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LIFE Sparc

action D1 (General scientific assessment) – T1 report

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LIFE Sparc

action D1 (General scientific assessment) – T1 report

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The Life Sparc project has received funding from
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Abstract

Within the LIFE Sparc project, 8 sigma areas are being developed to serve as climate buffers and 428 hectares of freshwater tidal nature.

This report contains the contribution to action D1 (scientific reporting), specifically the T1 reporting at the end of the project.

Because not all areas have been developed, the assessment of expected ecosystem services (chapter 5), and of estuarine habitat evolution and associated sedimentation (chapter 6) is done based on models that were calibrated on past experience in the Scheldt.

The LIFE Sparc areas and their effects on the Scheldt estuary will be monitored following the existing systemic monitoring protocol which is described in chapter 7

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1 Abbreviations

Abbreviation	Meaning
CRT	Controlled Reduced Tide (GGG in Dutch)
dVW	De Vlaamse Waterweg (in Dutch)
ET	Exposure Time
DSi	Dissolved Silicon
FCA	Flood Control Area (GOG in Dutch)
HW	High Water
INBO	Research Institute for Nature and Forest Instituut voor Natuur- en Bosonderzoek (in Dutch)
LW	Low Water
MR	Managed Realignment
OMES	Research on Environmental Effects within the framework of the Sigma Plan Onderzoek naar de Milieueffecten in het kader van het Sigmaplan (in Dutch)
SET	Surface Elevation Table
TAW	Tweede Algemene Waterpassing (in Dutch) Vertical reference datum in Belgium
TDIN	Total Dissolved Inorganic Nitrogen
VLIZ	Flanders Marine Institute Vlaams Insitituut voor de Zee (in Dutch)
WFD	Water Framework Directive

2 Introduction

2.1 LIFE

The LIFE programme is the EU's funding instrument for the environment and climate action. The general objective of LIFE is to contribute to the implementation, updating and development of EU environmental and climate policy and legislation by co-financing projects with European added value.

The European Commission (DG Environment and DG Climate Action) manages the LIFE programme.

The LIFE 2014-2020 Regulation (EC) No 1293/2013 was published in the Official Journal L 347/185 of 20 December 2013. The Regulation establishes the Environment and Climate Action sub-programmes of the LIFE Programme. The 'Environment' strand of the new programme covers three priority areas: environment and resource efficiency; nature and biodiversity; and environmental governance and information. The 'Climate Action' strand covers climate change mitigation; climate change adaptation; and climate governance and information.

This project falls under Climate Change Adaptation.

From the LIFE 2014-2020 Regulation, article 15:

> Specific objectives for the priority area Climate Change Adaptation
>
> With a view to contributing to supporting efforts leading to increased resilience to climate change, the priority area Climate Change Adaptation shall in particular have the following specific objectives:
>
> (a) to contribute to the development and implementation of Union policy on climate change adaptation, including mainstreaming across policy areas, in particular by developing, testing and demonstrating policy or management approaches, best practices and solutions for climate change adaptation, including, where appropriate, ecosystem-based approaches;
> (b) to improve the knowledge base for the development, assessment, monitoring, evaluation and implementation of effective climate change adaptation actions and measures, prioritising, where appropriate, those applying an ecosystem-based approach, and to enhance the capacity to apply that knowledge in practice;
> (c) to facilitate the development and implementation of integrated approaches, such as for climate change adaptation strategies and action plans, at local, regional or national level, prioritising, where appropriate, ecosystem-based approaches;
> (d) to contribute to the development and demonstration of innovative climate change adaptation technologies, systems, methods and instruments that are suitable for being replicated, transferred or mainstreamed.

2.2 LIFE Sparc

2.2.1 Project

LIFE Sparc is a project under the LIFE programme (project number LIFE16 CCA/BE/000107). Sparc is the acronym for "Space for Adapting the River Scheldt to Climate Change". The project runs from 01/09/2017 till 31/08/2025.

The project partners are:

- Agentschap voor Natuur en Bos (coordinating beneficiary)
- Eigen Vermogen Flanders Hydraulics
- Flanders Hydraulics (WL)
- Regionaal Landschap Schelde-Durme
- De Vlaamse Waterweg (dVW)

2.2.2 Background

Climate change entails raising sea levels and increasing risks from extreme weather phenomena. The Scheldt estuary (Belgium) is highly vulnerable to flooding because of its open connection to the sea, its funnel-shape and surrounding low-lying land, especially when high tides coincide with heavy rainfall. The Scheldt is laden with sediment, so tidal marshes are systematically rising along with high waters. Consequently, the transition to the waterway is becoming steeper (squeeze). The steep tidal marshes risk being eroded. As a result, protected freshwater mud flat and tidal marsh habitats, which are rare in Europe, are disappearing. These habitats also provide important ecosystem services.

Financial damage from flooding in the Scheldt estuary can exceed €50 million on an annual basis. In the Belgian part of the estuary (the tide-affected area) there are approximately 720 000 inhabitants and 10 000 businesses situated in low-lying areas at potential risk of flooding. In the port of Antwerp, where economic activity is concentrated, the consequences of a flood could be disastrous. Serious flooding would also affect inland waterways.

2.2.3 Objectives

The LIFE Sparc project proposes measures to make the Scheldt estuary and its highly urbanised area more resilient to climate change. In practice, this means providing much greater protection against flooding by creating open space for water and developing a robust estuarine ecosystem. More specifically, the project has the following goals:

1. Reduce flood risk using nature-based solutions appropriate to tidal rivers, in line with the EU Floods Directive, such as the construction of flood areas that can safely fill with water during flood events, thereby decreasing water levels on the river and reducing the risk of flooding in urban areas;
2. Restore habitats to make the ecosystem more resilient to the effects of climate change, and enabling tidal mud flats and freshwater tidal marshes to develop in line with the Habitats Directive. The aim is for the restored sites to form a network, to improve the implementation of the Habitats and Birds directives and to act as green infrastructure ('corridors') to give species greater opportunity for movement;
3. Reinforcing public support, by actively engaging stakeholders and the general public, and sharing knowledge. Opportunities in the field of recreation and tourism will also be taken to boost the local economy; and
4. Demonstrating the transferability and replicability of new techniques for nature-based solutions appropriate to tidal rivers.

2.2.4 Areas

The specific locations chosen in this project (C1 until C8, see Figure 1) are all located in the area where the most critical water levels occurred during the last dangerous storm (6/12/13).

- Depoldering Uiterdijk (C1, 11ha)
- Depoldering Groot Schoor Hamme (C2, 26ha)
- Depoldering Groot Schoor Bornem/Hingene (C3, 23ha)

- Depoldering Groot Broek (C4, 58ha)
- Depoldering Klein Broek (C5, 38ha)
- Construction of Flood Control Area with Controlled Reduced Tide (FCA CRT) ‘Vlassenbroek’ (C6, 91ha)
- Construction of FCA CRT ‘Wal Zwijn’ (C7, 148ha)
- Construction of FCA CRT ‘De Bunt’ (C8, 99ha)

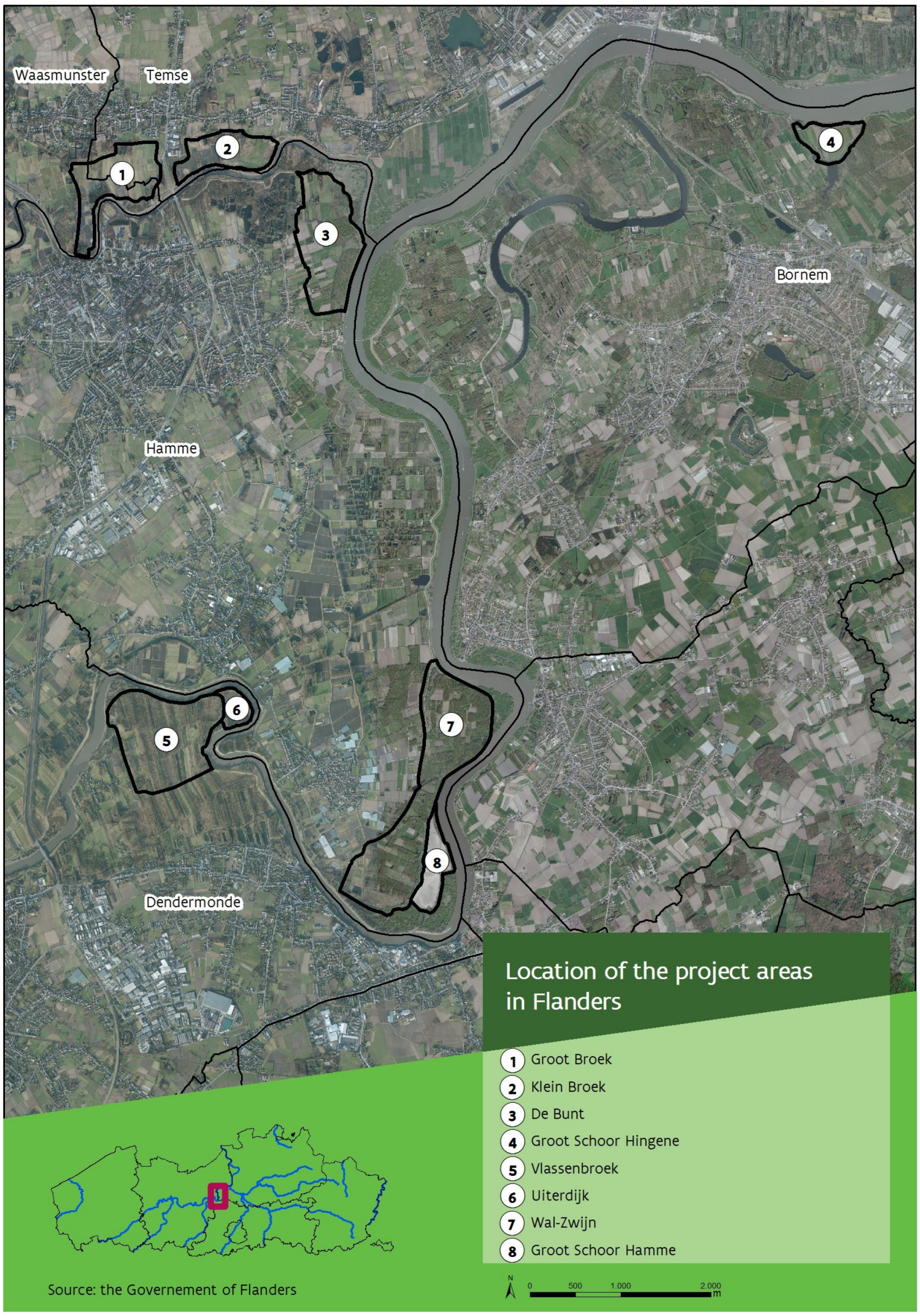

Figure 1 - Location of the 8 project areas (Source: project proposal LIFE Sparc).
Note that the numbering is different than the numbering of the C actions

For depoldering ‘Uiterdijk’ (action C1, area 6 in Figure 1), 11ha of tidal nature will be created by 2026 by lowering the old Scheldt dyke to ground level.

For depoldering ‘Groot Schoor Hamme’ (action C2, area 8 in Figure 1); 26 ha of tidal nature was developed in 2021 by lowering the Old Scheldt dyke over 1500m and digging an onset of creeks.

For depoldering 'Groot Schoor Hingene' (action C3, area 4 in Figure 1), 23ha of tidal nature will be created by 2026 by creating a ring dyke, and making a 100m wide opening in the old Scheldt dyke.

For depoldering 'Groot Broek' (action C4, area 1 in Figure 1), 58ha of tidal nature is to be created in 2026 by lowering the Durme dike over 1200m and creating 2 openings: one of 30m and one of 100m.

For depoldering 'Klein Broek' (action C5, area 2 in Figure 1), 38ha of tidal nature is to be created by 2026 by lowering the Durme dyke over a distance of 1000m and creating two openings: one of 40m and one of 60m.

For the Flood Control Area with Controlled Reduced Tide (FCA CRT) 'Vlassenbroek' (action C6, area 5 in Figure 1) 91ha of tidal nature was created in 2024 by building a northern inlet and outlet sluice, and digging the onset of a creek. Currently only a limited amount of water passes through the in- and outlet sluice, the area is expected to be fully operational in 2026.

For the FCA CRT 'Wal Zwijn' (action C7, area 7 in Figure 1) 148ha of tidal nature was created in 2025 by building two inlet and outlet sluices

Construction of FCA CRT 'De Bunt' (action C8, area 3 in Figure 1) 99ha of tidal nature will be created in 2026 (source De Bunt | Sigmaplan) by building an inlet and outlet sluice and digging the onset of a creek. The main works are already finished in 2025, but the connection to the Durme still needs to be dredged.

2.3 Action D1: General scientific assessment of the habitat restoration and effects on water management

The assessment of the effects on water management consists of tracking hydrodynamic and physical parameters such as water levels, sedimentation and erosion and water quality.

For reasons of efficiency, we aim for the extension of existing monitoring programs to monitor the effects of this project.

For the monitoring of various parameters in and around the tidal Scheldt (Western Scheldt and Sea Scheldt), we will call on the Flemish-Dutch monitoring program (MONEOS) MONitoring Effecten Ontwikkeling-Schets (MONitoring of Effects Development Outline): comprehensive monitoring performed in the mouth of the Scheldt estuary, in the Western Scheldt (Dutch part of the estuary) and in the Sea Scheldt (Flemish part). The LIFE project area is entirely situated inside the field of operation of these ongoing programs, making them perfectly useable to monitor the efficacy of the actions proposed under the LIFE project.

The hydrodynamics, the physical parameters as well as some biotic parameters are to be monitored by MONEOS. MONEOS has been designed to meet the aims of various policy frameworks, and to deliver insights into the system function of the Scheldt estuary and the effects of interventions/measures in the system. The bulk of the parameters has been measured for decades. As such, the MONEOS data provide a clear picture of the status and the changes in the tidal Scheldt. For water management for example, elements monitored include water levels, upstream discharge, temperatures, conductivity, chloride levels, current flows (incl. water flow rate and direction of currents), turbidity and suspended sediment concentrations of the Scheldt water. The current elevation of the project areas has already been measured using laser-altimetric airborne surveys (LiDAR).

3 Expected effect on tidal propagation

3.1 Effect on high waters during storm (Mike11)

The effects of the LIFE Sparc areas on storm wave propagation was calculated using the Mike11 model of the Scheldt which is typically used in the design and assessment of sigma areas. The calculations are described in the memo from Coen, L. (2016b).

3.1.1 The 1D model

The 1D model that was used for this scenario analysis is described in Coen et al. (2016a) and is briefly summarised here.

The model covers the entire Western Scheldt and Sea Scheldt, the tidal arm of the Scheldt in Ghent downstream of Gentbrugge, the eastern section of the Ringvaart around Ghent, and the tidal arm up to Zwijnaarde. The entire stretch of the Western Scheldt and Sea Scheldt from the mouth at the North Sea (Vlissingen) up to Liefkenshoek is represented using a quasi-2D model, in which the flood channels and ebb channels are modeled as separate branches. These branches are interconnected by so-called 'link channels,' which represent the transverse channels that (via the sandbanks) interconnect the various channels. This quasi-2D approach allows for the explicit consideration of the different phenomena occurring during ebb and flood, as the channels and branches are not affected to the same extent. The Durme is included in the model from the dam at Lokeren to the mouth in the Sea Scheldt. In the basins of the Dijle, Nete, and Demer, all waterways classified as 'navigable' are included in the model. In addition, some (sections of) first-category waterways are represented.

The software used for the 1D hydrodynamic calculations is Mike11, version 2012 SP3 (DHI, 2012).

The model files used for the scenario calculations are stored in the version control system under:

https://wl-subversion.vlaanderen.be/svn/repoSpNumMod/MIKE11/Sigma/Sigma20161118_15_091

3.1.2 Synthetic boundary conditions

The scenario calculations are performed for composite storms with return periods of 1, 10 and 100 years. These composite storms always consist of two parts. In the first part, during the storm period, the water level on the waterways is raised by wind setup from the downstream boundary of the model at Vlissingen. In the second part of the composite storm, during the wash period, the water level is increased by elevated upstream discharge from the upstream boundaries of the model.

3.1.3 Results

Figure 2 to Figure 4 present longitudinal profiles with maximum water levels for the different scenarios during composite storms with return periods of 1, 10 and 100 years.

The results are stored on

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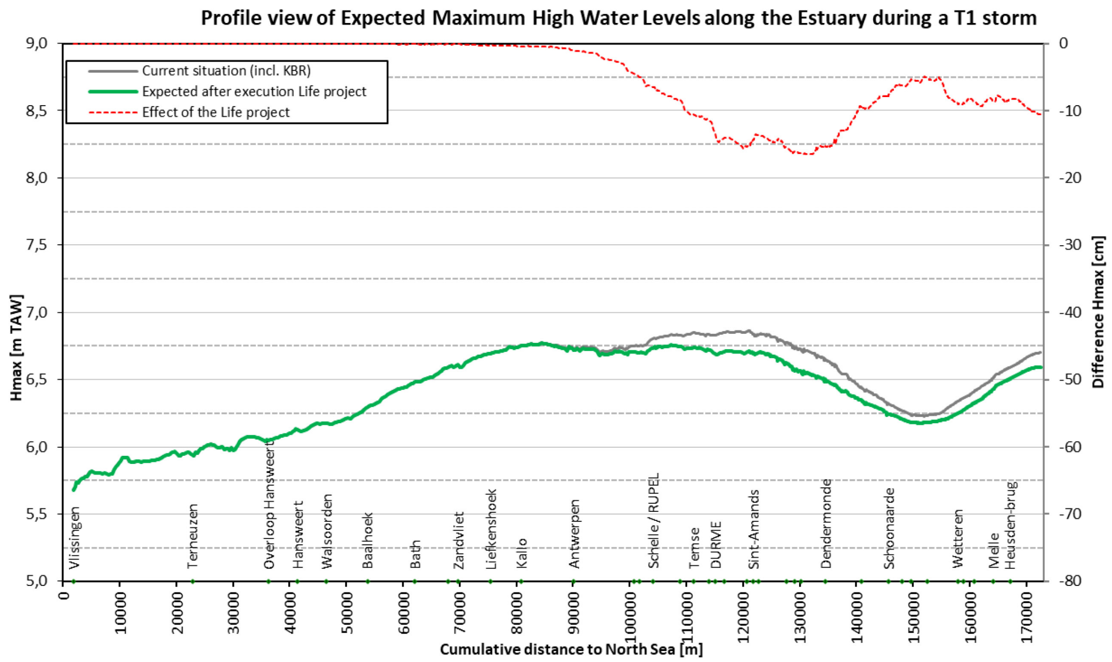

Figure 2 - Profile of HMAX during a T1 event, both with (green) and without (grey) the LIFE Sparc areas. Effect on HMAX (red dashed) on right axis

