites on the adjacent estuarine marsh (Ref1 to Ref3) are marked with white squares. Arrows show the position of in- and outlet sluices.(Maris et al.)

Monitoring techniques:

1. Spring-neap tide cycles
   - Tidal characteristics are measured at each of the 10 sites and at the sluices. Diver dataloggers (Van Essen Instruments) monitor the water level by measuring the pressure of the water column with a pressure sensor. Correction for changes in air pressure is performed. From these water level records tidal characteristics are derived: absolute high (HW) and low water (LW) levels, inundation frequency (IF), inundation height and inundation time (for definitions see (Cox et al. 2006)).
   - From May 2006 onward, water levels and flow velocities at the inlet and outlet sluices of the pilot CRT are monitored continuously on a 2 to 5-minute time interval. At distinguished moments (5 to 10 measurements campaigns for each in- and outlet sluice), discharge measurements were executed using portable measurement devices (e.g. Flo-MateTM and Qliner).

2. Topography: Sedimentation / erosion, and creek formation
   - At Lippenbroek several methods (at the 10 sample sites) are used for the **sedimentation and erosion** part of the monitoring program.
     - Marker horizons are used to identify the thickness of disposed sediment on a clearly recognisable place.
     - Surface elevation tables (SETs) measure very accurate (approximately 1 mm) the elevation changes of the sediment surface, both sedimentation and erosion.
     - Sediment traps measure at specific locations the quantity of disposed sediment.
     - Siphon samplers are positioned in the main channel to determine the suspended sediment concentration in the water column at inflow.
   - **Creek morphology** is monitored using a total station (Sokkia, with accuracy of 1 to 3 mm).

3. Water- and sediment quality
   - Water quality analysis and exchange studies (nutrients, sediments, metals, biota (fish, algae)) were performed near the sluices during several separate 13 hour campaigns: water quality was monitored every half hour during the flood phase, every hour during the ebb phase. Subsurface samples were taken near the sluice by means of bucket hauls, stored at 4°C and analysed within 24 hours using a SKALAR SA 5100 colorimeter. Dissolved silica was analysed spectrophotometrically on a Thermo IRIS ICP (Inductively Coupled Plasmaspectrophotometer).

4. Colonization fauna and flora
   - Vegetation mapping
   - monitoring of fish and birds

1.3 Monitoring results

1.3.1 Spring-neap tide cycle

Theory

The spring-neap tide cycle is studied in detail because it determines, in combination with the elevation of the area, the inundation frequency and hence the marsh restoration potential. The Controlled Reduced Tide (CRT)-principle enables the creation of an intertidal habitat without a suitable elevation for normal dike removal. By using a system with high inlet and low outlet, a high variation of inundation frequencies is possible however the tidal curve will be with a stagnant phase instead of sinusoidal (Figure 9). The inlet construction has to be high enough (4.70 m at Lippenbroek) because only then enough variation in the water entering duration and –volume to enable the high variation in water levels in the polder.

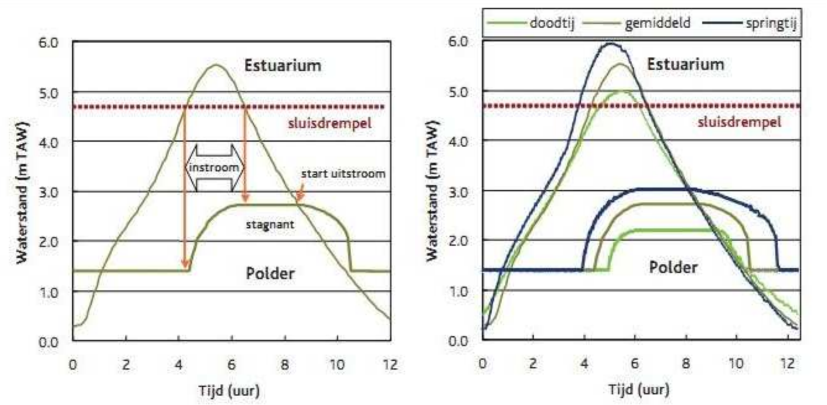


Figure 9. Modelling (1D) of the tide in CRT Lippenbroek for an average tide (left), with indication of in-stream and out-stream. The tidal difference between the end of the in-stream and the start of the out-stream results in a stagnant phase. The right panel visualises the same modelling for neap-, average- and spring tide. Only with a high inlet culvert the difference in in-stream will be large enough to result in large spring-neap tide variation. (Maris et al. 2008a)

Results on the spring-neap tide cycle at Lippenbroek

The tidal amplitude is reduced, on average, from 5.5 m in the Scheldt to 1.3 m in the pilot CRT and the high water (HW) level is about 3 m lower in the polder than in the Scheldt (Figure 10). The spring- neap tidal cycle is however maintained, the difference between spring and neap tide HW being approximately 1.0 m in the Scheldt and in the pilot CRT (Maris et al.). In contrast to estuarine marshes, in the CRT the low water levels are lowest during neap tides.

When analysing the characteristics of the inundations more in detail by calculating distribution of inundation frequencies (IF) for both the CRT and the adjacent estuarine marsh, very similar inundation frequencies (IF) are found (Maris et al.). For comparing both sites with different elevation, elevation is expressed relative to the level corresponding with an IF of 50% (Figure 11).