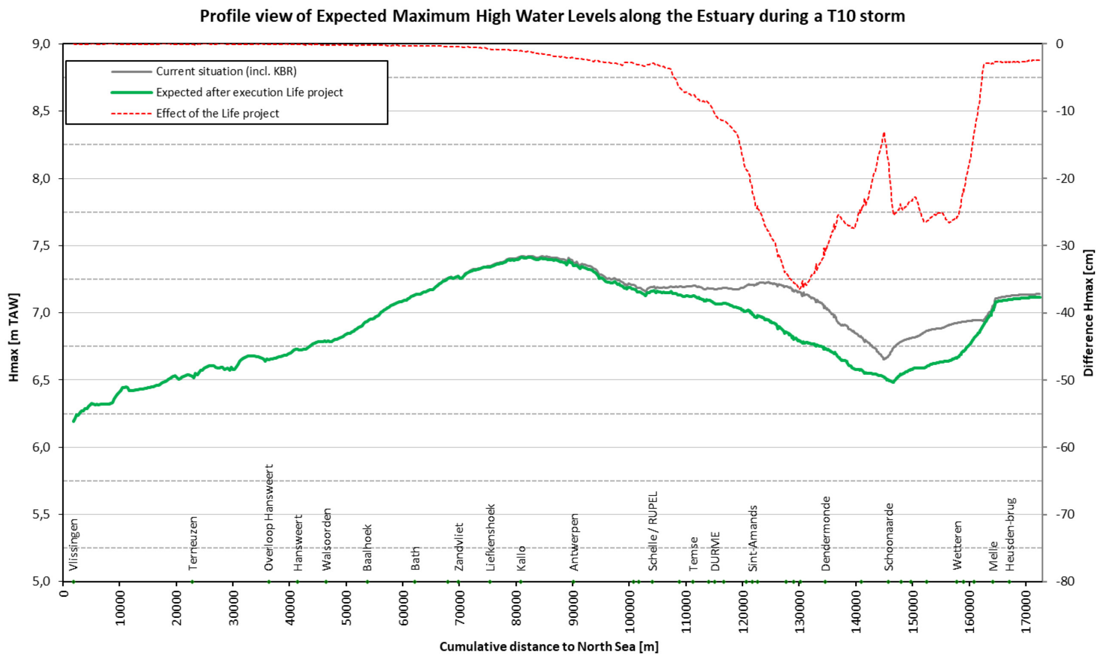

Figure 3 - Profile of HMAX during a T10 event, both with (green) and without (grey) the LIFE Sparc areas. Effect on HMAX (red dashed) on right axis

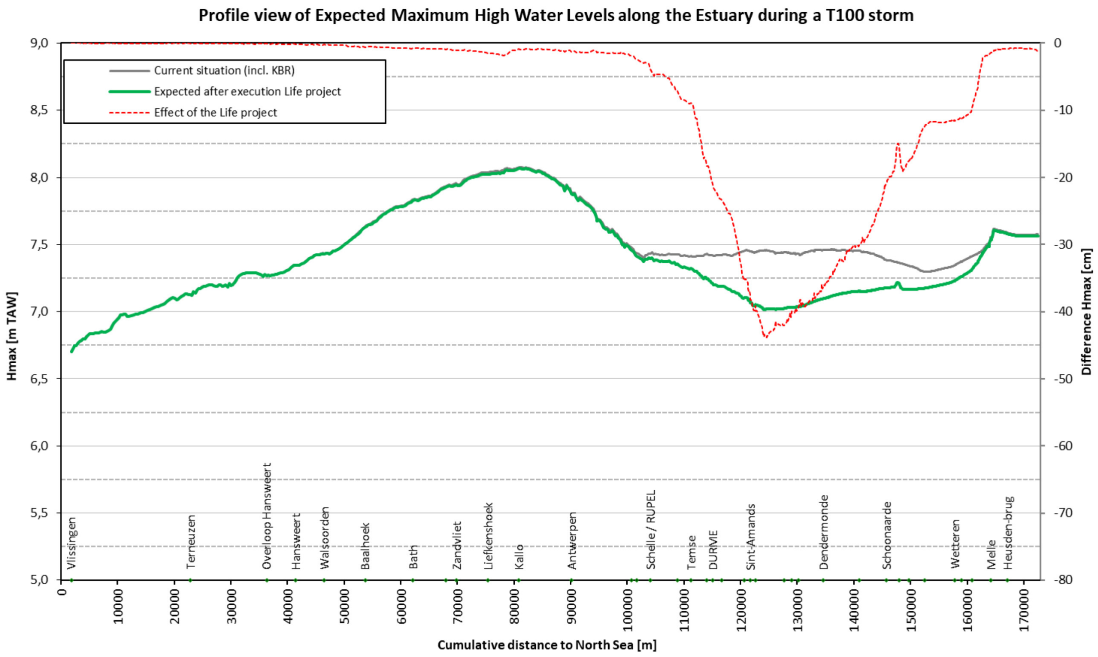

Figure 4 - Profile of HMAX during a T100 event, both with (green) and without (grey) the LIFE Sparc areas. Effect on HMAX (red dashed) on right axis

The LIFE Sparc areas have a clear combined effect on flood safety, as apparent in the HMAX plots which show the maximum water levels during a storm event of a specific return period. The combined effect is shown in the red dashed line in the figures, and ranges from -15 cm for an event with a return period of 1 year (T1) to -45 cm for a T100 event.

3.2 Effect on tidal propagation (Telemac)

Bi et al. (2022) describe a detailed model for the Scheldt estuary which is built for assessing the effect of the eight project areas (five de-embankments and three FCA-CRTs) on the hydrodynamics. The detailed model is based on the Scaldis 2013 model (Smolders et al., 2016), with necessary mesh refinements and bathymetry updates in the target areas.

Two scenarios are studied, a normal period with average tide and upstream discharge, and a storm surge period in the event of Sinterklaas storm (06/12/2013).

In the normal scenario (Figure 5), the implementation of the eight project areas already shows a moderate reduction (~12cm) on the high water level. The maximum reduction is at 124 km, where the FCA-CRT area Wal-Zwijn and depoldered area Groot Schoor (Hamme) are located.

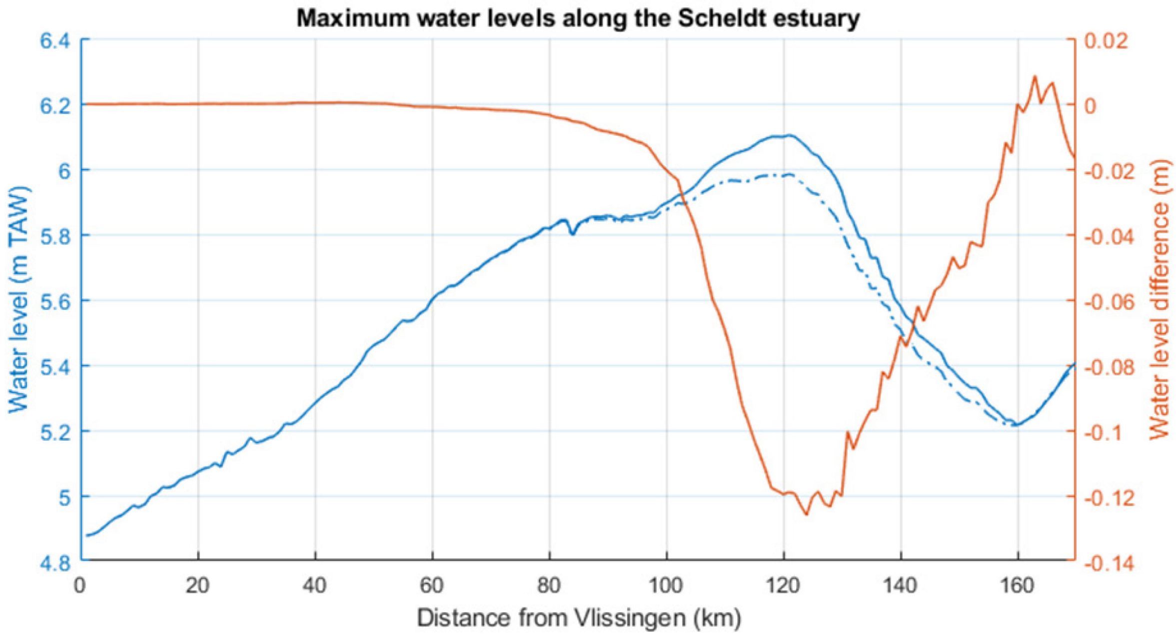

Figure 5 - Comparison of maximum water level along the Scheldt under the normal scenario (solid lines represents the reference situation, dot-dash lines represents the situation with the implementation of the 8 project areas) (Bi et al., 2022)

In the storm surge scenario (Figure 6), after activating the depoldered areas and FCA/FCA-CRTs, the maximum water level in the Upper Sea Scheldt is significantly reduced. The maximum reduction is at 130 km.

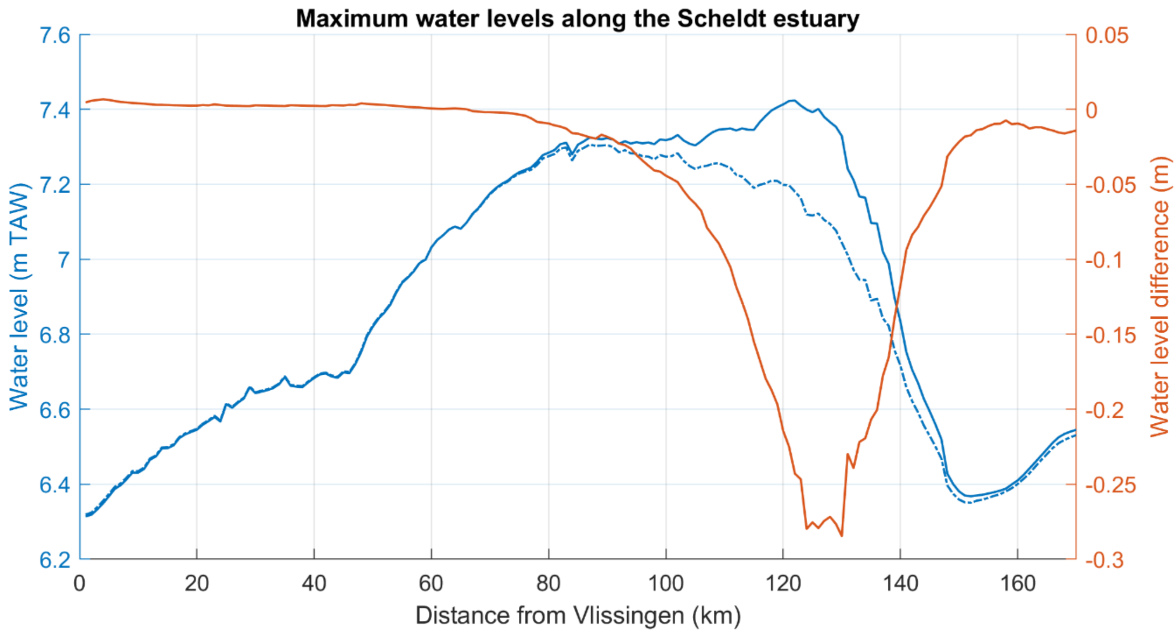

Figure 6 - Comparison of maximum water level along the Scheldt under the storm surge scenario

In both normal and storm surge scenarios, the effect of high water reduction is not restricted in the project areas (km 110-134), instead, it extends further upstream and downstream, starting from km 75 to km 170.

Note that the “normal period” and “storm surge period” used in Bi et al. (2022) were established for less extreme conditions than the synthetic events used in the 1D model, per the preceding paragraph and Coen et al. (2016). That is why the effect figures don’t correspond one-on-one. As expected however, the effects on HW as calculated with the Telemac model lie in the range of effects for different return periods as calculated with the 1D model.

4 Monitoring in the Durme

ADCP measurements in the Durme tributary near Tielrode (see Figure 7) were conducted between 2019 and 2024. The measurements were performed on the following dates:

- 16/09/2019
- 29/04/2021
- 30/08/2023
- 05/09/2024

Three areas of LIFE Sparc are foreseen in the Durme (areas 1-3 in Figure 1). Groot Broek is a depoldering of 58 ha that became active in 2025. Klein Broek is a smaller depoldering of 38 ha that is expected in 2026. De Bunt is a FCA-CRT that will become active in 2026.

Since the measurements took place in 2019-2024, we won't analyse the effects of these three areas in the measurements described in this chapter. The measurements do provide valuably system insight and ground truth data for the calibration/validation of numerical models that can be used for impact assessment studies.

The measurement results in this chapter are taken from the full factual data report (Meire & Vanlede, 2025).

4.1 Location

The full tide (13h) measurements are carried out between the mouth of the Durme with the Upper Sea Scheldt and the ferry at Tielrode. This is shown in Figure 7. Due to the limited depth at low tide, consideration was given to moving the transect measurements downstream. This was not pursued because interference with the future outflow of the GOG-GGG area De Bunt was expected.

Figure 7 - Indication of the measurement location for the 13-hour measurement ("Tielrode") and a possible alternative location ("Tielrode v2")

4.2 Setup

The measurements are carried out on board the MS Veremans. Here, one frame is used, namely the frame with Delft bottle and an Aanderaa Seaguard (see Figure 8).

The Delft bottle on the frame is used to measure sediment transport directly. The frame is lowered and raised in the water using a crane. Depending on the measured sediment transport, the frame remains on the bottom for 5 or 10 minutes. After retrieval, the sediment is rinsed from the bottle into a bucket. The suspension is poured into a funnel, and the amounts of sand and silt are read off in the measuring tube and recorded. Periodically, a sample is retained for the purpose of performing a grain size distribution analysis.

The Aanderaa Seaguard measures continuously physical parameters like water velocity, turbidity, temperature, conductivity, oxygen and pressure. These data series help in interpreting and contextualising the Delft bottle sediment transport measurements.

Figure 8 - Delft bottle suspended on frame, with Aanderaa (photo 16/09/2019)

Figure 9 - ADCP flow measurements using the support boat

4.3 Water levels

Figure 10 shows the water levels at Tielrode during the different measurement campaigns. An overview of the characteristics is presented in Table 1. The maximum tidal differences were observed during the 2021 measurement. The measurements of 2023 and 2024 show a very similar tidal curve and tidal difference.

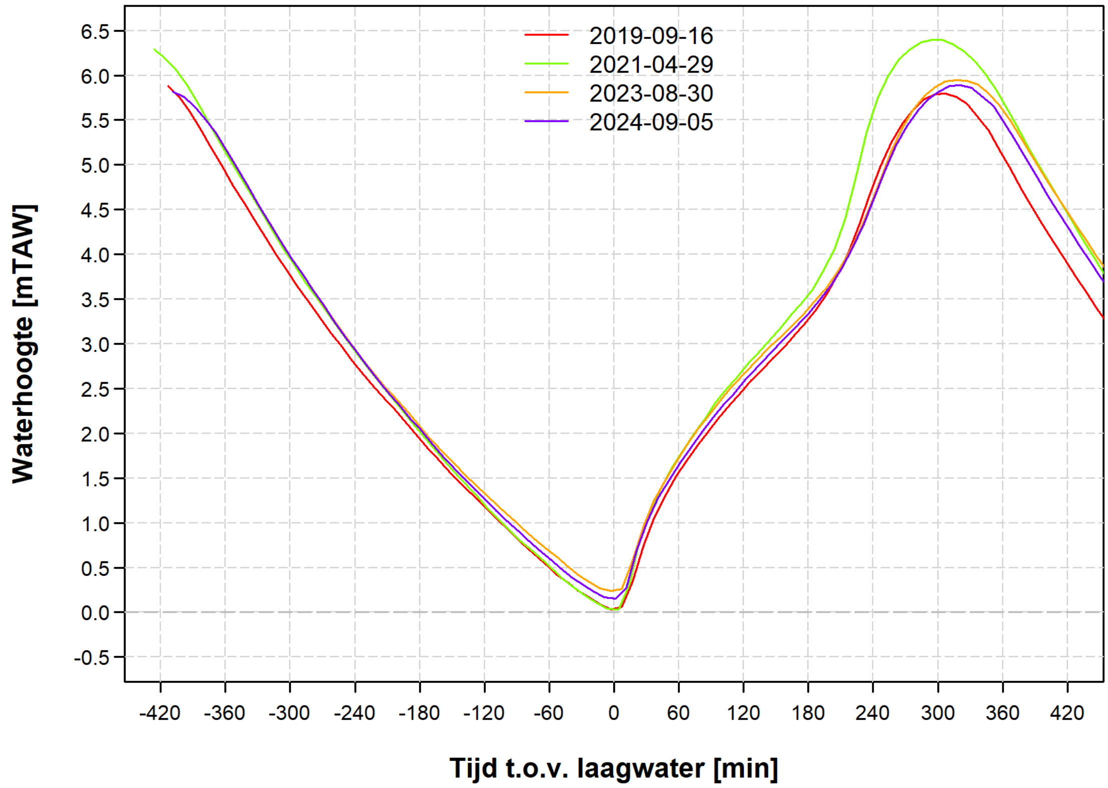

Figure 10 - Tidal curve at Tielrode for the four 13-hour measurements. Time to LW in minutes on X, and water level in mTAW on Y.

Table 1 - Overview of tidal conditions during the different 13-hour measurements

Datum	Time start [MET]	Time end [MET]	HW [mTAW]	LW [mTAW]	HW [mTAW]	Tidal Range [m]
19/09/2019	6:18	18:47	5,98	0,02	5,80	5,96 - 5,78
29/04/2021	6:00	18:42	6,38	0,02	6,41	6,36 – 6,39
30/08/2023	5:33	18:30	5,88	0,23	5,95	5,65 – 5,72
05/09/2024	5:58	18:56	5,84	0,15	5,89	5,69 – 5,74

4.4 Water flux [m³/s]

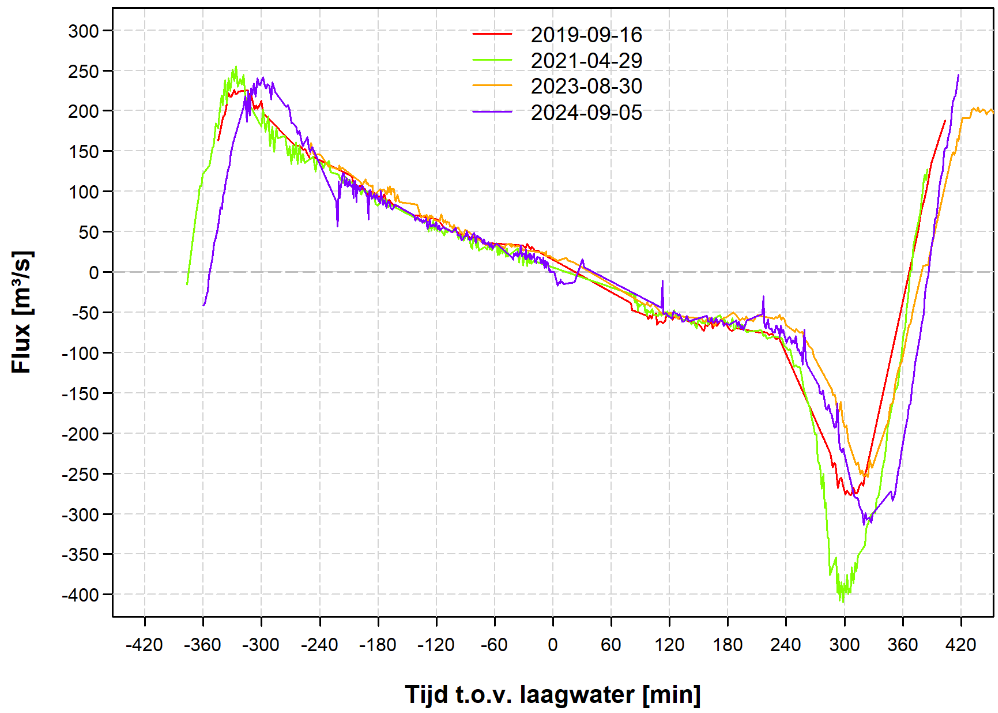

Figure 11 - Water flux at Tielrode during the different campaigns

Figure 11 shows the water flux during the 13-hour measurements for the different campaigns. Positive values correspond to outflow from the Durme (ebb), while negative values indicate flow towards the Durme (flood).

Note the clear asymmetry in the tidal signal. In terms of peak water velocity/flux, the Durme near the mouth is a flood dominated system. This corresponds with earlier findings (e.g. Meire et al., 2020) that also found the Durme to be flood dominated by analysing the vertical tide (i.e. water levels). This flood dominance points to sediment import. The Durme tributary is known for relatively fast sedimentation (order of 10-20 cm/year) linked (among others) to the disappearance of the natural upstream discharge due to human intervention.

Also note that in separate research (Meire et al., 2024) it was shown that the expected combined effect of Klein Broek, Groot Broek and De Bunt was a weaker flood dominance in the middle and downstream sections. In terms of sediment transport, these measures could slow down the sedimentation process in the downstream part of the Durme river.

4.5 Sediment transport

4.5.1 Near-Bed sediment transport measured with the Delft bottle

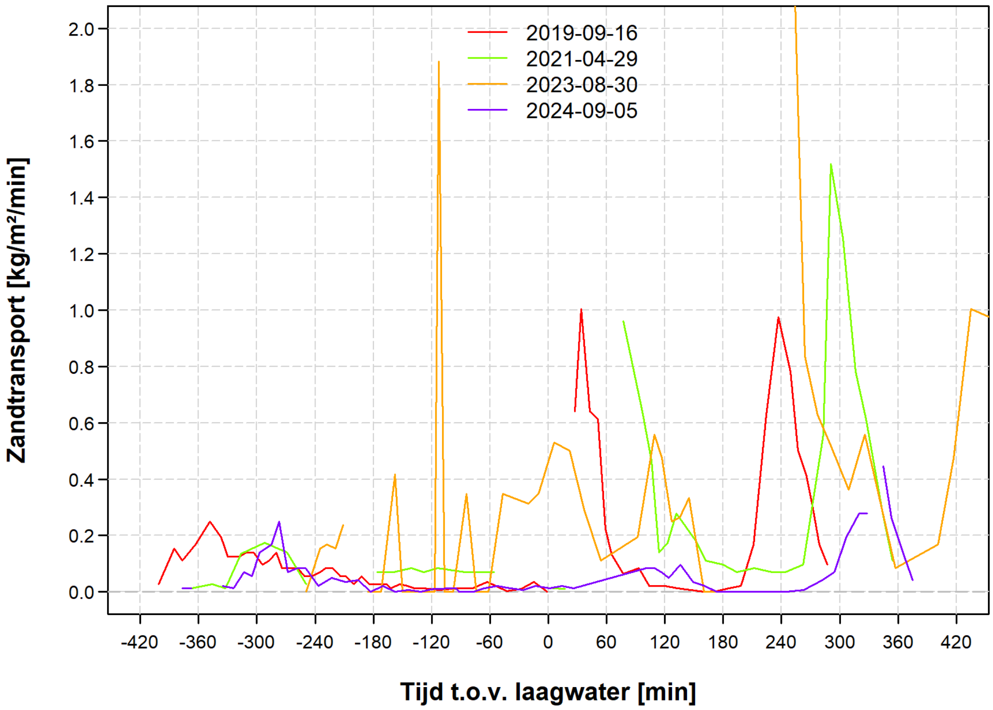

Figure 12 - Near-Bed sediment transport as measured with the Delft bottle

In Figure 12, the results of the measurements with the Delft bottle are shown. The highest peaks in sediment transport are mainly observed during the flood phase. Note the natural variability in the signal (difference in result from one campaign to the next) which complicates direct effect quantification solely from measurements.

The first peak in sediment transport occurs just after low water slack tide. A second peak was observed at the time of maximum flood, approximately at high water.

4.5.2 Suspended sediment concentrations

Periodically during each campaign, water samples are taken which are analysed by filtration in the lab to determine the suspended sediment concentration [mg/l]. The results are shown in Figure 13.

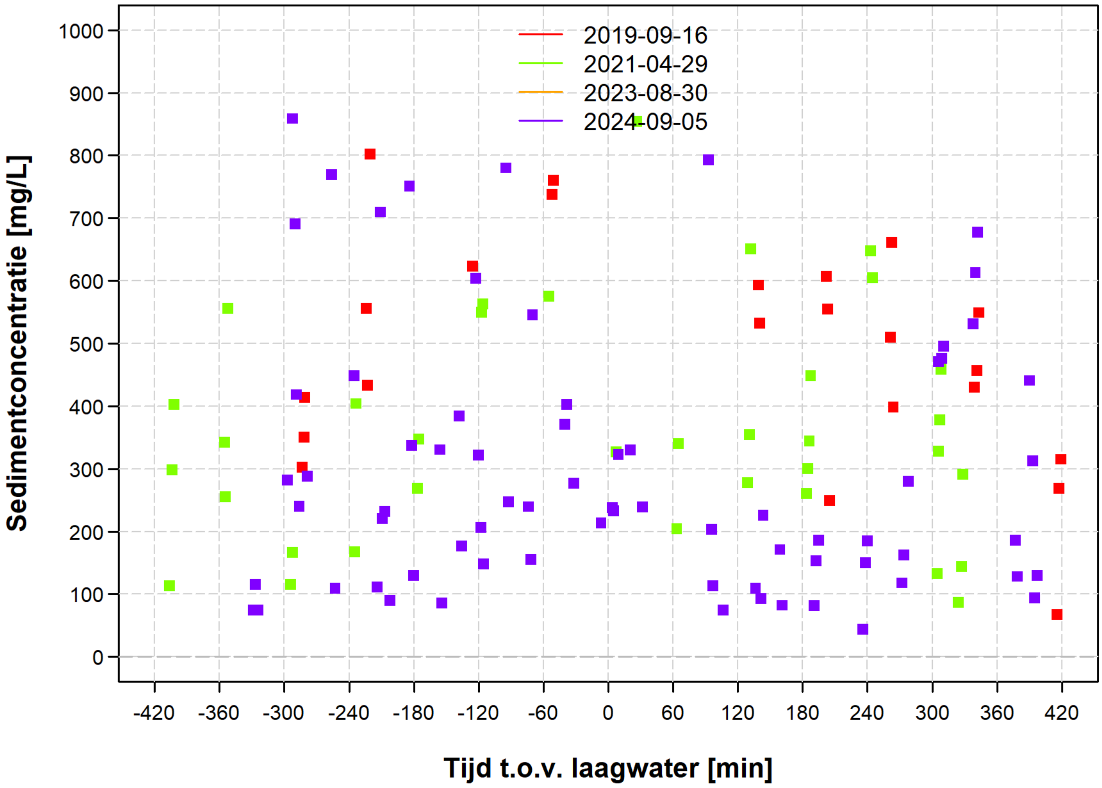

Figure 13 - Suspended sediment concentration [mg/l] as measured by filtration

In contrast to the near-bed sediment transport measurements discussed in §4.5.1, there is no clear tidal signal or ebb/flood asymmetry detectable in the data. This indicates the presence of a persistent “wash load” of suspended sediment which remains in suspension during the tidal cycle (Van Rijn, 1993).

5 Ecosystem services by LIFE Sparc areas

The contents of this chapter is taken over from the note Maris et al. (2025)

5.1 Introduction

A major ecosystem service that tidal marshes provide is its beneficial effects on water quality. Marshes remove nitrogen and phosphorus from the water column, two nutrients that are present in excess in the Scheldt and are partly responsible for eutrophication. In addition, tidal marshes provide silicon, an essential nutrient for diatoms. By removing Nitrogen (N) and Phosphorus (P) and enriching Silicon (Si) in the floodwater, salt marshes contribute to a healthier N/P/Si ratio in the water column, and thus provide an important ecosystem service to the Scheldt. The Sigma Plan therefore aims to improve water quality by creating extra tidal marshland with the associated ecosystem functions. These tidal marshes can be realized through managed realignment (MR) or through the new concept of controlled reduced tide (CRT).

The Lippenbroek area (10 ha) was the first Flood Control Area with a Controlled Reduced Tide (FCA-CRT) that was developed worldwide. It was delivered in 2006, and served as a demonstrator site for the concept of CRT, with daily tidal inflow and outflow in the area. The area and its evolution have been monitored since 2006 to gather unique scientific data on the functioning of, and effects of CRT areas in an estuarine context.

In order to study the influence of CRT on water quality, many monitoring campaigns have been done during a complete tidal cycle in the Lippenbroek area. Water quality of the incoming and outgoing water was continuously monitored during a full tide, which allows a balance to be drawn up for various nutrients. Since the start of Lippenbroek, several such campaigns have been organized every year. It is only after many campaigns that patterns become clearer, because every tide is different and there are many factors (e.g. temperature or concentration at inflow) that influence the water purifying function of the CRT. Also, for certain parameters, the functioning of the marsh evolved over the years.

The monitoring of the incoming and outgoing flows is carried out by Flanders Hydraulics. Incoming and outgoing flow rates were determined continuously. Samples for water quality are taken at least every hour. In the case of high discharge, e. g. during inflow, the sampling frequency is increased to every half hour. The samples are stored in a dark and cool place for further analysis. For a detailed description of the water analysis methods, please refer to the OMES report (Maris et al., 2017). With nutrient concentrations and discharge data during in- and outflow, a nutrient flux and nutrient balance can be calculated, as demonstrated in Figure 14 for a tidal campaign on 30/6/2015. During that tide, a net Dissolved Silicon (DSi) export of 10 kg was observed.

Between 2006 and 2024 more than 40 of these campaigns were performed.

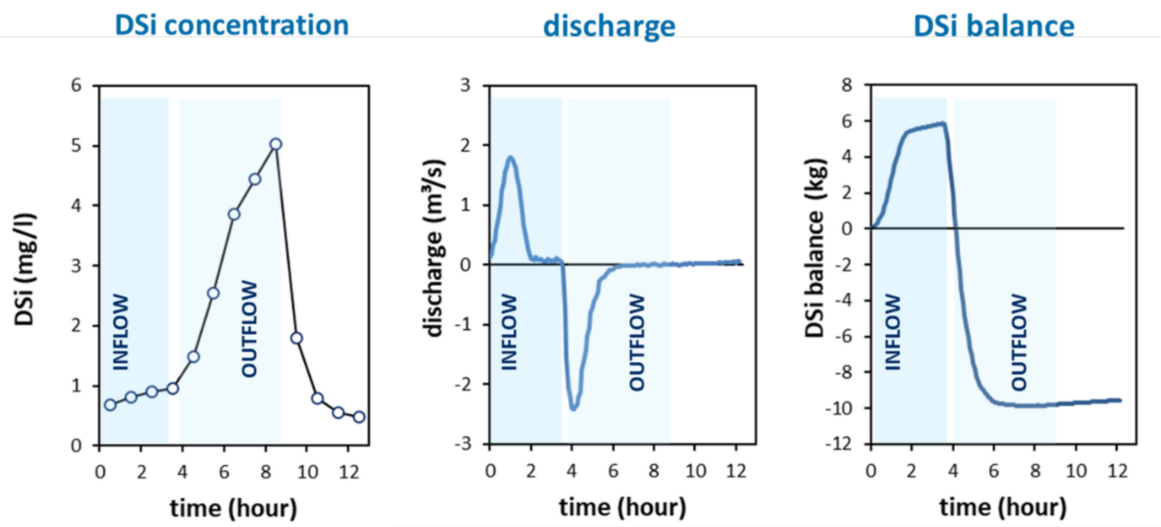

Figure 14 - DSi concentration (left) discharge (middle) and resulting DSi balance during a tidal campaign on 30/6/2015 at Lippenbroek

5.2 Conservative balances

In order to investigate the ecosystem functioning of a tidal marsh (Lippenbroek), we will mainly look at discharge weighted average concentrations of several nutrients, and not so much at the net, actual nutrient balance of a certain campaign. After all, we are interested in the general functioning of Lippenbroek, and not so much in the absolute result of 1 specific tide. Whether or not there is retention of nutrients in Lippenbroek during a specific tide depends very much on the water balance of that tide: was there retention or additional delivery of water during that campaign. Figure 15 clearly shows this for TDIN (total dissolved inorganic nitrogen): the net TDIN delivery or retention is clearly correlated with the net water balance. The net TDIN balance therefore says more about the water balance than about the ecosystem functioning of Lippenbroek. Therefore net balances will not be used in this report, but instead conservative balances are made: a balance drawn up on the assumption that the same amount of water enters and leaves the marsh during a tidal cycle. This provides information about the functioning of the area, regardless of whether it was a water importing or exporting tide.

To draw up conservative nutrient balances, discharge-weighted average concentrations of inflow and outflow are first determined. This determines the concentration difference between inflow and outflow: delta. When this delta is multiplied by the incoming water volume, we get a conservative balance: the amount of retention or subsequent delivery during 1 full tidal cycle, assuming that the same volume of water that entered the site, also leaves the same tide. A small leakage rate at the outlet sluice is also taken into account for the incoming volume: a limited amount of water flows into the area via the outlet at high tide, because the valve at the outlet never closes completely.

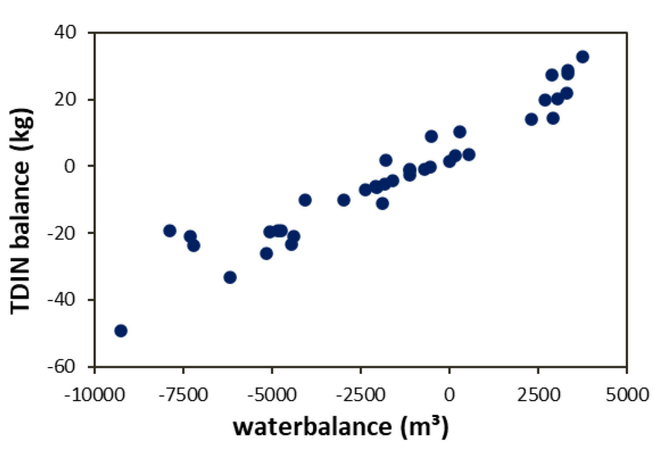

Figure 15 - Correlation between the real TDIN balance and the real water balance for various 13-hour measurements. Negative values indicate retention, positive values indicate subsequent delivery.

5.3 Dissolved silicon (DSi)

The export of dissolved silicon out of tidal marshes is an important ecosystem service of these estuarine habitats. The supply of dissolved silicon (DSi) is crucial to maintain a balanced P-N-Si ratio in the estuary and ultimately in the North Sea. This 'good' ratio is the ratio in which these nutrients are needed for the growth of diatoms. Diatoms form the basis of the estuarine food chain and are therefore desirable in the estuary. However, nowadays there is an excess of N and P in the rivers of the Schelde catchment and the estuary. In the event of a strong bloom of diatoms, when light, temperature and other growing conditions are favourable, DSi will therefore be depleted first. The growth of diatoms will consequently stop and green algae, which do not need DSi, will take over. Green algae are less appreciated as a food source and will therefore accumulate in the estuary, leading to typical eutrophication symptoms. To avoid the transition from diatoms to green algae in the event of an excess of N and P compared to Si, either the N and P concentration must be reduced or the Si concentration must be increased. When the transition to green algae occurs, these green algae can continue to grow, as long as the growing conditions are still OK, until nitrogen (N) or phosphorus (P) is depleted.

By adding extra marsh habitat to the estuary, the DSi concentration in the estuary can be increased. Based on many mass balance studies in Lippenbroek, the supply of DSi from a tidal marsh area can be estimated. The supply of dissolved silicon to the Scheldt is an important ecosystem objective of this area. Figure 16 clearly shows that both retention and subsequent delivery occur, but there is a clear, significant trend from retention to increasing export. If we disregard the campaigns at water temperatures below 10°C, only export has been measured since 2020.

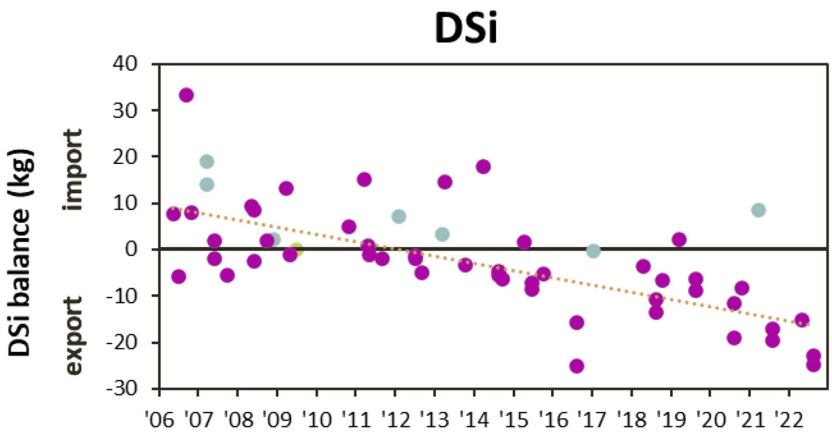

Figure 16 - Conservative balances for dissolved silicon (kg) for the various 13-hour measurements of the past 15 years. The trend line indicates a significant evolution towards DSi export, whereby the campaigns at temperatures below 10°C (shown in grey) were not taken into account.

In a natural tidal marsh at Tielrode in the Schelde estuary, Struyf et al. (2005) consistently measured silicon export. In his study the marsh yielded up to 250 mg/m² DSi per tide at low silicon concentrations. Based on 6 tidal campaigns in the period 1997-2002, under different conditions, it could be extrapolated that up to 400 mg/m² can be expected at the lowest observed silicon concentrations. The strongest DSi export was always observed at the end of a tidal cycle, when the last water (the so-called seepage) from the tidal marsh bottom drains out of the tidal marsh via the creeks. The amount of export appeared to be correlated with the concentration of DSi in the incoming water: the less DSi entered the tidal marsh, the greater the export. This is why this is also being investigated at Lippenbroek.

The first observation is a temperature dependency (Figure 17). At water temperatures below 10°C, no export was observed, only import.

Just like at Tielrode, at Lippenbroek the delta DSi is correlated with the DSi concentration at inflow ($r = 0.55$; $p<0.01$). The lower the incoming DSi concentration, the greater the export (negative concentration difference between inflow and outflow). At the highest DSi inflow concentrations, export is never measured, only import.

The delta concentration is also significantly correlated with the tidal volume ($r = 0.46$; $p>0.01$). The export (negative concentration difference between inflow and outflow) is greatest at small tidal volumes, which suggests that DSi release is not a pelagic process but rather a bottom process. In a bottom-linked process, the DSi release from that bottom is more diluted at large tidal volumes, which results in the lower delta concentration at export. After all, the silicon balance does not seem to be correlated with the tidal volume.