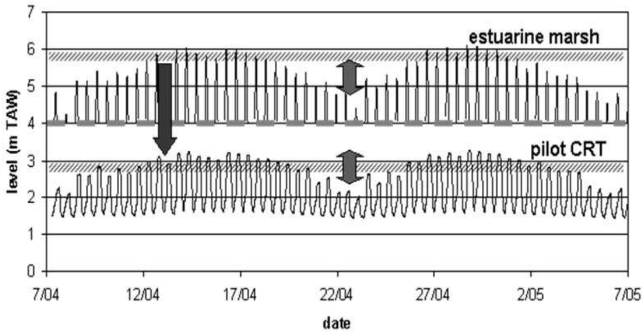


Figure 10. Tidal waves in Scheldt and the pilot CRT (Lippenbroek). Hatched areas indicate the elevation of the adjacent marsh and the mean surface elevation of the polder. The big arrow indicates the reduction of the high water levels by about 3 m. The smaller arrows show that the difference between HW spring tide and HW neap tide is preserved in the CRT. Note that for the tidal curve of the Scheldt, only the upper parts (above 4 m TAW) are shown. (Maris et al.)

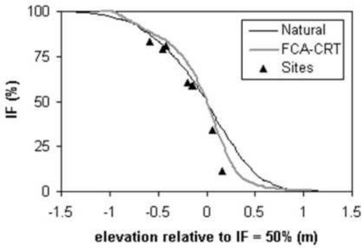


Figure 11. Inundation frequencies in the adjacent marsh and in the pilot CRT in function of elevation. Elevation is expressed relative to the level corresponding with an IF of 50%. Based on tidal data for the period March 2006 – March 2008, this IF corresponds to 5.63 m TAW on the reference marsh and 3.02 m TAW in the CRT. Black triangles represent the different research sites in the CRT.(Maris et al.)

At the scale of one single tide, some important differences with the estuarine marshes occur: after the water has entered through high inlet culverts, a stagnant high water phase develops (1-2 hours), before it evacuates through the low outlet culverts (Maris et al.), as predicted by the theory (Cox et al. 2006). The length of this phase is dependent on the elevation difference of the site with the mean high water level. The seepage phase, when water gravitationally drains from the marsh during low tides, the end of outstream can be blocked by the next flood. Both are consequences of the gravitational outlet sluice, which only opens when the water level in the river is lower than the water level within the site. This stagnant phase, together with the extreme maximal dry droughts and flooding durations, could well have consequences on sediment biogeochemistry, plant and benthos colonization and nutrient exchanges, while hampered seepage could lower the exchange capacity with the estuary.
Also, on a larger temporal scale, some important deviations from the river tides appear (Maris et al.). During neap tides, the threshold of the inlet construction might not be reached, and no flooding at all occurs. This provokes drought events, which are longer (seasonal maxima 4 to 27 days) then in adjacent river marshes (seasonal maxima 12 to 14 days). Also, prolonged flooding events occur at storm tides, provoking extreme flooding durations much higher and more variable (seasonal maxima 12 to 35 hours) then in the river marshes (seasonal maxima 3 to 7 hours).

Lippenbroek is characterised by a wide range of inundation frequencies (IF): sites with high IF (4, 5, 6), intermediate IF (1, 2, 3), low IF (7, 10), constantly flooded (8, 9).

1.3.2 Topography: Sedimentation / erosion and creek formation

Sedimentation (import of fresh sediment) is important for the development of typical marsh morphology (eg. creeks) and the typical marsh soil, which is determining for the colonization of estuarine vegetation and macrobenthos. Inadequate sedimentation when removing/breaching a polder dike could lead to only bare mudflats without marsh development. This will for example occur when tidal dynamism is too high (Maris et al. 2008a). On the other hand can sedimentation also endanger the safety function of a Flood Control Area with Controlled Reduced Tide (FCA-CRT). Strong sedimentation can lead to a loss of water storage capacity and hence oppose flood protection.
A CRT risks more sedimentation because dynamism is low (completely embanked and with reduced tide). Also, during the stagnant phase the water is stable for some hours and suspended matter can deposit. Indeed, the results show net accretion at all sites (except for sites in a tidal pool: site 8 and 9), with a variation between 0.5 and 12.5 cm/year (Figure 12) (Maris et al. , Maris et al. 2008a). At Lippenbroek, a positive relation between average elevation and inundation frequency is observed; lower sites (eg. 4 and 5) are characterised by higher inundation frequency and hence higher sedimentation rates (Figure 13a) and elevation (Figure 13b) than higher sites (eg. 7 and 10). The highest accretion rates (at sites 4 and 5) are however decreasing over time while elevation increases and corresponding inundation frequency decreases. Overall, this had led to a fast flattening of Lippenbroek. The relationship between sedimentation rate and inundation frequency is similar on Lippenbroek and the adjacent river marsh (Figure 14). Hence, sites with comparable inundation frequencies show similar accretion rates in the CRT as on the river marsh. Sedimentation rates of 1.5 to 10 cm/year at marshes in the Sea Scheldt are observed and related to variations in elevation and inundation frequency. Hence, Lippenbroek acts similar as a natural marsh. The effect of sedimentation on the water storage capacity of Lippenbroek is however not clear yet.