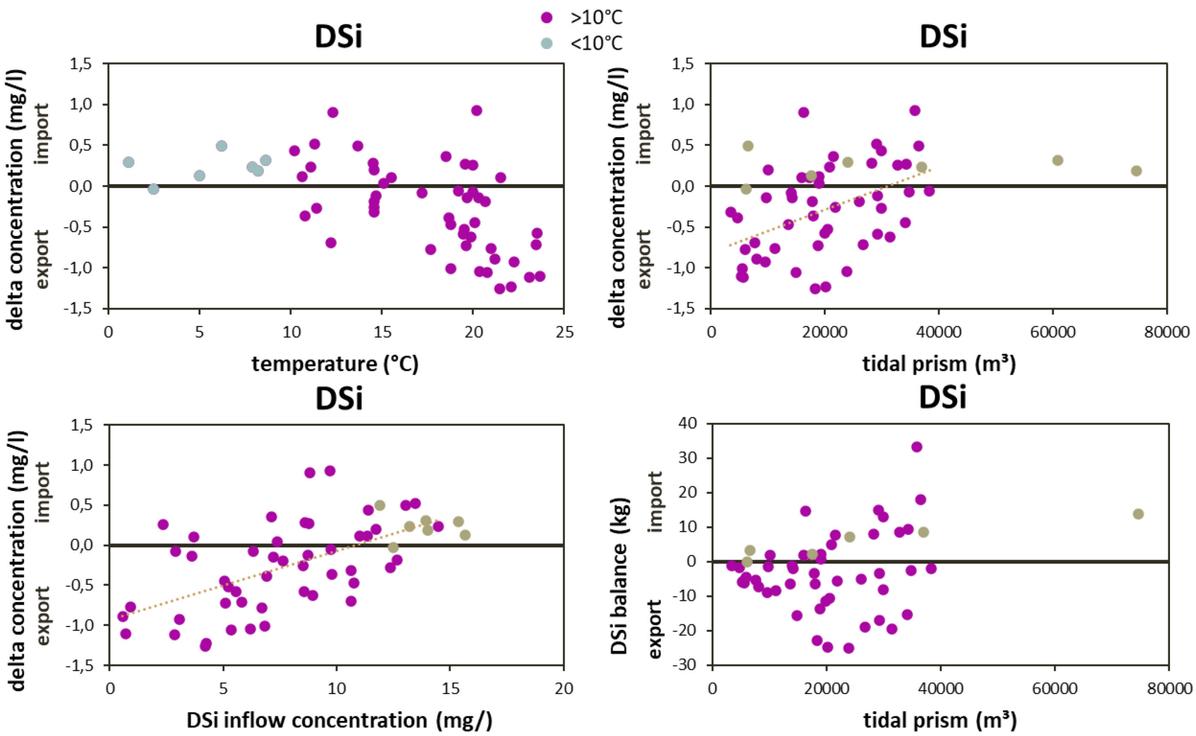

Figure 17 - Top left: Concentration difference (discharge-weighted concentrations) for DSi between inflow and outflow as a function of the average water temperature; top right: concentration difference for DSi as a function of the tidal volume (inflow); bottom left: concentration difference for DSi as a function of the flow-weighted DSi concentration of the inflow; bottom right: conservative DSi balance as a function of the tidal prism.

In Figure 16 a clear trend from earlier DSi uptake to mainly DSi supply is observable, which is not explained by trends in the DSi concentration at inflow or tidal volume. The function of Lippenbroek as a source of DSi has effectively increased over the years. Since a soil process is suggested, this seems logical: in recent years a typical salt marsh soil has been built up on top of the polder clay by sedimentation, in which soil processes such as DSi release may proceed better than in the underlying clay. Lippenbroek has thus become an increasingly better supplier of DSi. Apparently it took the restored site about 8 years to become a functional DSi delivering marsh. Based on the most recent years, Lippenbroek supplied an average of around 350 mg DSi per m² per tide, which corresponds to the earlier predictions of Struyf et al. (2005) based on more limited data. We can therefore consider an equal DSi supply by natural tidal marshes and well developed (after 8 years) restored marshes (both MR and CRT).

Based on the above, the following conclusions are made:

- DSi delivery is independent of the tidal volume
- DSi delivery depends on the flooded surface (Figure 18).
- DSi delivery is correlated with DSi inflow concentration (Figure 18).
- DSi delivery is different for young and old restoration sites.

With a flooded surface of about 7 ha and an average tidal prism of 19600 m³, delivery of DSi from the marsh can be calculated:

For young areas (0 to 8 years old):
DSi flux/m² = (0.0517 * DSi_in – 0.3443) * V / A

For areas with soil development (from 8 years):
DSi flux/m² = (0.0932 * DSi_in – 1.2627) * V / A

with V = average exchanged water volume (tidal prism) [m^3]
DSi_in = DSi inflow concentration (mg/l or g/m^3 Si)
A = surface area [m^2]

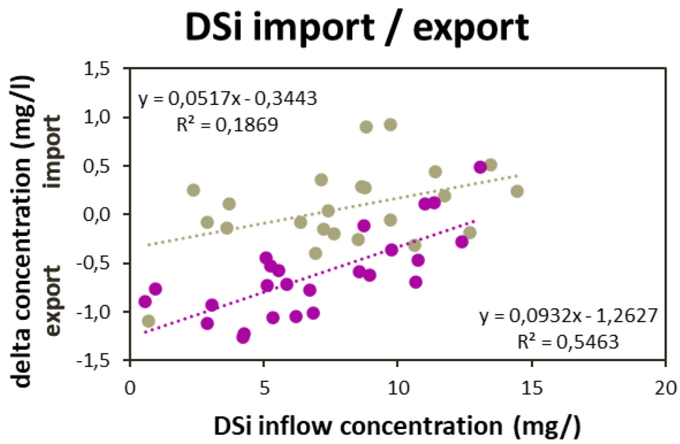

Figure 18 - Concentration difference between inflow and outflow for DSi during the first 8 years after opening of the GGG (2006-2013) and the period from 2014 (2014-2022) as a function of the DSi inflow concentration.

5.4 Estimated DSi export from the Sparc sites

5.4.1 Modeling DSi export

The studied LIFE Sparc areas are listed in Table 2.

DSi delivery depends on the flooded surface during a tidal cycle. Average flooded surfaces for different tidal conditions have been calculated by Flanders Hydraulics (Nazarali & Vanlede, 2025 based on the detailed HD simulations of Bi et al., 2022) and are summarized in Table3.

Also the incoming DSi concentration are of importance for the delivery of DSi. Monitoring stations in the estuary that are used as a reference for the incoming water quality are listed in Table 2.

Table 2 - list of the Sparc project areas, with project type, surface and nearby reference station for water quality

Name	Type	Area [ha]	Reference station water quality
Uiterdijk	Depoldering	11	Dendermonde
Groot Schoor Hamme	Depoldering	26	Baasrode
Groot Schoor Bornem	Depoldering	23	Temse
Groot Broek	Depoldering	58	Tielrode (Durme)
Klein Broek	Depoldering	38	Tielrode (Durme)
Vlassenbroek	FCA-CRT	91	Dendermonde
Wal	FCA-CRT	69	Baasrode
Zwijn	FCA-CRT	70	Baasrode
De Bunt	FCA-CRT	67	Tielrode (Durme)

Table 3 - Total surface and flooded surface at different tidal conditions in the LIFE Sparc areas

Area [ha]	total	neap	average	spring
Uiterdijk	11	5,4	6,2	6,4
Klein Broek	38	11,3	13,3	14,2
Groot Broek	58	38,3	40,8	41,5
Groot Schoor Bornem	23	18,3	18,4	18,5
Groot Schoor Hamme	26	18,7	20,5	20,9
Vlassenbroek	91	56,1	60,7	68,2
Wal	69	37	40,1	42,5
Zwijn	70	30,5	36,8	42,2
De Bunt	67	10,2	15,4	18,4

Table 4 lists the average winter and summer half year concentrations for these stations, but also averages and minima for July and August, when lowest DSi concentrations usually occur. DSi depletion in the estuary occurs if DSi becomes lower then 0,28 mg/l. When DSi is depleted in the estuary, maximal export is expected. DSi depletion typically occurs during longer periods of strong diatom bloom, in periods with low freshwater discharge and hence limited input coming from the catchment. Due to the very low DSi concentrations, the export out of the marsh can double, compared to normal summer conditions.

Table 4 - DSi concentration (mg/l) for several reference stations for the period 2014-2024: a winter half year average (from October until March); a summer half year average (from April until September); an average and minimum for July-August and the concentration at which DSi depletion occurs.

station	winter	summer	Jul-Aug	Jul-Aug	depletion
	average	average	average	min	
Melle	6,7	3,5	2,7	0,06	0,28
Dendermonde	6,3	2,3	1,7	0,11	0,28
Baasrode	6,1	2,2	1,7	0,11	0,28
Temse	6,0	3,1	2,2	0,13	0,28
Durme (Tielrode)	6,1	2,6	1,8	0,11	0,28

Figure 19 shows DSi delivery for all LIFE Sparc areas, assuming full functionality after 8 years, for different tidal conditions and different seasonal conditions. The seasonal conditions differ in DSi inflow concentrations. In the winter half year, typical higher DSi concentrations occur in the estuary, while in the summer half year, due to more algal growth and lower influx from the catchment, lower DSi concentrations prevail. This will influence the flux of DSi coming out of the marsh. During the winter half year, there is even no outflow but retention of DSi in the LIFE Sparc marshes, due to the high DSi inflow concentrations. These results are only valid for water temperatures above 10 °C. Below that temperature, little import or export is expected. When DSi concentrations in the estuary are high and consumption is low due to the colder and darker conditions in the winter half year, there is no ecosystem demand for additional DSi.

In the summer half year, there is always delivery of DSi from the marsh to the estuary. Especially in the months July and August, we see on average more export. Larger areas such as Vlassenbroek will deliver more. Also during a spring tide, more delivery is expected due to the larger flooded surface and the larger tidal exchange volume.

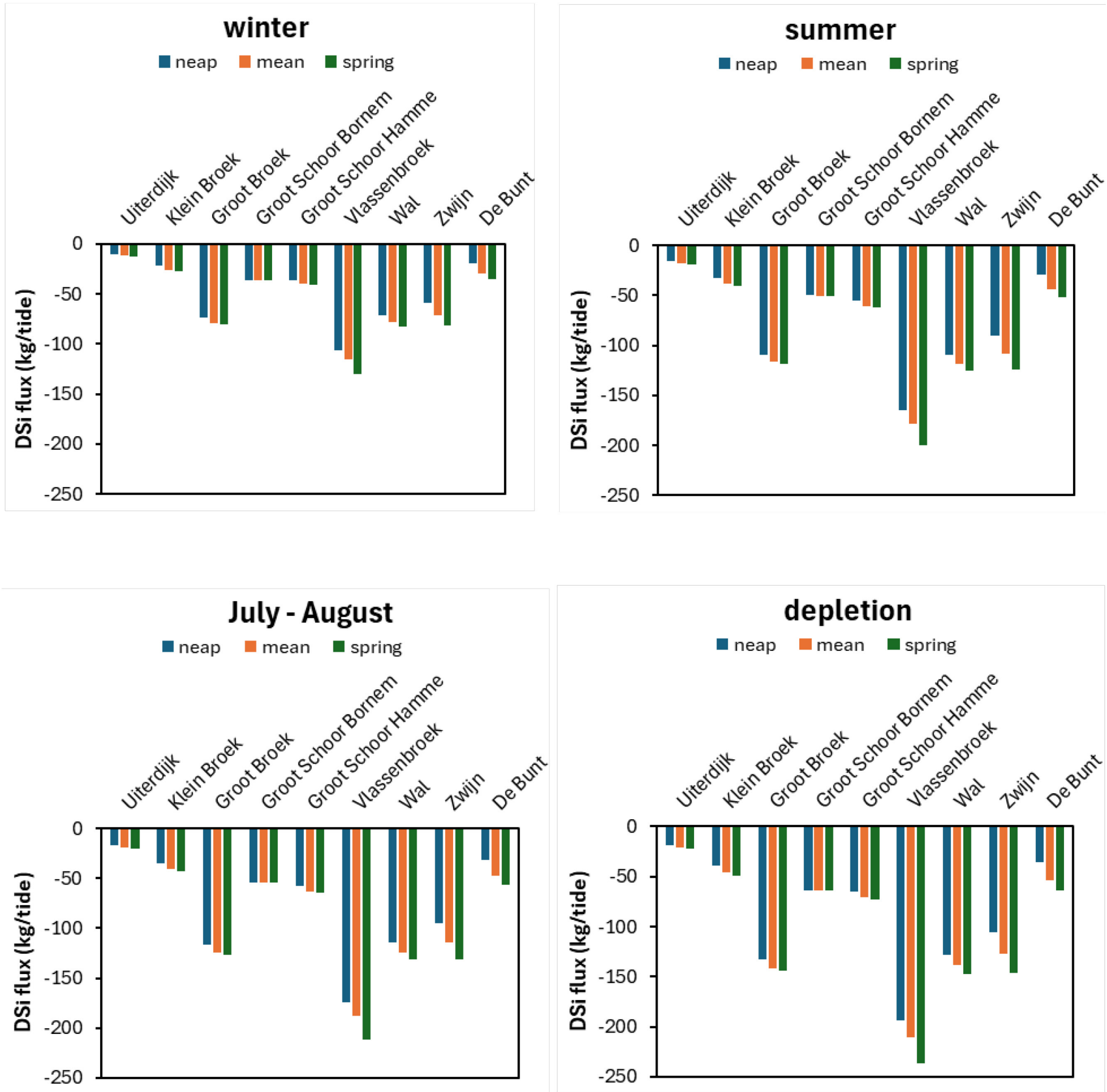

Figure 19 - DSi delivery (negative values) for the LIFE Sparc sites after 8 years of development for different tidal conditions (neap, mean and spring tide) and DSi inflow concentrations. For the latter, average DSi inflow concentrations for the winter half year, summer half year, July-August and DSi depletion are used.

5.4.2 Relevance of the LIFE Sparc areas for the DSi cycling in the estuary.

From Figure 19 it is clear that the LIFE Sparc marshes can always deliver DSi, especially when DSi concentrations are low in the estuary. To estimate the relevance of this, the total export for all LIFE Sparc marshes is calculated for an entire month. The fluxes per tidal cycle (as shown in Figure 19) are summed for a month, assuming on average 10 tides with neap tide conditions, 40 with mean conditions and 10 with spring tide conditions in a month. This monthly DSi flux from the Sparc marshes can be compared with monthly DSi fluxes at several transects in the estuary (Table 5). These monthly DSi fluxes in the estuary are estimated as the product of the monthly averaged discharge and DSi concentration data (period 2014-2024) at the several locations and climatological conditions.

During winter conditions, the Sparc marshes deliver about 29 ton of DSi a month. This represents only about 3% of the estuarine DSi flux, because of the higher concentrations and discharge in the estuary. At temperatures below 10°C, these calculations would no longer be valid, but in winter DSi export is less relevant.

During the summer half year, and especially the months July and August, there is a stronger negative monthly DSi flux, meaning that the marshes deliver DSi to the estuary. The monthly export ranges from 44 to 46 ton DSi, and peaks to 52 ton DSi when the DSi concentration in the estuary is being depleted. These number matter: the export from the marsh is between 27 and 52% of the estuarine DSi flux at Melle, the most upstream measuring station, and increases up to 40 to 85% at Dendermonde. This station is in the middle of the tidal freshwater zone, where DSi usually reaches a minimum.

When DSi is depleted in the estuary, the export out of the LIFE Sparc marshes can be more than 1000% of the estuarine flux at Melle or Dendermonde. DSi depletion typically occurs at low freshwater discharge, leading to extremely low estuarine DSi fluxes. On these moments, the Sparc marshes will make a difference and avoid DSi depletion in the estuary. These conditions of DSi depletion will therefore most likely never occur when all Sparc marshes are functional.

Table 5 - Monthly DSi flux into the estuary at average conditions for the winter half year, summer half year, July and August and times of DSi depletion for the LIFE Sparc areas when **fully functional** and the monthly estuarine influx at Melle, Dendermonde and Temse. The column % gives the ratio of the DSi flux coming from all Sparc aeras compared to the estuarine flux.

	Sparc areas	**Melle**			**Dendermonde**			**Temse**		
	DSi export	DSi conc.	DSi flux	DSi flux	DSi conc.	DSi flux	DSi flux	DSi conc.	DSi flux	DSi flux
	ton/month	mg/l	ton/month	%	mg/l	ton/month	%	mg/l	ton/month	%
winter	29	6,7	861	3%	6,3	799	4%	6,0	1109	3%
summer	44	3,5	164	27%	2,3	109	40%	3,1	226	19%
July-Aug.	46	2,7	90	52%	1,7	55	85%	2,2	123	38%
depletion	52	0,28	3	1880%	0,3	3	1880%	0,28	6	812%

The above calculations assumed fully functional marshes in all LIFE Sparc sites. Results from the Lippenbroek study however show that this takes time. The first 8 years, DSi delivery is expected to be limited. Marshes can sometimes even take up DSi, especially in winter conditions when estuarine DSi concentrations are high.

The results in Table 5 have therefore also been calculated for the initial phase after restoration of the LIFE Sparc marshes, when these new marshes are not yet fully delivering all ecosystem services (Table 6). It is clear that these marshes will deliver less DSi in the first years. Still, in the summer half year or in the months July and August, the DSi delivery can range between 4 and 20% of the estuarine influx, and in periods of DSI depletion, up to 500%. So even in the first years, these areas can make a difference in controlling the N/P/DSi balance and hence undesired algal blooms.

Table 6 - Monthly DSi flux at average conditions for the winter half year, summer half year, July and August and times of DSi depletion for the LIFE Sparc areas during the **first 8 years** after construction and the monthly estuarine influx at Melle, Dendermonde and Temse. The column % gives the ratio of the DSi flux coming from all Sparc aeras compared to the estuarine flux.

	Sparc areas	Melle			Dendermonde			Temse		
	DSi export	DSi conc.	DSi flux	DSi flux	DSi conc.	DSi flux	DSi flux	DSi conc.	DSi flux	DSi flux
	ton/month	mg/l	ton/month	%	mg/l	ton/month	%	mg/l	ton/month	%
winter	1	6,7	861	0%	6,3	799	0%	6,0	1109	0%
summer	9	3,5	164	6%	2,3	109	9%	3,1	226	4%
July-Aug.	11	2,7	90	12%	1,7	55	20%	2,2	123	9%
depletion	14	0,28	3	501%	0,3	3	501%	0,28	6	216%

5.5 Nitrogen removal

Many rivers in Europe don't meet the Water Framework Directive criteria for nitrogen (e.g. nitrates), including the Scheldt estuary. Reducing the high nitrogen concentration in the estuary is mainly a task for the catchment: better waste water purification and stricter regulations for agriculture to reduce diffuse input. Within the estuary, tidal marshes offer however a last chance to remove some nitrogen from the water, before it reaches the coastal zone and open sea. It is known that marshes can remove N from the inflowing water. Particulate nitrogen can be accumulated in marsh soils trough sedimentation. Dissolved nitrogen can be taken up by marshes and finally converted to N_2 gas that escapes into the atmosphere.

Here we study the sink function of tidal marshes for dissolved nitrogen: total dissolved inorganic nitrogen (TDIN = sum of NH_4^+, NO_2^- and NO_3^-). Based on the mass balance studies performed in Lippenbroek, the removal of TDIN from the inflowing water by a tidal marsh area can be estimated.