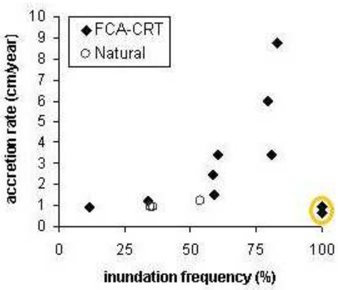


Figure 12. Average accretion rate in function of IF at the three sites on the adjacent marsh (reference sites at "De Plaat") and at all sites in the pilot CRT. Two sites have an IF of 100% (site 8 and 9), both are located in an intertidal pool (Maris et al.).

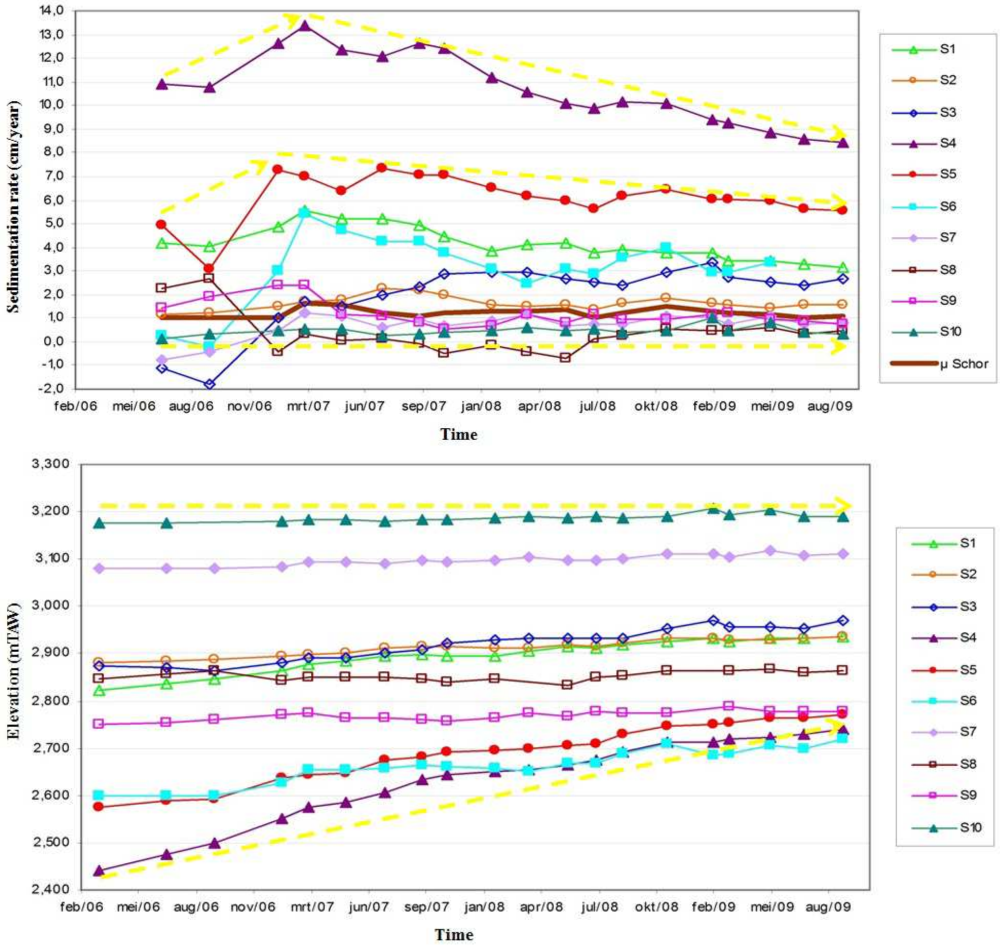


Figure 13. Comparison of sedimentation in the time at the 10 sites of Lippenbroek, February 2006-August 2009: sedimentation rate (cm/year) (a) and elevation changes (m TAW) (b) (Maris et al. , Maris et al. 2008b). Lower sites (eg. 4 and 5) are characterised by higher sedimentation rates and hence elevate much more than higher sites (eg. 7 and 10).

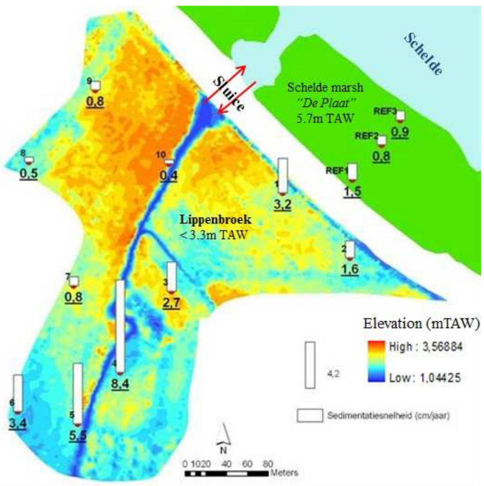


Figure 14. Spatial variation in sedimentation rate (cm/year) at Lippenbroek and the adjacent reference site (marsh "De Plaat"). The little numbers indicate the SET sites the underlined numbers is the sedimentation rate. Sedimentation rates are counted for the period between March 2006 and September 2009. The morphology of Lippenbroek is represented based on the digital elevation model of Flanders for the original polder (before the introduction of CRT in March 2006). (Maris et al. 2008b)

Besides sedimentation, also erosion occurs at Lippenbroek which results in channel and creek formation. Already during the first months, small creeks developed more or less perpendicular to the main drainage ditches (Figure 15 & Figure 16). 1029 meters of new creeks have formed three years after installing the tidal regime (December 2008), mainly at the lower sites of Lippenbroek. Newly formed creeks are relatively width (circa 1m) and shallow (0.1 to 0.35 m deep). Creek density increased from 150 m/ha to 325 m/ha.