Figure 20 shows the conservative balance for the various 13-hour measurements at Lippenbroek since 2006. Retention of TDIN was always observed, on average around 5 kg per tide. A downward trend however is striking: in recent campaigns, significantly less TDIN was removed. A significant decrease is also noticeable when looking at the concentration difference between inflow and outflow (Figure 21). However, this does not mean that Lippenbroek loses much of its functionality as a nitrogen sink. After all, TDIN retention depends on various factors, which also differ over time. The differences between campaigns are examined in Figure 22.

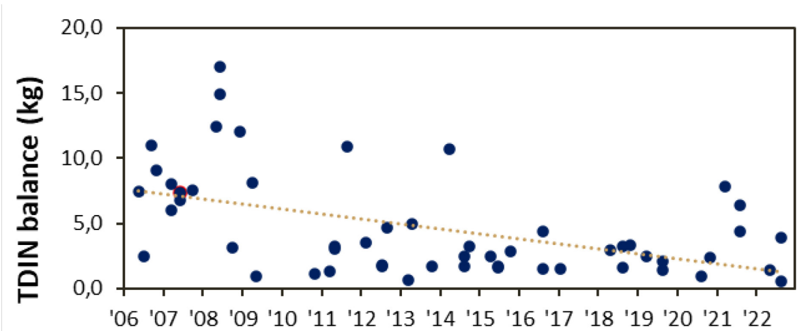

Figure 20 - Conservative mass balances (kg) for total dissolved nitrogen (TDIN) for Lippenbroek for the various 13-hour measurements of the past years. Positive balance indicates TDIN retention in Lippenbroek. The trend line indicates a significant downward trend.

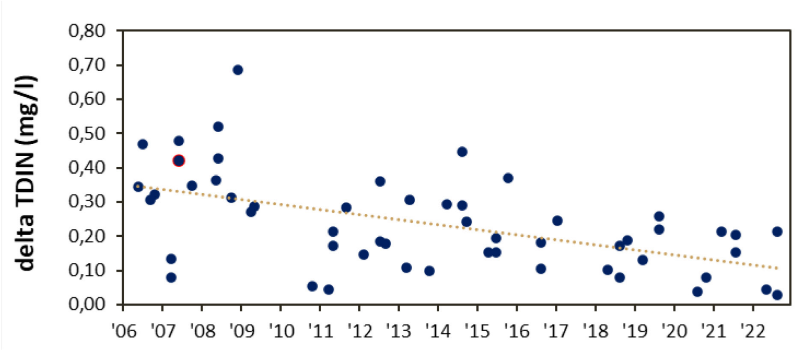

Figure 21 - Concentration difference (flow-weighted concentrations) for TDIN between inflow and outflow for the various 13-hour measurements of the past years. Positive balance indicates TDIN retention in Lippenbroek. The trend line indicates a significant downward trend.

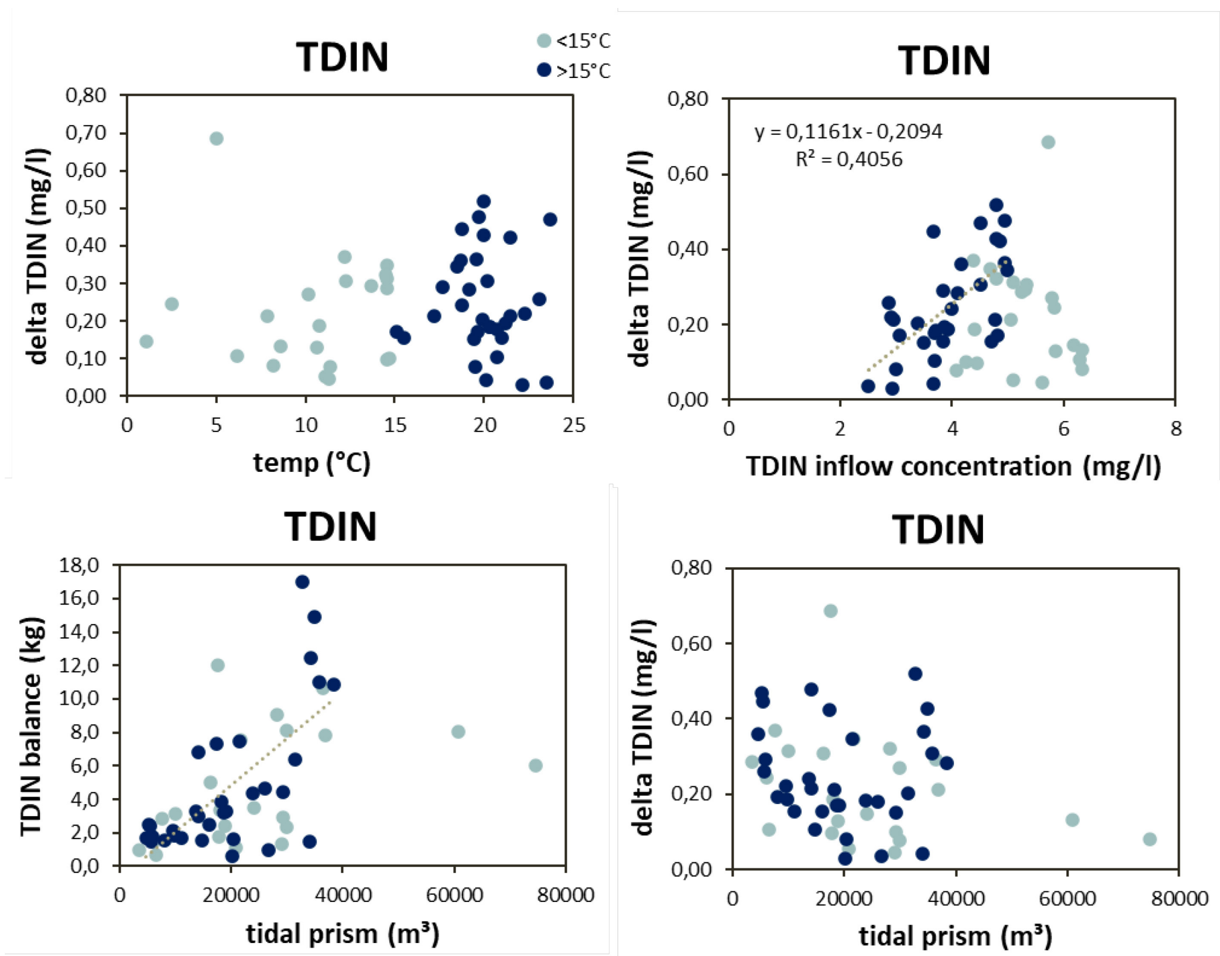

Figure 22 - Top left: Concentration difference (discharge-weighted concentrations) for TDIN between inflow and outflow as a function of the average water temperature; top right: concentration difference for TDIN as a function of the discharge-weighted TDIN concentration of the inflow; bottom left: conservative TDIN balance as a function of the tidal prism; bottom right: concentration difference for TDIN as a function of the tidal prism. In grey campaigns with average water temperature below 15 °C, in blue above 15 °C.

Figure 22 examines the relationships between the TDIN balance and possible explanatory factors. Since nitrogen removal via nitrification and denitrification are bacterial processes and therefore temperature-dependent, the concentration difference (discharge-weighted) between inflow and outflow is plotted related to the water temperature in the first plot. The concentration difference appears to be weakly correlated with temperature ($r=0.26$; $p<0.05$). At low temperatures, the concentration difference for TDIN between inflow and outflow is indeed lower on average. At temperatures below 10°C the difference is usually small and there seem to be fewer conversions of TDIN (1 campaign at 5°C does have an unexpectedly high delta TDIN). Between 10 and 15°C a range of delta TDIN and TDIN balances occur, but no clear correlation is found with the concentration of TDIN at inflow or the tidal volume. It is possible that the water temperature in the weeks preceding the campaign plays a decisive role in the presence or absence of active populations of nitrifying and denitrifying bacteria. At temperatures above 15°C these populations are probably always present; above 15°C there is no longer a correlation between temperature and delta TDIN. However, nice correlations are then found between TDIN removal and the TDIN concentration at inflow or the tidal prism. In campaigns at temperatures above 10°C these correlations are also present, although less strong. Below 10°C no significant correlations were observed.

When the concentration difference between inflow and outflow (delta TDIN) is plotted against the average concentration of the inflow (TDIN IN) for each tidal campaign, we get a cloud of points (Figure 22 top right).

However, if we only consider these 13 hour campaigns with an average water temperature above 15°C, the concentration difference is correlated with the concentration of the inflow ($r= 0.63$; $p<0.01$; at temperatures from 10°C the relationship is weaker: $r=0.34$). The higher the inflow concentration, the stronger the concentration difference will be and therefore the greater the retention can be. Since the TDIN concentration in the Schelde has shown a significant downward trend over the past 15 years ($R^2 = 0.37$; $p<0.01$; data not shown), a trend that fortunately continues in 2024, this explains why the TDIN retention shows a downward trend over time and will probably continue to decline. To put it simple: as the Schelde gets cleaner, there is less nitrogen to be removed.

The tidal volume exchanged between the Schelde and Lippenbroek (tidal prism) also plays a role. In Figure 22 (bottom left), the TDIN balance is plotted as a function of the tidal prism. Both are significantly correlated (above 15°C: $r = 0.67$; $p<0.01$ and above 10°C: $r = 0.63$; p0.01). Tidal volume and delta TDIN, on the other hand, are not correlated. This suggests that TDIN removal in Lippenbroek is mainly a pelagic process, and that bottom processes make up a smaller share: larger tidal volumes ensure proportionally larger TDIN retention, while the concentration difference only depends on the TDIN at inflow, and not on the tidal volume. With a significant contribution from bottom processes, one would rather expect a negative correlation between delta TDIN and tidal volume. This seems contradictory to the findings in natural tidal marshes, where water purification is mainly attributed to bottom processes. However, natural tidal marshes have a very porous soil through which water can flow relatively easily. In Lippenbroek, there is an impermeable compact clay layer underneath the layer of freshly deposited sediments, which means that this soil can hardly or not at all contribute to the water purification processes. In contrast to the increase delivery of DSi after some years of soil development, no increase in the removal capacity is observed in Lippenbroek. Nevertheless, the potential is there: measurements in Lippenbroek in pore water and water flowing from crab holes clearly show lower TDIN concentrations, but the contribution of this limited exchange is perhaps too limited to be measurable on the scale of the entire area. Furthermore, the flooding water in a CRT has a longer residence time compared to a natural salt marsh, which means that the pelagic processes can have a greater impact.

In pelagic processes, the previously mentioned bacterial processes play a role, whereby processes that continue in anoxic flocs can be important. Algal blooms in the water column also potentially influence the TDIN concentration, through the uptake of ammonium or nitrate. The delta TDIN is significantly correlated with the chl a concentration for both campaigns with water temperatures above 15°C ($r=0.47$; $p<0.05$) and for all measurements ($r=0.52$; $p<0.01$) (Figure 23).

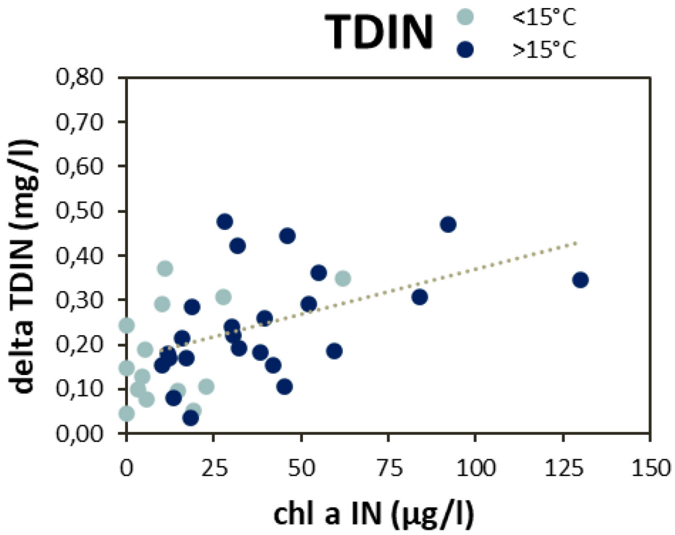

Figure 23 - Concentration difference (discharge-weighted concentrations) for TDIN between inflow and outflow as a function of the discharge-weighted chl a concentration of the inflow

Based on the above, the following conclusions are made:

- TDIN removal is correlated with the tidal prism
- TDIN removal is correlated with TDIN inflow concentration
- TDIN removal is independent of the flooded surface

There is no evidence that the TDIN removal capacity is decreasing in Lippenbroek, so we assume it remains constant over time to study the influence of the LIFE Sparc areas on water quality.

Based on a multiple linear regression (R^2 = 0,69) TDIN removal by the marsh can be estimated: TDIN flux/tide = 0,00025 * V + 2,80024 * TDIN_in – 11,1831

with V = average exchanged water volume (tidal prism, m^3)
TDIN_in = TDIN inflow concentration (mg/l TDIN)

The above formulation works fine in CRT areas. In young MR sites, the tidal prism can however be very different from CRT areas or natural marshes. Due to the often low elevation of MR sites right after opening, as is the case with the LIFE Sparc sites, it is unclear whether the TDIN removal still increases linear with the tidal prism. The above formulations most likely overestimate the TDIN removal. In a mass balance study of 1 single tide in the MR site Hedwige-Prosperpolder, a large MR site in the Schelde estuary at the Dutch-Belgian border, a removal of about 250 kg TDIN per tide was measured. This site has a low elevation, leading to a large tidal prism compared the natural marshes or CRT sites. Using the formulations based upon the Lippenbroek research, a removal of about 1000 kg was expected, clearly indicating the overestimation of this approach by a factor 4.

Therefore, MR sites and CRT sites will be calculated and discussed separately, to take into account this overestimation of removal in MR sites.

5.6 Estimated Nitrogen removal by the LIFE Sparc sites

5.6.1 Modeling nitrogen removal

The studied LIFE Sparc areas were listed in Table 2. TDIN removal depends on the tidal prism during a tidal cycle. Average tidal prism for different tidal conditions has been calculated by Flanders Hydraulics (Nazarali & Vanlede, 2025 based on the detailed HD simulations of Bi et al., 2022) and is summarized in Table 7.

Besides the tidal prism, also the incoming TDIN concentration is of importance for the removal of TDIN. Therefore, monitoring stations in the estuary used as a reference for the incoming water quality are also listed in Table 2. Table 8 lists for these stations the average winter and summer half year concentrations, and also averages for July and August, when lowest TDIN concentrations usually occur.

Table 7 - Average tidal prism (1000 m³) for the different Sparc sites at different tidal conditions.

Average tidal prism [1000 m³]	neap	average	spring
Uiterdijk	2,3	31,2	47,5
Klein Broek	63,2	152,7	218,6
Groot Broek	84,6	275,9	404,3
Groot Schoor Bornem	507,3	597,6	648,7
Groot Schoor Hamme	9,2	85,7	150
Vlassenbroek	45,6	98,1	123,4
Wal	48,9	84	112,2
Zwijn	69,2	129,4	176,2
De Bunt	38,3	85	121,9

Table 8 - TDIN concentration (mg/l) for several reference stations for the period 2014-2024: a winter half year average (from October until March); a summer half year average (from April until September and an average for July-August

Station	winter	summer	Jul-Aug
	average	average	average
Melle	6,3	4,8	4,2
Dendermonde	5,7	4,1	3,6
Baasrode	5,5	3,9	3,5
Temse	5,1	3,8	3,3
Durme (Tielrode)	5,3	3,7	3,3

In Figure 24 modeled TDIN removal for the Sparc sites in shown. Due to a larger tidal prism the TDIN removal at spring tides is significantly larger than at neap tides. Also the managed realignment (MR) sites show a larger removal, due to the initial large tidal prism. As discussed before, this removal is most likely overestimated, depending on the initial elevation and thus initial tidal prism of the site. In the MR sites with low initial elevation and hence large tidal prism, such as Groot Schoor Bornem, the TDIN removal will be overestimated more than in sites with an already high elevation and thus smaller tidal volume.

MR sites with a low elevation will silt up very fast to reach an elevation close to the level of high tide. A rough estimate of the reduced tidal prism that corresponds to this higher elevation was made, assuming a flooding height of 40 cm at springtide. This results in a lower TDIN removal in these MR sites, bringing these sites in the same range of TDIN removal as the CRT sites. The removal by the CRT sites is modelled more accurately, as the model is based on the Lippenbroek CRT.

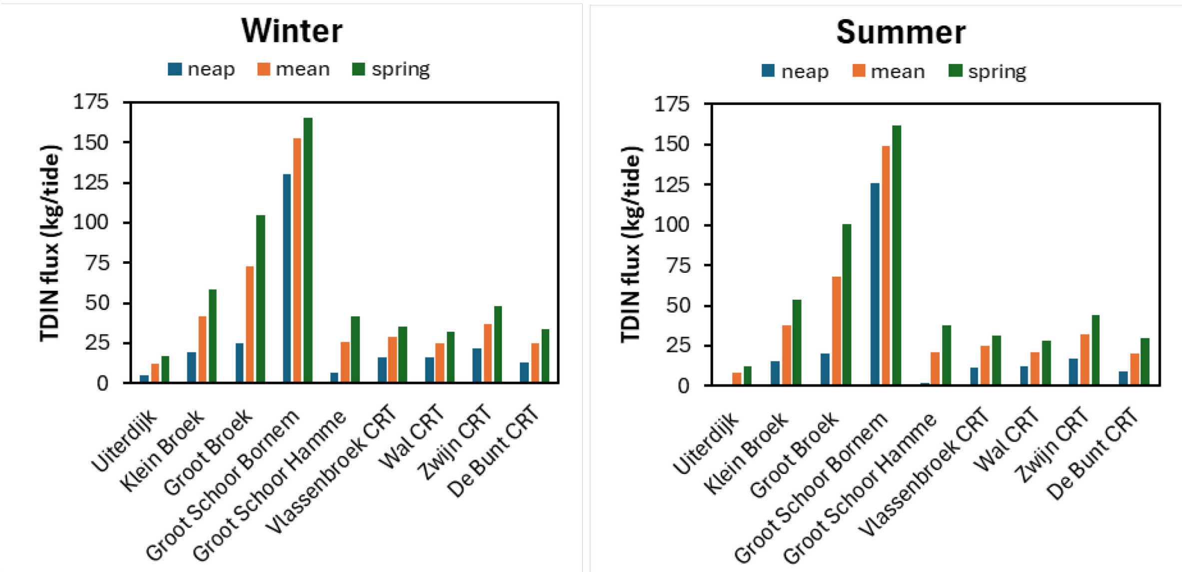

Figure 24 - TDIN removal (positive values) for the LIFE Sparc sites at different tidal conditions (neap, mean and spring tide) and TDIN inflow concentrations for the winter half year and the summer half year.