In the pre-existing central channel, erosion was observed near the sluices (-0.8m) and sedimentation near the head (+0.5m) (Figure 17). Most deepening and accretion occurred already in the first year after the introduction of the CRT. Also, meanders are developing, converting the former drainage ditch into a natural creek. New creeks incised the compacted agricultural soil, and many of them are still deepening (Figure 18). In the zones with high sedimentation rates, small creeks are more chaotic, sometimes disappearing and often changing shape. However, once a certain depth is established, they seem to consolidate and start eroding the accreted layers and underlying soils. Creek density and drainage capacity are not yet in equilibrium with the sites' surface area and exchanged water volumes, as indicated by the on-going structural evolution. Further development will most likely result in a flat marsh platform (merlons), incised by creeks (krenels) (Figure 18).

After 2008, no significant changes in the thalweg elevation of the main creek were observed (survey 2010). This suggests that (1) after the implementation of Lippenbroek as a FCA with CRT in 2006, in a period of three-year time (2006-2008), some important morphologic changes occurred in the main creek near the sluice; (2) the main creek near the sluice has reached a kind of quasi-balanced state with respect to coupled sedimentation-erosion processes in the last two years (2008-2010). Lateral creeks however further developed: It can be clearly observed that erosion has been taking place close to the sluice in the lateral creek 1 (up to -0.15 m) and even a bit stronger in the lateral creek 2 (up to -0.25 m), while sedimentation has been going on in the lateral creek 3 for about 0.1-0.2 m.

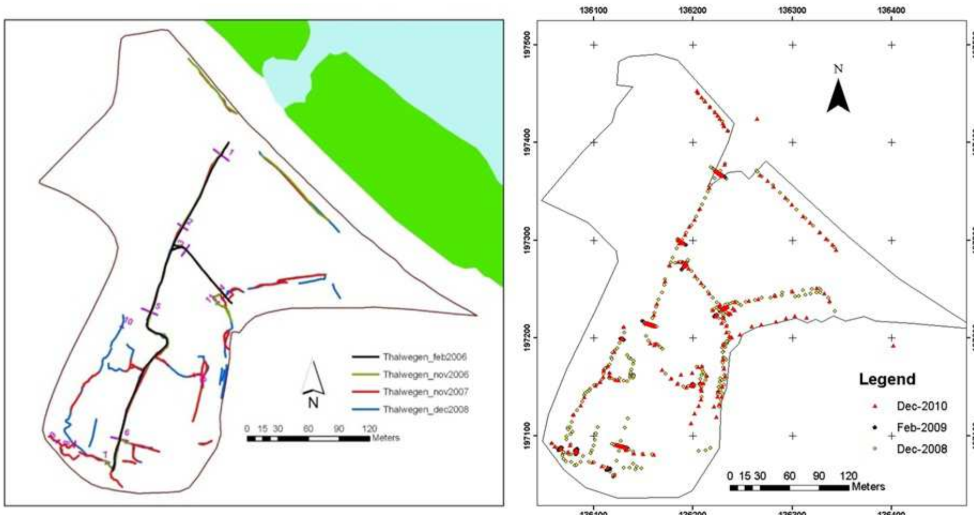


Figure 15. Left: Planimetric evolution of the creek network at Lippenbroek, March 2006-December 2008. Right: Topographic surveys performed in December 2010 (VUB-HYDR), February 2009 (UA-Ecobe), and December 2008 (UA-Ecobe) at Lippenbroek. Thalweg elevation was used as a measuring criterion for the monitoring of various creek developments.

Figure 16. Development of a creek in the CRT Lippenbroek. White square indicates position of the same stick in every photo. Note the deepening of the creek, decrease of stagnant water surface in the background, and emergence of mudflats and meandering structures.(Maris et al.)

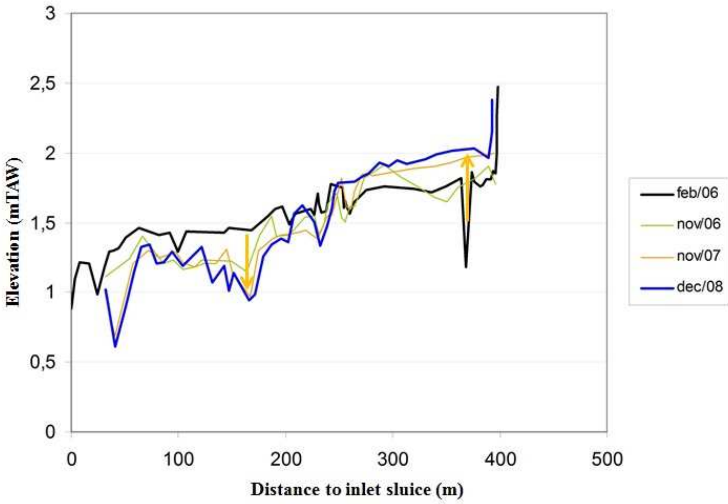


Figure 17. Vertical evolution of the main creek in the pilot CRT Lippenbroek, March 2006 – December 2008 (Maris et al. , Maris et al. 2008b).

Figure 18. Topographic structures in the CRT. Left: new developed creek. Right: typical merlon-krenel topography (Maris et al.).

1.3.3 Water and sediment quality

The influence of a CRT on water quality (oxygen and nutrients) is also monitored.

Oxygen: The pilot CRT never faced problems with anoxia because the inflow wave aerated the (often) oxygen poor Scheldt water (increase up to circa 60% oxygen saturation). This is followed by surface aeration: by spreading the water in a thin layer over the polder surface, a good contact with air results in a high oxygen transfer. In all seasons and weather condition, minimum oxygen saturation between 60% and 80% is reached. On the contrary, on sunny days, super saturation was recorded.

Nutrients: Lippenbroek plays, just like natural marshes, an important role as sink for nitrogen and source for dissolved silica. Retention of nitrogen and phosphorus is regarded as a potentially important process since it could partially compensate for excessive anthropogenic inputs of these nutrients. As detailed research on exchange mechanisms is ongoing, we can only conclude that monitoring results so far indicate no significant differences between the recorded CRT deliveries and earlier observations in river marshes (Van Damme et al. 2009) (

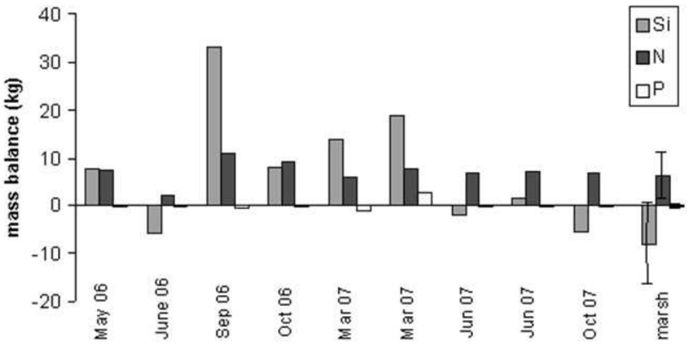


Figure 19).

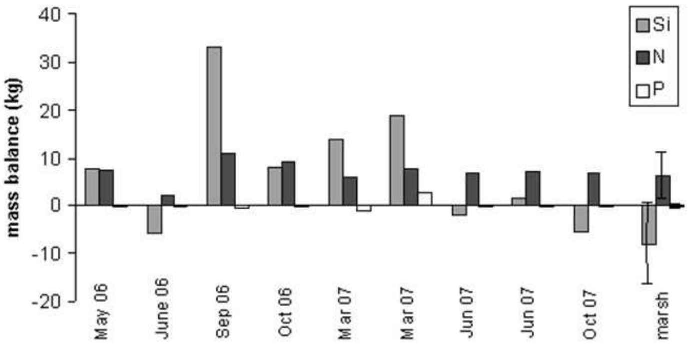


Figure 19. Mass balances for dissolved silica (Si), Total Dissolved Nitrogen (N) and Phosphate-P (P) for every tidal campaign in the CRT and for the Scheldt estuarine marsh (marsh) (Van Damme et al. 2009). Positive values indicate retention, negative delivery.

Heavy metals: Historical Scheldt sediment contaminated Lippenbroek with heavy metals. During the last decennia the sediment quality in the Scheldt had improved, the CRT functioning resulted in burying of contaminated sediment layers under a sediment layer with considerable lower heavy metal concentrations (Maris et al. 2008a). Furthermore, heavy metals that were present in the soil became less bioavailable because of changes induced by the floods.

1.3.4 Vegetation

After two years of controlled reduced tide, typical tidal freshwater vegetation has been restored in a former agricultural site. Establishment of an intertidal plant community in the CRT site was quick, with fast eradication of terrestrial species and colonisation by tidal freshwater marsh species already during the first few months. Moreover, communities which have mostly disappeared along the degraded Scheldt, but are described for several historic European references, are establishing in the pilot site. Presence of initial terrestrial vegetation slowed down establishment at higher as well as lower locations. The vegetation monitoring shows drastic movements in the favour of hydrophyte species. A dense vegetation cover with co-dominating ruderal species (Great hairy willow-herb (*Epilobium hirsutum*) and Stinging Nettle (*Urtica dioica*)) established on the abandoned and fertile agricultural land during the two year building period, and did this in a fairly homogenous way over the elevation gradient. After installation of the tidal regime, ruderal dominants were eliminated and replaced by a less dense hydrophyte and wetland pioneer vegetation. Colonisation by Purple loosestrife (*Lythrum salicaria*), Bulrush (*Typha latifolia*), Speedwell (*Veronica*), Common reed (*Phragmites australis*) and willow (*Salix*) has started (Figure 20), while at other sites the vegetation coverage moved for bare mudflat.

Vegetation communities seem to deviate from the nearby tidal freshwater marshes, but show similarities with tidal freshwater marshes described for the beginning of the 20th century. The CRT-technique provides strong potential for durable, adaptive restoration of tidal marshes on sites with low elevation. Wider implementation of the CRT technique could increase the total surface of tidal freshwater marshes with fully developed vegetation gradients.