5.6.2 Relevance of the LIFE Sparc sites for the TDIN cycling in the estuary.

From Figure 24 it is clear that the LIFE Sparc marshes remove nitrogen, especially at spring tide. The initial removal by MR sites is likely overestimated, but when the marshes silt up, they perform equally to the CRT sites. To estimate the relevance of this, the total removal by the all the LIFE Sparc MR ad CRT marshes is calculated for an entire month. The fluxes per tidal cycle are summed for a month, assuming on average 10 tides with neap tide conditions, 40 with mean conditions and 10 with spring tide conditions in a month. For the MR sites, also the fluxes after a period of sedimentation have been estimated, so with a strongly reduced tidal prism. An average flooding height of 40 cm at springtide was used to estimate an average tidal prism and calculate the average TDIN removal after a period of sedimentation.

The monthly TDIN fluxes from the Sparc marshes can be compared with monthly TDIN fluxes for several transects in the estuary (Table 9 to Table 11). These monthly fluxes in the estuary are estimated as the product of the monthly averaged discharge and TDIN concentration data (period 2014-2024) at the several locations and climatological conditions.

In the winter half year, TDIN removal by LIFE Sparc sites (both CRT and MR) is highest due to the higher TDIN concentration in the estuary on condition that the water temperature is above 15°C. This is of course very often not the case, so removal will be less. But even at 15°C, this removal is very small compared to the high estuarine TDIN flux. The impact of LIFE Sparc on the TDIN cycling in the winter half year is therefor considered to be very small.

In the summer half year, and especially in the warmer summer months (July and August), the absolute removal by the LIFE Sparc sites is less, but becomes relatively more important due to the smaller estuarine influx. The total TDIN removal by the LIFE Sparc CRT sites increases up to 3 or 4% of the estuarine flux (Table 9). In the MR sites, an initial higher contribution to the TDIN removal was calculated, but this is an overestimation due to the often very large initial tidal prism (Table 9). If a reduced tidal prism is used (after considerable sedimentation), similar removal values as CRT areas are achieved. In Table 11 the total contribution of all LIFE Sparc CRT and MR sites, after a period of sedimentation, are summarized. We can conclude that these areas together will minimally remove 5 to 8% of the TDIN flux entering the estuary in summer. This is an important contribution to a better water quality, but by far not enough to achieve WFD standards.

Table 9 - Monthly TDIN removal at average conditions for the winter half year, summer half year and the months July and August for the LIFE Sparc CRT areas, and monthly estuarine TDIN influx at Melle, Dendermonde and Temse. The column % gives the ratio of the TDIN flux coming from all Sparc CRT aeras compared to the estuarine flux.

	Sparc CRT	Melle			Dendermonde			Temse		
	TDIN import	TDIN	TDIN flux	TDIN flux	TDIN	TDIN flux	TDIN flux	TDIN	TDIN flux	TDIN flux
	ton/month	mg/l	ton/month	%	mg/l	ton/month	%	mg/l	ton/month	%
winter	7	6,3	805	1%	5,7	728	1%	5,1	1048	1%
summer	6	4,8	227	3%	4,1	194	3%	3,8	303	2%
July-Aug.	5	4,2	138	4%	3,6	118	4%	3,3	202	2%

Table 10 - Monthly TDIN removal at average conditions for the winter half year, summer half year and the months July and August for the LIFE Sparc MR sites at initial elevation, and monthly estuarine TDIN influx at Melle, Dendermonde and Temse. The column % gives the ratio of the TDIN flux coming from all Sparc MR sites compared to the estuarine flux.

	Sparc MR	Melle			Dendermonde			Temse		
	TDIN import	TDIN	TDIN flux	TDIN flux	TDIN	TDIN flux	TDIN flux	TDIN	TDIN flux	TDIN flux
	ton/month	mg/l	ton/month	%	mg/l	ton/month	%	mg/l	ton/month	%
winter	18	6,3	805	2%	5,7	728	2%	5,1	1048	2%
summer	17	4,8	227	7%	4,1	194	9%	3,8	303	5%
July-Aug.	15	4,2	138	11%	3,6	118	12%	3,3	202	7%

Table 11 - Monthly TDIN removal at average conditions for the winter half year, summer half year and the months July and August for the LIFE Sparc CRT sites and MR sites after a period of sedimentation, and monthly estuarine TDIN influx at Melle, Dendermonde and Temse. The column % gives the ratio of the TDIN flux coming from all Sparc MR sites compared to the estuarine flux.

	Sparc MR	Melle			Dendermonde			Temse		
	TDIN import	TDIN	TDIN flux	TDIN flux	TDIN	TDIN flux	TDIN flux	TDIN	TDIN flux	TDIN flux
	ton/month	mg/l	ton/month	%	mg/l	ton/month	%	mg/l	ton/month	%
winter	14	6,3	805	2%	5,7	728	1%	5,1	1048	1%
summer	12	4,8	227	5%	4,1	194	6%	3,8	303	4%
July-Aug.	11	4,2	138	8%	3,6	118	9%	3,3	202	5%

6 Estuarine habitat mapping of the LIFE Sparc areas

This chapter is based on the work of INBO which is reported in Vanermen et al. (2025)

6.1 Aims & scope

The main goal of this study was to produce physiotope maps for all eight LIFE Sparc areas, five of which are planned to be de-embanked and three of which will be constructed as so-called flood control areas with reduced tides (FCA-CRT's, Maris *et al*. 2020). Note that at the time of writing two LIFE Sparc areas were already subject to tidal dynamics after de-embankment. Apart from producing habitat maps reflecting the current reference situation, we aimed at estimating the expected sedimentation rate inside these areas over a period of 25 years and, as such, at generating habitat maps reflecting the situation in 2050.

6.2 Methods

6.2.1 Sedimentation

The expected sedimentation of the LIFE Sparc areas over the period 2025-2050 was estimated making use of the sedimentation model recently developed at the Research Institute for Nature and Forest (Vanermen *et al*. in prep.). This model was calibrated using the evolution in mean DTM level of five de-embankments along the Lower Sea Scheldt across timeframes of 4 to 15 years. The point model predicts the amount of sedimentation based on the mean depth at high water within a specific year, according to the following linear model:

$$\Delta E_y = -0.0565 + 0.2306\, h_y$$

In which:

- ΔE_y : sedimentation (m) in year y
- h_y : mean depth at high water (m) in year y

As mean water depths decrease with increasing sedimentation, the model needs to be applied in an iterative manner, each time taking in account the predicted sedimentation of the year before.

Within this study we explored several pathways to apply this point model on a two-dimensional DTM, in order to generate input for the 2050 physiotope mapping. Part of this exploration exercise is illustrated in Figure 25, with the de-embankment of Burchtse Weel as a case study, the cumulative frequency plot of the area's DTM values in 2014 as the reference situation and the hypsometry of 2018 as validation. Considering the nature of the sedimentation model, the most straightforward way would be to perform a year-by-year raise of the entire DTM with the predicted mean sedimentation (Figure 25.a). This way, however, the upper regions of the area tend to silt up in an unrealistic manner, at places that are barely flooded. In a second step, we applied the 1D model on fixed percentile interval heights (every 2 percent) to build a sedimented frequency plot. Though some flattening of an area's DTM profile is likely to occur due to sedimentation, the flattening obtained through this strategy appears to be far too extreme (Figure 25.b). Note that both above strategies suffer from overestimating sedimentation around the lowest point of the frequency plot.

This point is likely to coincide with the outlet of the main creek where sedimentation is actually rather weak or even absent due to local erosion.

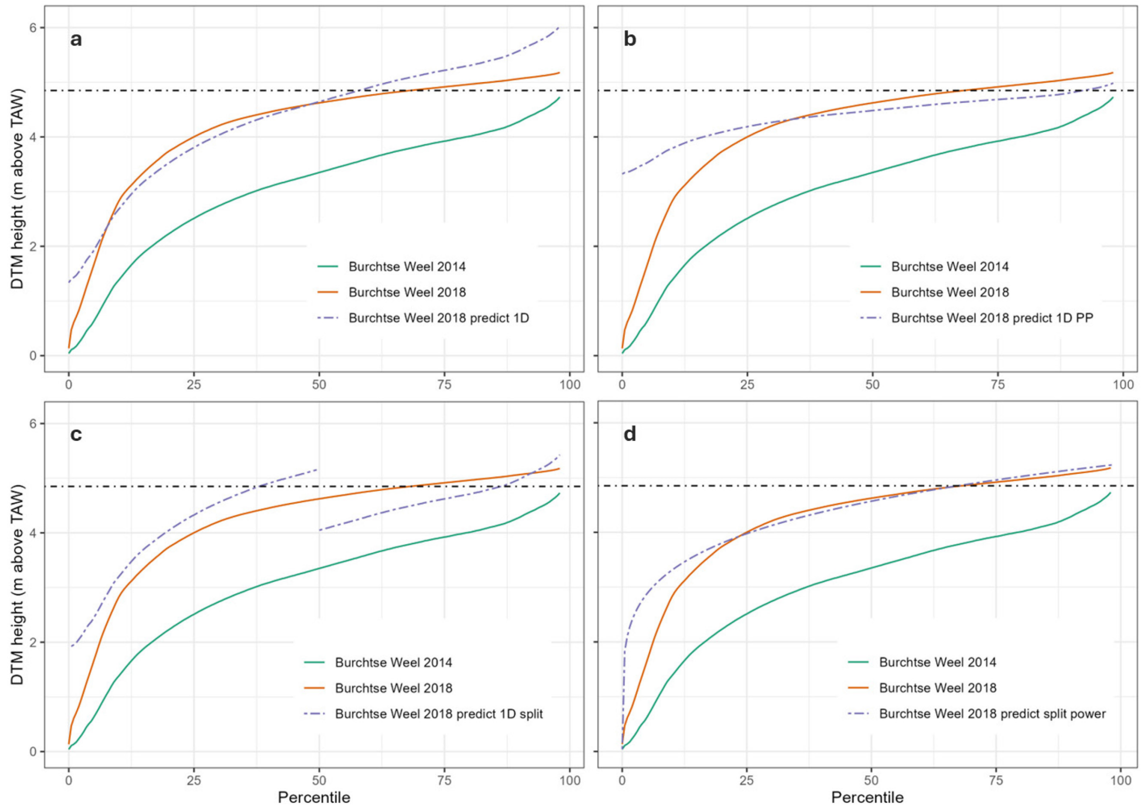

Figure 25 - Illustration of several possible methods (**a**, **b** & **d**) to apply the 1D sedimentation model on a two-dimensional DTM, with **c** to be interpreted as an intermediate step towards method **d**; the black dot-dash line depicts the theoretical boundary between tidal mudflat and tidal marsh.

Trying to meet the above concerns we implemented a two-step strategy by:

- splitting the area in a lower and an upper half, calculating the expected sedimentation for each half, and performing a uniform lift for both parts of the cumulative frequency plot (Figure 25.c)
- fitting a power curve through the lowest point of the DTM of the reference year and through the split cumulative frequency plot as generated in the step above (Figure 25.d).

While step 1 avoids unrealistically strong sedimentation in the uppermost parts of the de-embankment, step 2 avoids overestimating sedimentation at the outlet of the main creek.

The exercise as shown in Figure 25 was done for each of the same 5 de-embankments that were used to calibrate the sedimentation model in the first place. Strategy **d** resulted in the best overall fit with the validation curve for 3 out of 5 areas, and was chosen as the preferred option.

The coefficients of the modelled power curve then allow to simulate a new DTM, which in turn is used to generate physiotope maps representing the situation 25 year ahead of this moment (see §6.2.2). Important to note is that we only used the estuarine part of the reference DTM's (as defined by the physiotope map of the reference year) to model sedimentation rates. Also, tidal pools were left out of the 2050 maps since no DTM information was available for these locations.

6.2.2 Physiotope mapping

Physiotopes can be defined as spatial units that are homogeneous regarding abiotic conditions, which in turn shape the biotic environment. In this respect, the physiotope mapping within this project aimed to predict the occurrence and distribution of estuarine habitats by combining DTM's (Digital Terrain Models) with tidal water level data.

DTM's of the entire Upper Sea Scheldt are available for every third year (GIS-cel AMT 2025) and are generated based upon area-wide LiDAR and bathymetry measurements. We used the most recent available DTM of 2022 for six out of eight areas to represent the reference situation. Note that none of these six areas were subject to tidal dynamics in 2022, nor were they at the time of writing. For the two already de-embanked areas Groot Schoor Hamme & Klein Broek we used more recently generated DTM's, following targeted drone flights and referenced as 'Groot Schoor T5 - 19/02/2025' & 'Klein Broek T3 - 03/03/2025'.

The necessary water level data were delivered by Flanders Hydraulics (FH) and are the result of a hydrodynamic modelling exercise departing from so-called synthetic boundary conditions. Note that this is the same strategy as followed during the project 'Integral Plan for the Upper Sea Scheldt'. The synthetic boundary conditions in turn were derived from a statistical analysis of historical data and are regarded to be suitable for long-term studies. The synthetic data include a normal scenario (QN) that lasts about 3 months and a storm surge scenario (QE) of about 15 days. The combination of four times QN plus one time QE (4QN+QE) is assumed to represent a full year. The boundary conditions are described in more detail by Bi *et al*. (2022) and Figure 26 shows the QN and QE data series for the Vlassenbroek FCA-CRT by means of example.

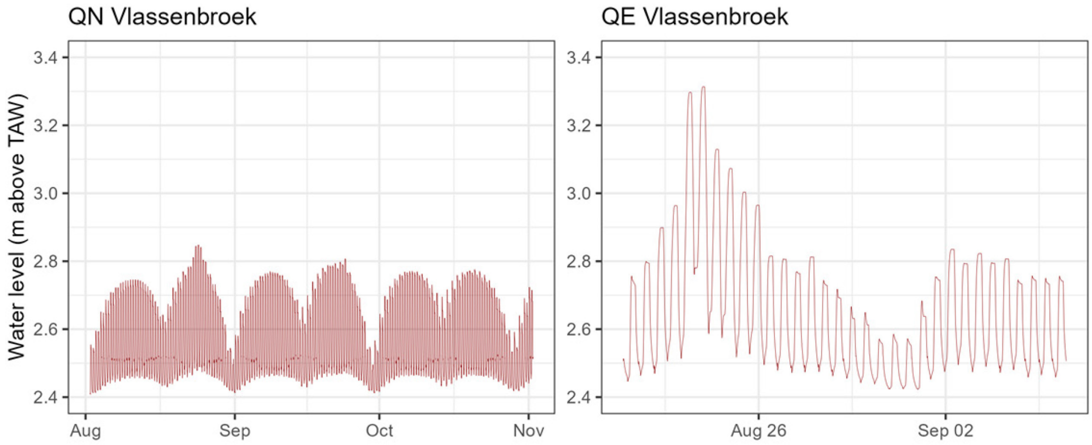

Figure 26 - Illustration of the QN (92 days) & QE (15 days) water level data series, as modelled by FH for the Vlassenbroek FCA-CRT.

In a next step, the DTM's were merged with the local water level data to delineate physiotopes using specific percentiles of low water (LW), high water (HW) or exposure time (ET) (Table 1). For the FCA-CRT's we derived the ET boundaries directly from the water level data as modelled by FH at one specific point inside each area. For de-embankments on the other hand, we interpolated the available water level data within stretches of 0 to 7 km for the Durme and of 30 to 80 km for the Upper Sea Scheldt. Applying 50 m intervals, we combined these interpolated water levels with the so-called allocation zones to capture the expected (yet slight) variation in water levels occurring within each de-embankment (Van Braeckel *et al.* 2008). Note that this strategy was assuming a full removal of the dyke, which was also the assumption in the FH modelling exercise (Bi *et al*. 2022).

Table 12 - Physiotope boundaries applied for the LIFE Sparc habitat mapping.

	Physiotope boundaries	
	De-embankments (Van Braeckel *et al*. 2019)	FCA-CRT's (MONEOS methodology)
Shallow subtidal	< LW 10%	< ET 4%
Low tidal mudflat	LW 10% – ET 25%	ET 4% – ET 35%
Medium high tidal mudflat	ET 25% – ET 75%	ET 35% – ET 60%
High tidal mudflat	ET 75% – HW 90%	ET 60% – ET 85%
Tidal marsh	HW 90% – HW 0.5%	ET 85% – ET 99.5%
Non-estuarine habitat	> HW 0.5%	> ET 99.5%
Tidal pool	Manually digitalised shallows or standing water	

6.2.3 Open science

All R and Python scripts written in the framework of this study are stored in an open-access Github repository.

6.3 Results

6.3.1 Expected sedimentation on de-embankments

The results of applying our sedimentation methodology on the cumulative frequency plots of the LIFE Sparc de-embankment DTM's is shown in Figure 27. Also showing the HW 90% boundary (see Table 12), these figures illustrate how the major part of all five areas is expected to develop to tidal marsh in a period of 25 years, all of which will be discussed in more detail in §6.3.2.

Applying the current methodology, the uppermost parts of the '2050 model' curves run below the reference lines ('2025 DTM'), as is particularly obvious for Groot Broek & Uiterdijk. We didn't catch this aberrancy earlier, possibly because we applied an inward buffer on the areas used for calibrating the sedimentation model, thus cutting out dyke foots and starting off with a more flattened and less S-shaped curve. For the purpose of physiotope mapping, however, this is not regarded as a major issue. The upper parts of the DTM are classified as tidal marsh both in 2025 and 2050, only a very little part of which can be expected to actually evolve to non-estuarine habitat by 2050. Yet for more detailed analyses, this issue should be taken care of.

Also note that for Groot Schoor Hamme & Klein Broek the '2050 sim > 50%' line overlaps with the '2025 DTM' line. Due to the negative intercept in the equation of the sedimentation model (see §6.2.1), low mean HW depths result in negative sedimentation values. In this specific case, we continued with a zero sedimentation value in the further workflow. This too will be looked into and fine-tuned when updating the sedimentation model with additional data, but again is not expected to effect the physiotope maps in any significant way.