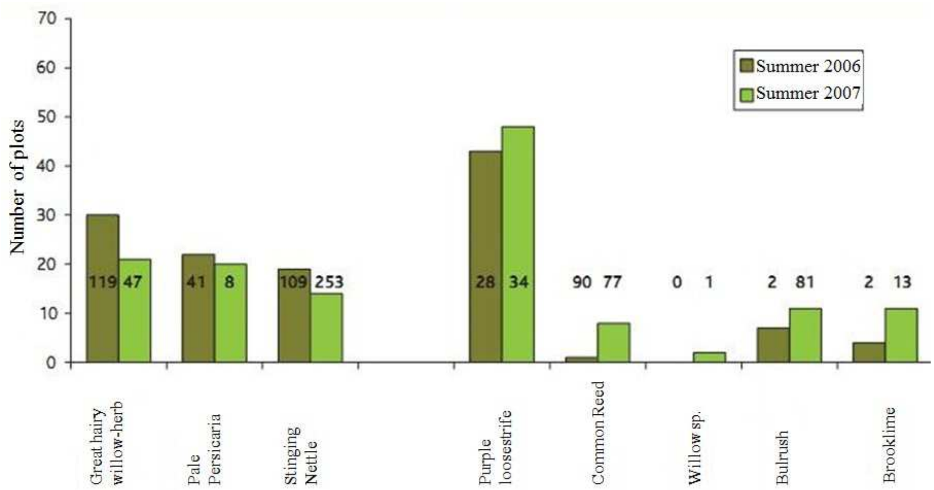


Figure 20. Appearance (number of plots) of some characteristic species at Lippenbroek in the summer of 2006 and 2008. In total 70 plots were monitored (10 sites with 7 plots). The left handed species are terrestrial species; right the more fresh-estuarine species. The number at each bar indicates the average coverage rate. To calculate the average, only the plots where the specie appears, is counted for. (Maris et al. 2008a)

1.3.5 Macroinvertebrates

The first estuarine macroinvertebrates were observed after three months of tidal inundation. After one year taxonomic richness on the frequently flooded sites exceeded the richness observed in the river sites, and alike the vegetation development, taxa which are absent in the river are observed to establish in the CRT. Oligochaete densities six fold exceed the river site densities. After three years, macroinvertebrate colonization continues, albeit with lower pace, on the less frequently flooded sites.

1.3.6 Fish

Flood control areas are important breeding, foraging and nursery areas for fish. A safe passage through the sluices of the CRT is therefore crucial. Apparently, fish mainly enters Lippenbroek via the outlet sluice (oxygen rich water stream). Because the outgoing discharge rapidly increases, fish passage is assumed to be possible only during a limited period of time after outflow starts. Adaptations of the tidal gate are investigated to broaden the time frame for fish passage.

1.3.7 Birds

Despite high disturbance (terrain visits, monitoring campaigns, cyclers and hikers on the dike), a clear positive evolution in the number and diversity of bird species was observed at Lippenbroek. In total, 98 species were inventoried, of which 30% aquatic bentivores (19 species), 54% wetland generalists (11 species), 8% terrestrial species (18 species) and 8% forest species (13 species).

2 Execution of main effectiveness criteria

2.1 Effectiveness according to development targets of measure

Step 1: Definition of development target

The creation of a Flood Control Area with Controlled Reduced Tide (FCA-CRT) aims to develop an intertidal area that is qualitatively and quantitatively similar to outer-dike intertidal habitat. For Lippenbroek the objective was more specifically to restore tidal freshwater marsh habitat in an agricultural site where elevation relative to the estuarine marshes has lowered. Different processes (eg. tidal cycling; nutrient processing Si, N, P, O; and Sedimentation) and structures (eg. tidal marsh topography; tidal marsh vegetation; tidal marsh fauna) are monitored and studied since the opening of the CRT to analyse the functionality of the FCA-CRT. In fact, Lippenbroek is a pilot project for all other planned FCA-CRT such as Kruibeke-Bazel-Rupelmonde.

Step 2: Degree of target achievement

Overall, Lippenbroek started functioning as freshwater intertidal habitat since the introduction in March 2006 and hence was successful. The pilot test proved that also an embanked area that is not suitable for basic managed realignment (because it is situated too low in reference to the water levels in the estuary) can be restored by a FCA with CRT. Therefore this technique increases the number of suitable sites and avoids problems with suboptimal tidal regimes and artificial elevation increase with dredged material.

- The CRT construction (high inlet and low outlet) results in a normal tidal dynamism, however high tides are flattened (stagnant phase). Monitoring now shows that the development of an estuarine ecosystem is not hampered by prolonged inundation times when inundation height is limited (Maris et al.).
- A high sedimentation rate was monitored in Lippenbroek as well as erosion and the formation of a channel and creek network. This is positive for the creation of typical tidal marsh topography but can form a risk for the safety aspect of the FCA (storage capacity of the area). It is however too early to conclude about the effect on the safety aspect. Also at Lippenbroek, creek density and drainage capacity are not yet in equilibrium as indicated by the on-going structural evolution. Further development will most likely result in a flat marsh platform (merlons), incised by creeks (krenels, Figure 18).
- An important advantage of the high inlet sluice is that is aerates the incoming and often oxygen poor Scheldt water so that the pilot CRT never faced problems with anoxia. If hypoxia ever prevails in the estuary, which is not unlikely to occur in the Scheldt, a CRT will act as an oxygen rich refugia (Maris et al.). Also, the shallow water depth and low dynamics create a more favourable light climate in the CRT than within the estuary, so primary production is assumed to be much higher (Maris et al.).
- Nutrient processing (nitrogen, phosphorus and silica) was shown to be comparable in the CRT as in river marshes. CRTs act, just like estuarine marshes, as a sink for nitrogen. Lippenbroek shows a nitrogen removal of 1.0 kg/ha/tide with a sedimentation rate of approximately 30 mm/year on average (Maris et al.).
- The effect of Lippenbroek on the water quality of the Scheldt estuary is however not measurable since the pilot project is too small. Model measurements and the results of the pilot study however indicates that larger CRT areas (like Kruibeke-Bazel-

Rupelmonde) could significantly improve the Scheldt ecosystem (Maris et al. 2008a).

- Shortly after the construction, an intertidal plant community established with fast eradication of terrestrial species and colonisation by tidal freshwater marsh species (Jacobs et al. 2009). Also the presence of bird and fish species indicates the installation of a fully developed intertidal ecosystem. This proofs that the prolonged inundation times when inundation height is limited (stagnant phase) does not hamper the colonisation by fauna and flora (Maris et al. 2008a). Furthermore, in the CRT sites which are currently being built (eg. Kruibeke-Bazel-Rupelmonde), biota is expected to develop even better as the habitat will be larger, less disturbed and more variable [3].

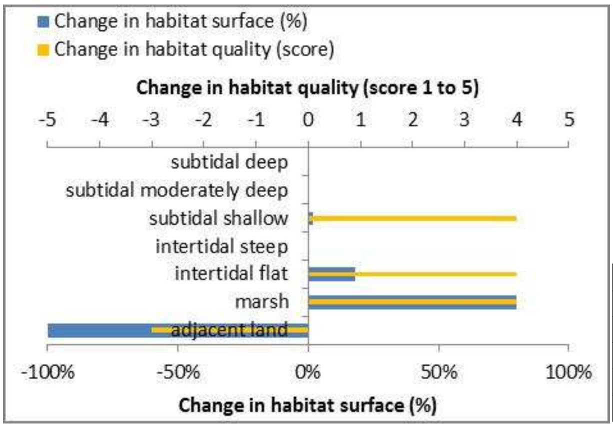
2.2 Impact on ecosystem services

Step 1: Involved habitats

The measure Lippenbroek in the freshwater zone of the Scheldt estuary was about the creation of intertidal habitat by transforming adjacent land into mainly marshland with a high change in the habitat quality (Figure 21).

Before the CRT construction, Lippenbroek was an agricultural field (mainly maize and potatoes) with also small area of poplar planting and salix wood.

After construction an intertidal ecosystem with marsh and intertidal flat habitat developed. The share of marsh habitat increased in the years after the construction. In autumn 2009 around 80% of the area was covered by marsh habitat (based on (Maris et al. 2008b)). The other 20% was intertidal flat habitat and shallow water (channels and creeks).



Score habitat quality
1 = very low quality
2 = low quality
3 = medium quality
4 = high quality
5 = very high quality

Figure 21. Ecosystem services analysis for Lippenbroek: Indication of habitat surface and quality change, i.e. situation before versus after measure implementation. The change in habitat quality, i.e. situation after the measure is implemented corrected for the situation before the measure, is '1' in case of a very low quality shift, and '5' in case of a very high quality shift.

Step 2: Expected impact on ecosystem services, compared with targeted ecosystem services, and expected impact on beneficiaries

More information about the methodology and the correct interpretation of the results could be found in the overall measures report (Saathoff et al. 2013).

(1) Overall expected impact on ES:

From the ES assessment it is concluded that this measure generates overall a positive expected impact for many ES, mainly for “biodiversity”, cultural service (Aesthetic information), and some regulating services (Erosion and sedimentation regulation (by water bodies); Water quality regulation: reduction of excess loads coming from the catchment; Climate regulation: Carbon sequestration and burial; Regulation extreme events or disturbance: Flood water storage).

Because the site is not directly linked with the estuary (sluice in between), some ES are not relevant such as Wave reduction and Water current reduction (indicated between brackets).

(2) Expected impact on targeted ES

The expected impact for the three development targets (“biodiversity”, “Regulation extreme events: flood water storage” and “Information for cognitive development”) is positive to very positive.

(3) Expected impact on beneficiaries

The expected impact for the different beneficiary groups is overall positive, with a very positive expected impact for future use and for local use.

Table 1. Ecosystem services analysis for Lippenbroek: (1) expected impact on ES supply in the measure site and (2) expected impact on different beneficiaries as a consequence of the measure. ES which are not relevant in the local context are between brackets.

Lippenbroek - flood control area with controlled reduced tide (FCA-CRT)

Cat.	Ecosystem Service	Score
S	"Biodiversity"	3
R1	Erosion and sedimentation regulation by water bodies	3
R2	Water quality regulation: reduction of excess loads coming from the catchment	3
R3	Water quality regulation: transport of polutants and excess nutriënts	0
R4	Water quantity regulation: drainage of river water	0
R5	Erosion and sedimentation regulation by biological mediation	2
R6	Water quantity regulation: transportation	0
R7	Water quantity regulation: landscape maintenance	2
R8	Climate regulation: Carbon sequestration and burial	3
R9	Water quantity regulation: dissipation of tidal and river energy	0
(R10)	(Regulation extreme events or disturbance: Wave reduction)	1
(R11)	(Regulation extreme events or disturbance: Water current reduction)	1
R12	Regulation extreme events or disturbance: Flood water storage	3
P1	Water for industrial use	0
P2	Water for navigation	0
P3	Food: Animals	0
C1	Aesthetic information	3
C2	Inspiration for culture, art and design	2
C3	Information for cognitive development	2
C4	Opportunities for recreation & tourism	2

Beneficiaries:	
Direct users	0
Indirect users	2
Future users	3
Local users	3
Regional users	2
Global users	1

X Targeted ES

Legend: expected impact*	
3	very positive
2	positive
1	slightly positive
0	neutral
-1	slightly negative
-2	negative
-3	very negative

*: Indicative screening based on ES-supply surveys and estimated impact of measures on habitat quality and quantity. Quantitative socio-economic conclusions require local supply and demand data to complement this assessment.