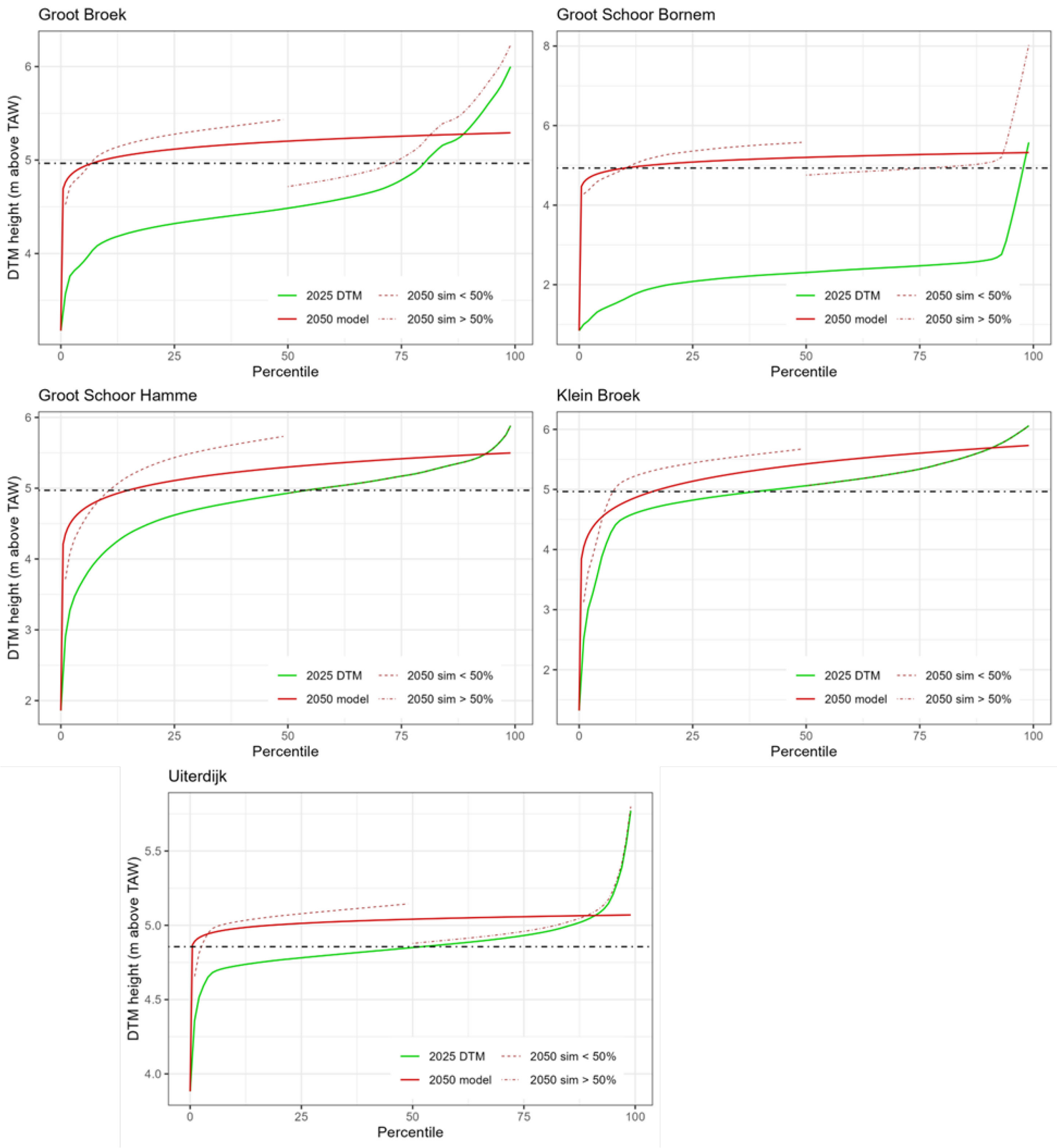

Figure 27 - Illustration of the sedimentation results for the five LIFE Sparc de-embankments; the black dot-dash line depicts the HW 90% height or the theoretical boundary between tidal mudflat and tidal marsh (Table 12).

Table 13 lists the differences in mean bed levels of the (estuarine parts of the) reference and the (simulated) 2050 DTM's. With a 2.82 m increase in mean elevation, by far the most sedimentation is expected to occur at Groot Schoor Bornem. For the other LIFE Sparc de-embankments the amount of sedimentation is much more limited due to higher mean bed levels in the reference year, and the expected sedimentation ranges between 15 and 56 cm only over a period of 25 years.

Table 13 - Overview of the mean elevation of the reference and 2050 DTM's, as well as the expected amount of sedimentation (m) at the five LIFE Sparc de-embankments.

Areas	Reference DTM (mean m above TAW)	2050 DTM (mean m above TAW)	Sedimentation (m)
Groot Broek	4.60	5.17	0.56
Groot Schoor	2.33	5.15	2.82
Groot Schoor	4.83	5.22	0.39
Klein Broek	5.02	5.32	0.30
Uiterdijk	4.88	5.03	0.15

6.3.2 Physiotope maps of the LIFE Sparc de-embankments

Groot Broek

The planned de-embankment at Groot Broek is expected to create 50.8 ha of estuarine habitats. Breaching the dykes would initially result in a large surface area of high tidal mudflat, this physiotope taking in 65% of the total area, with smaller shares of the area coloured as medium high mudflat (10%) and tidal marsh (13%) (Figure 29). Scattered across the area are tidal pools (2%). Non-estuarine habitat takes in about 10% of the total 56.6 ha, because of the inclusion of dykes and a centrally elevated zone (a former landfill) in the area's perimeter.

It should be noted that there was a large gap in the reference DTM due a temporary flooding in the southern extension of the area at the time of the LiDAR measurements. This gap was manually digitalised and classified as high tidal mudflat and tidal marsh based on satellite pictures.

Running the sedimentation model over a period of 25 years results in the physiotope map as shown in Figure 30. By then, most of the area is expected to have evolved to tidal marsh (83%) with only a small share of high tidal mudflat left (5%) (Figure 28). Considering this general trend, the manually classified mudflat in the southern extension of the area was also classified as tidal marsh when producing the 2050 map.

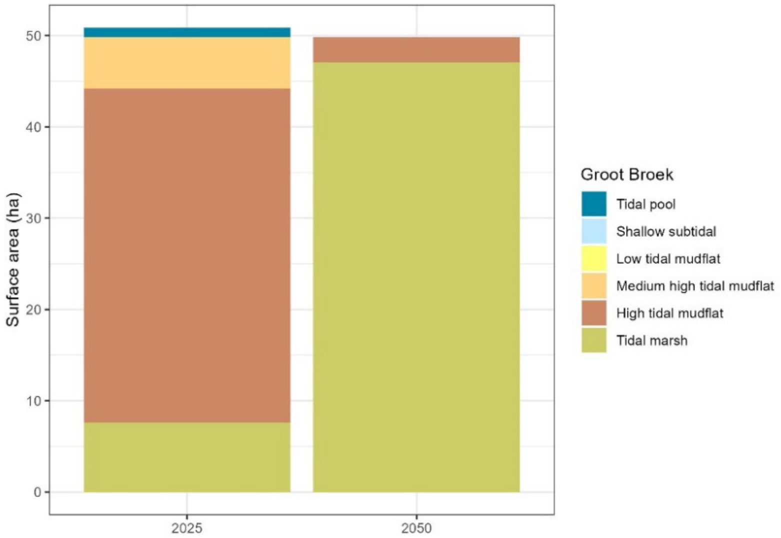

Figure 28 - Summary of the physiotope surface areas (ha) based on the reference and the (simulated) 2050 DTM's at the LIFE Sparc area Groot Broek (excluding non-estuarine habitat).

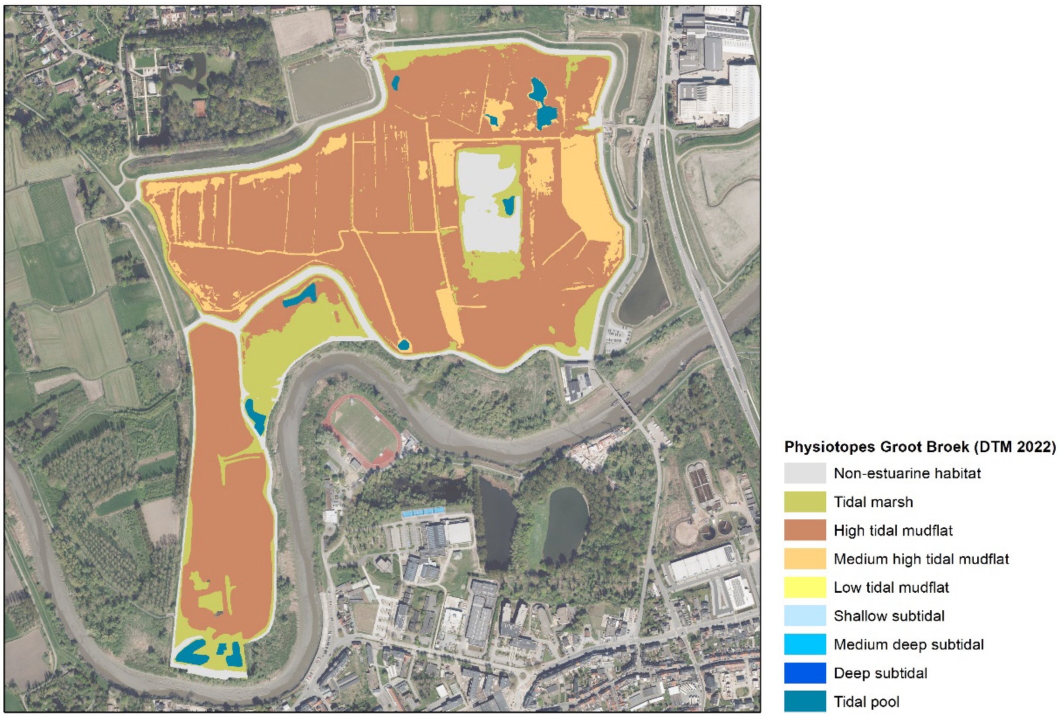

Figure 29 - Physiotope map of the LIFE Sparc area Groot Broek based on the DTM of 2022 and assuming the planned de-embankment.

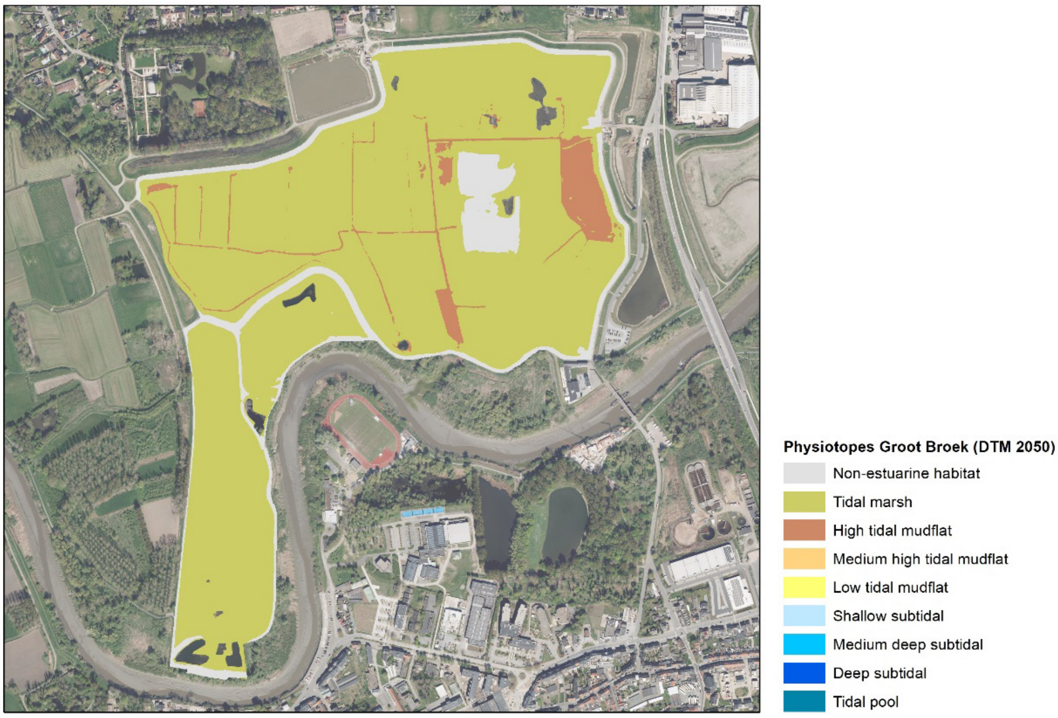

Figure 30 - Physiotope map of the LIFE Sparc area Groot Broek based on a simulated DTM of 2050 taking in account 25 years of sedimentation.

Groot Schoor Bornem/Hingene

The de-embankment of Groot Schoor Bornem (19.8 ha) will initially create a large tidal mudflat (94%), most of which is classified as medium high (Figure 31 & Figure 33). As the perimeter of the area includes some dykes, 4% or 0.7 ha is classified as non-estuarine habitat.

After 25 year the area should have evolved almost entirely to tidal marsh (88%), with only 8% of (high) tidal mudflat left (Figure 32). By then, additional mudflat will have originated in a yet undeveloped creek system, but the location and extent of this creek system is unknown and hard to predict.

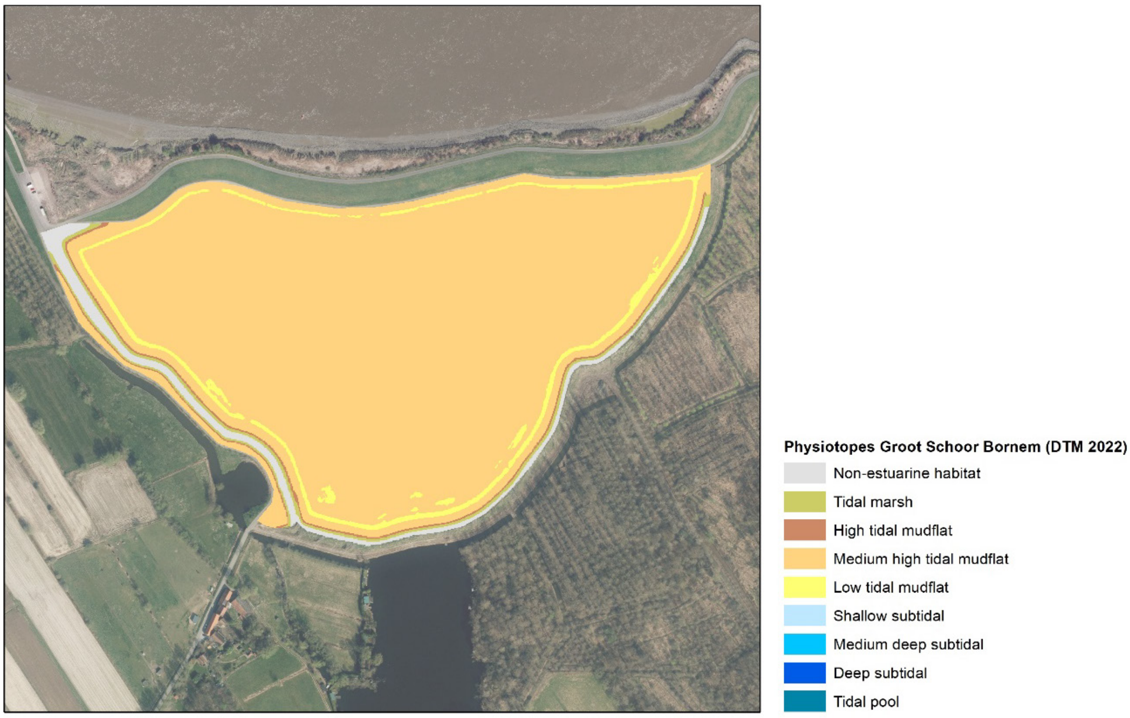

Figure 31 - Physiotope map of the LIFE Sparc area Groot Schoor Bornem based on the DTM of 2022 and assuming the planned de-embankment.

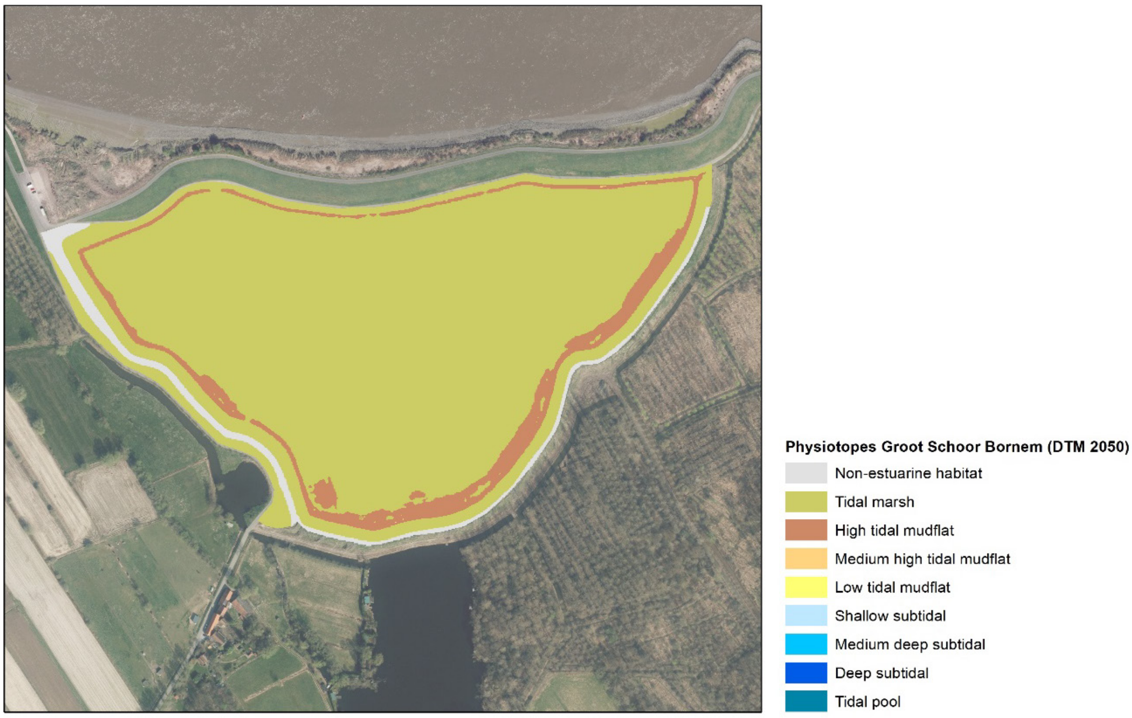

Figure 32 - Physiotope map of the LIFE Sparc area Groot Schoor Bornem based on a simulated DTM of 2050 taking in account 25 years of sedimentation.

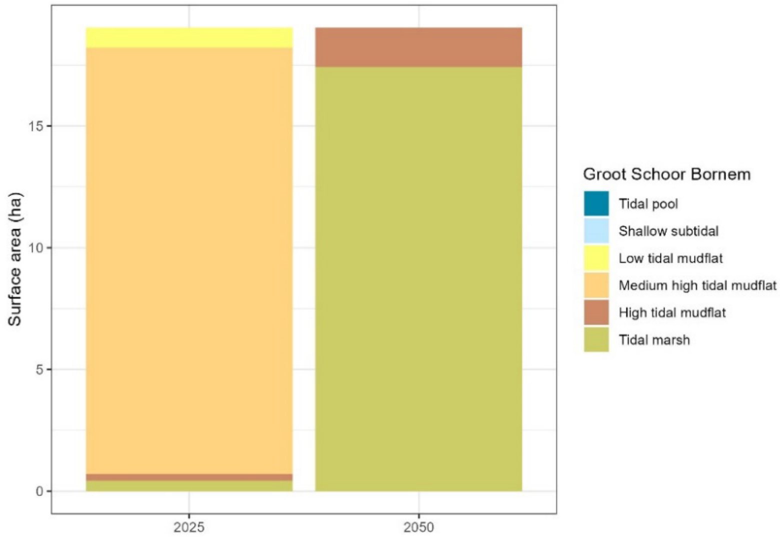

Figure 33 - Summary of the physiotope surface areas (ha) based on the reference and the (simulated) 2050 DTM's at the LIFE Sparc area Groot Schoor Bornem (excluding non-estuarine habitat).

Groot Schoor Hamme

Groot Schoor Hamme was de-embanked in July 2021 and is subject to tidal dynamics ever since. For the habitat mapping, we used a recent DTM representing the situation in February 2025. In the resulting physiotope map, three main creek systems clearly stand out (Figure 34). About 48% of the area is coloured as (mostly high) tidal mudflat and 46% as tidal marsh. Due to the inclusion of dykes in the area's perimeter, 6% or 1.6 ha of the total 26.5 ha is classified as non-estuarine habitat.