2.3 Degree of synergistic effects and conflicts according to uses

Throughout the world, tidal marshes are being restored to obtain natural protection against recurring storm surges and sea level rise and to preserve the resources these habitats provide [6]. Furthermore, this technique enhances opportunities to combine different societal functions (safety, agriculture, ecology, inhabitation…) in coastal defence schemes and will increase the public acceptability and political willingness to implement coastal defence schemes (French 2006, Weinstein 2007) [6].

However, a possible conflict is related to the high sedimentation at Lippenbroek. On the one hand this is positive from an ecological point of view (diverse morphological topography) but on the other hand this could be negative for the water storage capacity of the area. Monitoring showed a net sedimentation on the site and hence a loss of the safety function. Measures are taken to try to minimise sedimentation to an acceptable level for safety. How this will work on the long term is still uncertain at Lippenbroek.

The public acceptance during implementation was medium because there are no neighbours and little was known about the project. Only few conflicts were observed. After implementation, a lot of positive reactions followed. For example, some municipalities included Lippenbroek in touristic brochures. However, also negative reactions were given by people that fear that such a FCA-CRT will be installed in their backyard (but often with people that have not visited the site yet).

3 Additional evaluation criteria in view of EU environmental law

3.1 Degree of synergistic effects and conflicts according to WFD aims

The construction of a Flood Control Area with Controlled Reduced Tide can attribute to five of the six main pressures in the freshwater zone of the Scheldt. However, Lippenbroek is only a small scale pilot project (8 ha). The real effect of Lippenbroek to the Scheldt estuary is hence minimal. The main objective of Lippenbroek was also limited to the research aspect. Lessons learned from Lippenbroek are now used in the large scale project Kruibeke-Bazel-Rupelmonde (KBR).

Indicator	code	Main pressures **freshwater** zone Scheldt	Effect?					Description
			- -	-	0	+	++	
S.I.	1.1	Habitat loss and degradation during the last about 100 years: Intertidal					X	Restoration of intertidal ecosystems.
S.I.	1.5	Gross change of the hydrographic regime during the last about 100 years					X	At larger scale, a FCA-CRT can contribute to the hydrographic regime of the estuary (eg. water storage capacity and safety function)
S.I.	3.1/3.2	Decrease of water and sediment chemical quality					X	Nutrient processing and aeration in a CRT can improve water and sediment quality (at larger scale).
D.I.	1.3	Land claim during the last about 100 years					X	Land is given back to the estuary.
D.I.	1.7	Relative Sea Level Rise					X	A FCA-CRT can attribute to protect the adjacent area against sea level rise (at larger scale).
D.I.	2.4	Maintenance dredging			X			Sedimentation in the FCA-CRT could theoretically reduce the sediment load in the estuary, but the effect is very small and sedimentation in the FCA-CRT is limited to conserve the flood control function. Furthermore, the navigability in the estuary is not influenced by the FCA-CRT and with the ever larger ships maintenance dredging will be still crucial in the future.

S.I. = state indicator; D.I. = driver indicator

3.2 Degree of synergistic effects and conflicts according to Natura 2000 aims

The construction of a FCA-CRT is an important mechanisms to contribute to the restoration (and creation) of freshwater tidal wetlands. Also, several rare and endangered bird species are regularly foraging in the Lippenbroek CRT.

CO	Details	Effect?					Description
		- -	-	0	+	++	
HD: Scheldt- and Durme-estuary from the Dutch boarder to Ghent (BE2300006)	Tidal freshwater wetland					X	Newly created freshwater tidal wetland in the protected area BE2300006, and quality improvement for this type of habitat.

BD: Durme and the mid streams from the Scheldt (BE2301235)	Birds					X	In total, 98 species were inventoried, of which 30% aquatic bentivores (19 species), 54% wetland generalists (11 species), 8% terrestrial species (18 species) and 8% forest species (13 species).

4 Crux of the matter

Tidal marsh restoration with a FCA-CRT construction can happen very fast and spontaneously. The inlet sluice has to be situated sufficiently high to allow sufficient differences in inflow duration and volume and thus to create a large variation in inundation frequencies and water levels in the polder.

The inundation curve is different than in natural intertidal areas (duration is longer, and has three phases: ebb, stagnant and flood) but this does not obstruct the colonisation by fauna and flora. Initial terrestrial vegetation slowed down the establishment of estuarine species and thus removal before culvert opening could decrease this impact. The area is however too small to influence measurably the water quality of the Scheldt.

Based on the Lippenbroek pilot project, a lot of scientific insight was generated with respect to FCA-CRT and with intertidal mudflat and marsh in general.

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