In 2050 the area is expected to have largely evolved to tidal marsh (82%) with 12% of (high) tidal mudflat remaining in the three creek systems (Figure 35).

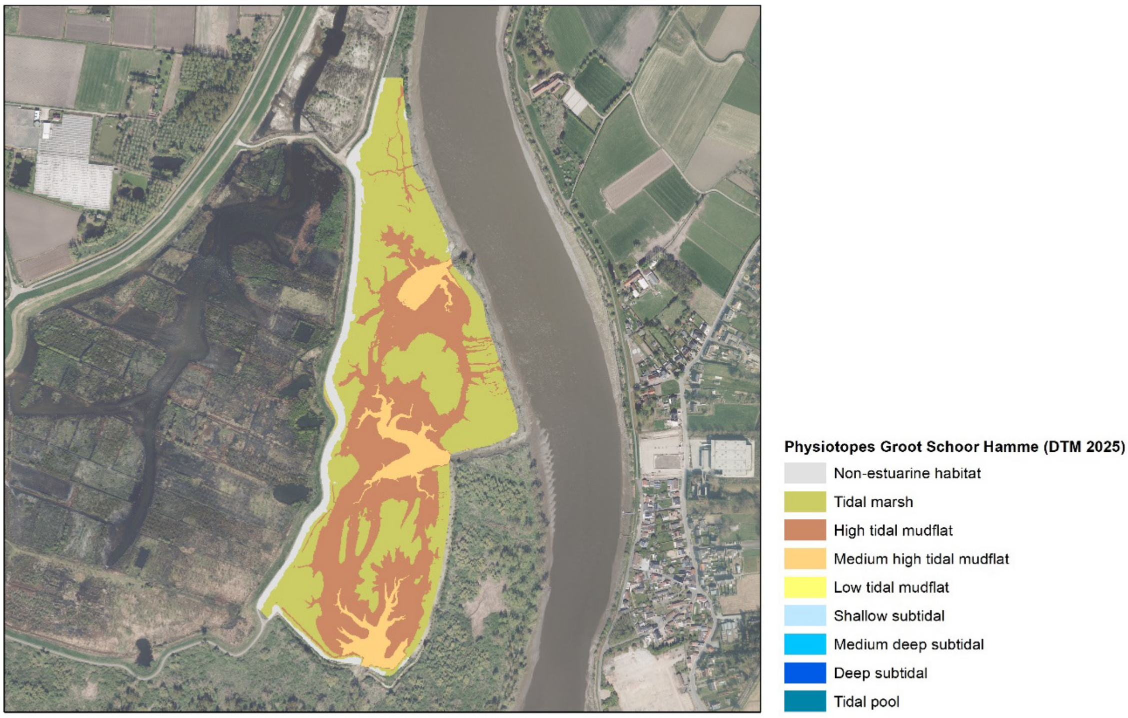

Figure 34 - Physiotope map of the LIFE Sparc area Groot Schoor Hamme based on the DTM of 2025, after de-embankment in 2021.

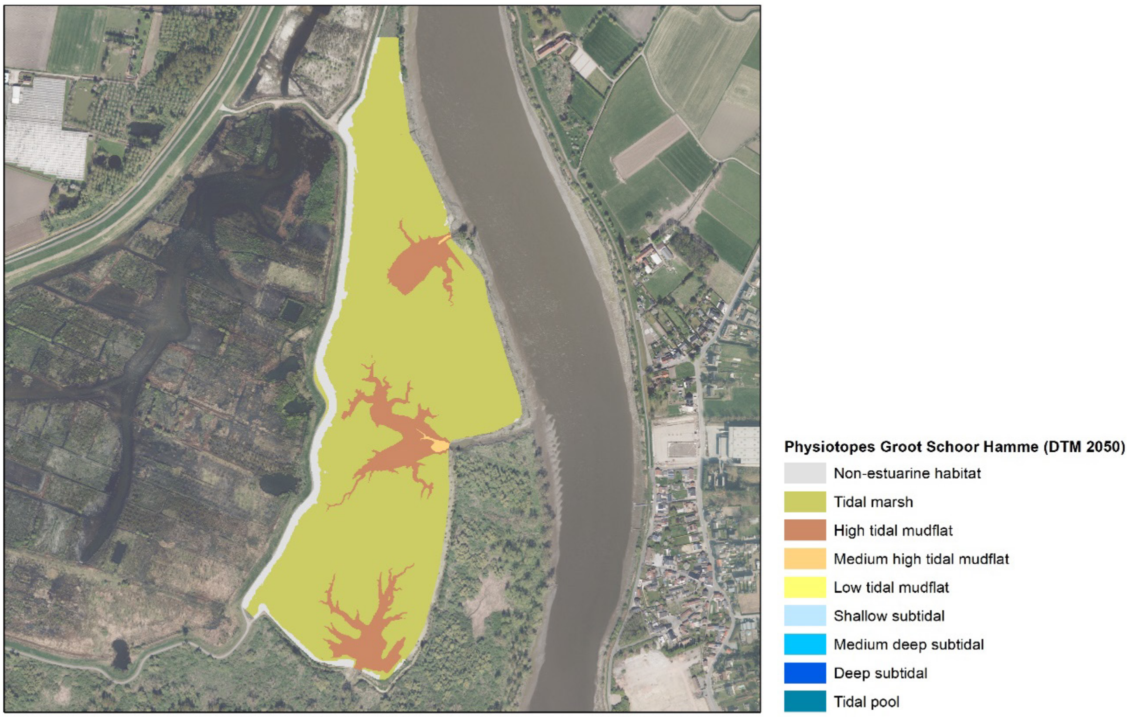

Figure 35 - Physiotope map of the LIFE Sparc area Groot Schoor Hamme based on a simulated DTM of 2050 taking in account 25 years of sedimentation.

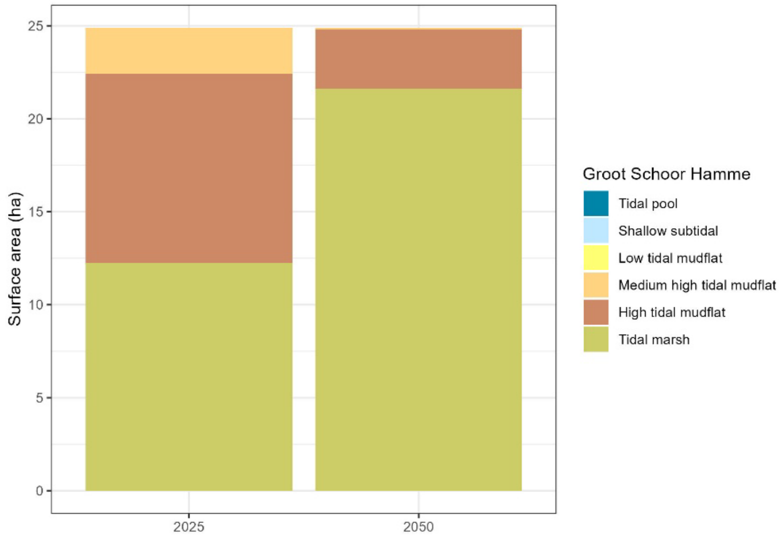

Figure 36 - Summary of the physiotope surface areas (ha) based on the reference and the (simulated) 2050 DTM's at the LIFE Sparc area Groot Schoor Hamme (excluding non-estuarine habitat).

Klein Broek

For Klein Broek (40.3 ha) we also used a recent DTM (March 2025) for our physiotope mapping. The area was de-embanked in 2024 by two breaches in the former dyke. Both creeks are clearly visible in Figure 38 but the in- and outgoing tides have not (yet) led to the formation of a dendritic creek system as prevails in Groot Schoor Hamme (see previous paragraph). The area's elevation is slightly higher compared to the latter, resulting in relatively more tidal marsh (54%) and less tidal mudflats (34%). A relatively large share of the area (13%) is classified as non-estuarine, due to dykes and elevated zones along the northern border, leaving Klein Broek with 35.2 ha of estuarine habitat (Figure 37).

By 2050 most of the area should have evolved to tidal marsh (73%), with 14% of the area still covered by tidal mudflats (Figure 39).

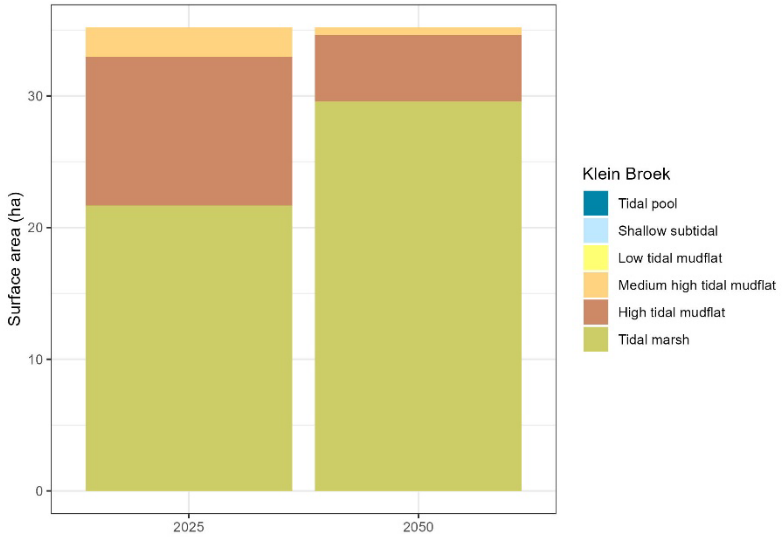

Figure 37 - Summary of the physiotope surface areas (ha) based on the reference and the (simulated) 2050 DTM's at the LIFE Sparc area Klein Broek (excluding non-estuarine habitat).

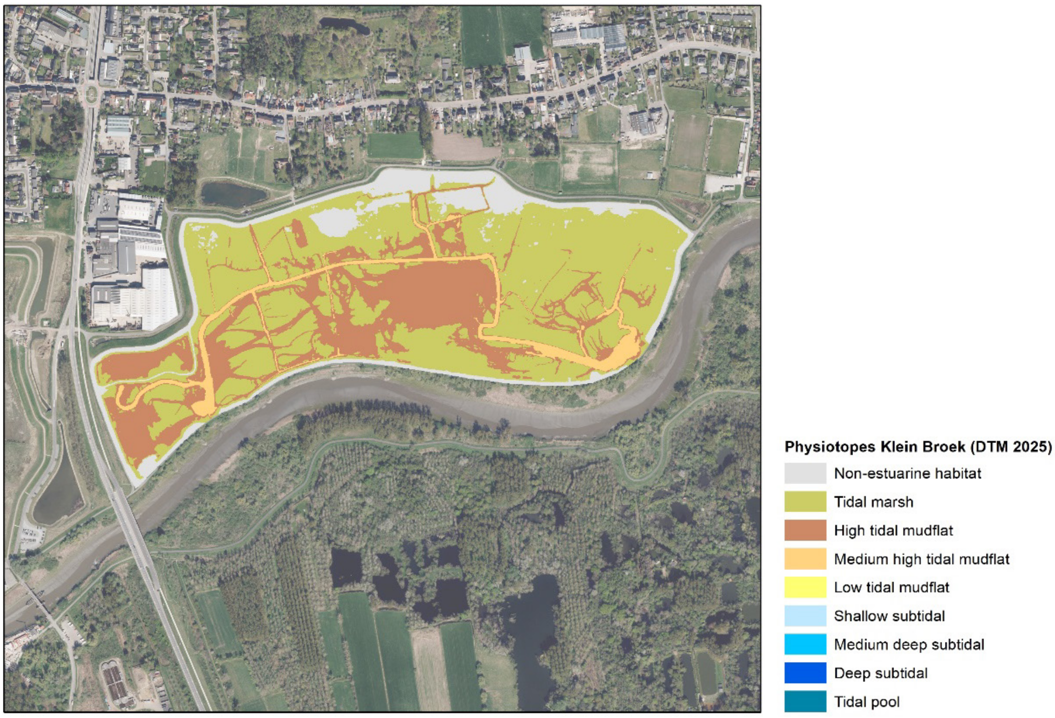

Figure 38 - Physiotope map of the LIFE Sparc area Klein Broek based on the DTM of 2025, after de-embankment in 2021.

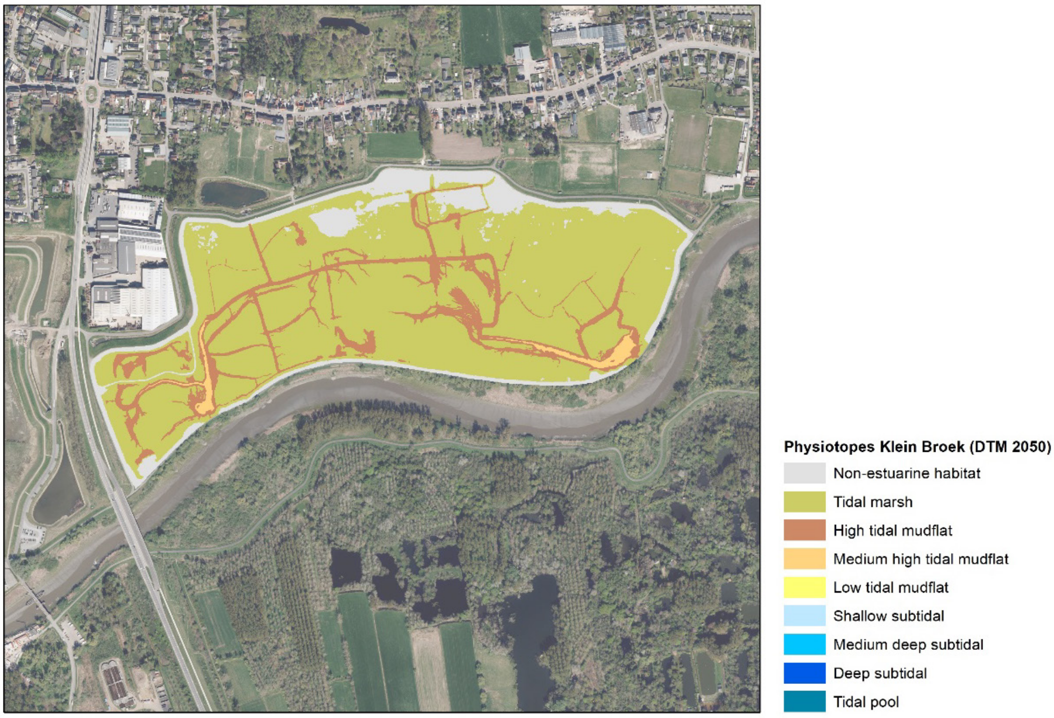

Figure 39 - Physiotope map of the LIFE Sparc area Klein Broek based on a simulated DTM of 2050 taking in account 25 years of sedimentation.

Uiterdijk

Uiterdijk is the smallest of the LIFE Sparc study areas (11.7 ha) and lies at an elevation level which would result in a more or less equal share in high tidal mudflat (48%) and tidal marsh (44%) after de-embankment (Figure 41). About 7% of the area is classified as non-estuarine habitat due to dykes that are (partly) included in the perimeter, and there is one tidal pool. In total the area can host 10.9 ha of estuarine habitats.

By 2050, almost the entire area (92%) will have evolved to tidal marsh due to sedimentation (Figure 40 & Figure 42).

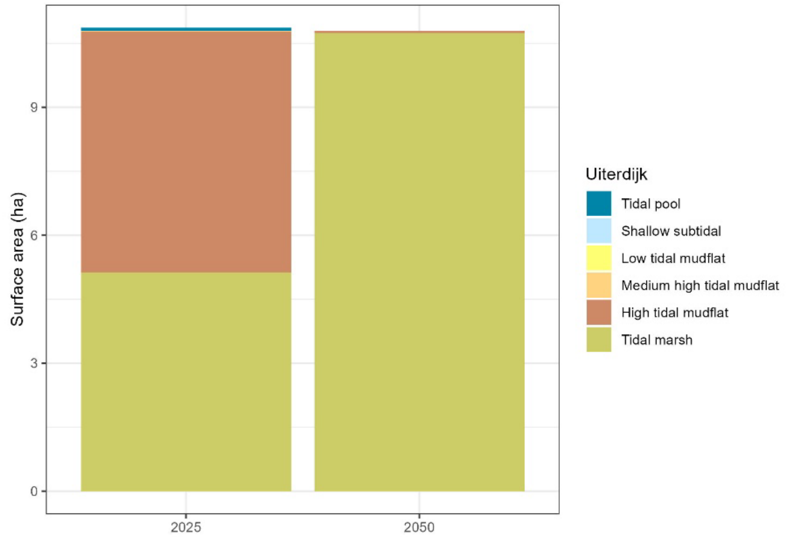

Figure 40 - Summary of the physiotope surface areas (ha) based on the reference and the (simulated) 2050 DTM's at the LIFE Sparc area Uiterdijk (excluding non-estuarine habitat).

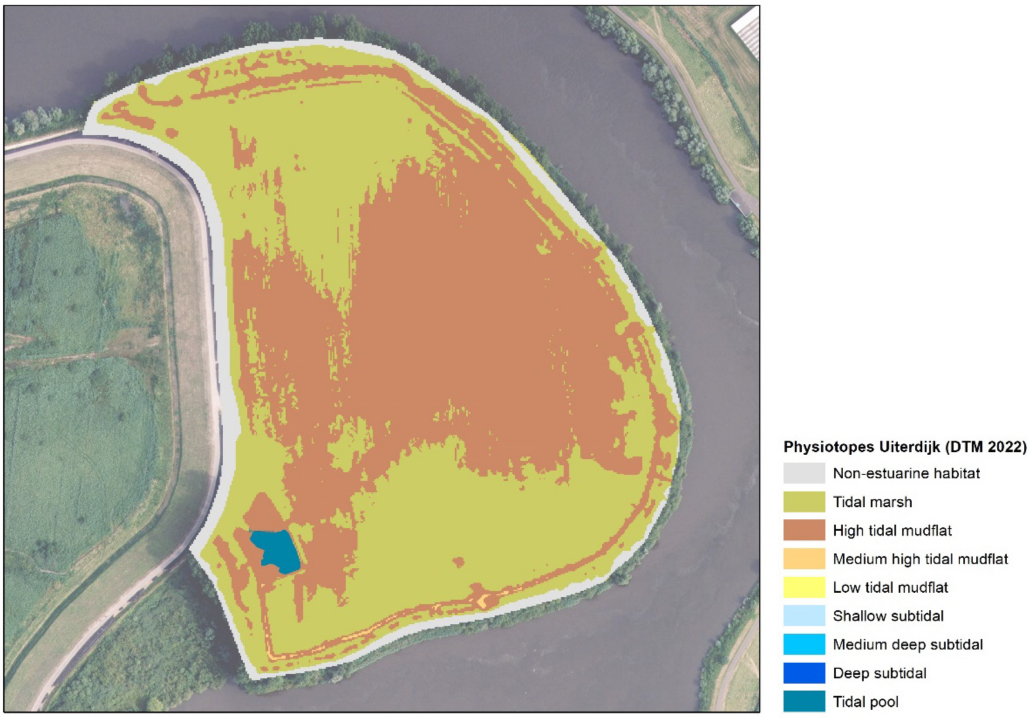

Figure 41 - Physiotope map of the LIFE Sparc area Uiterdijk based on the DTM of 2022 and assuming the planned de-embankment.

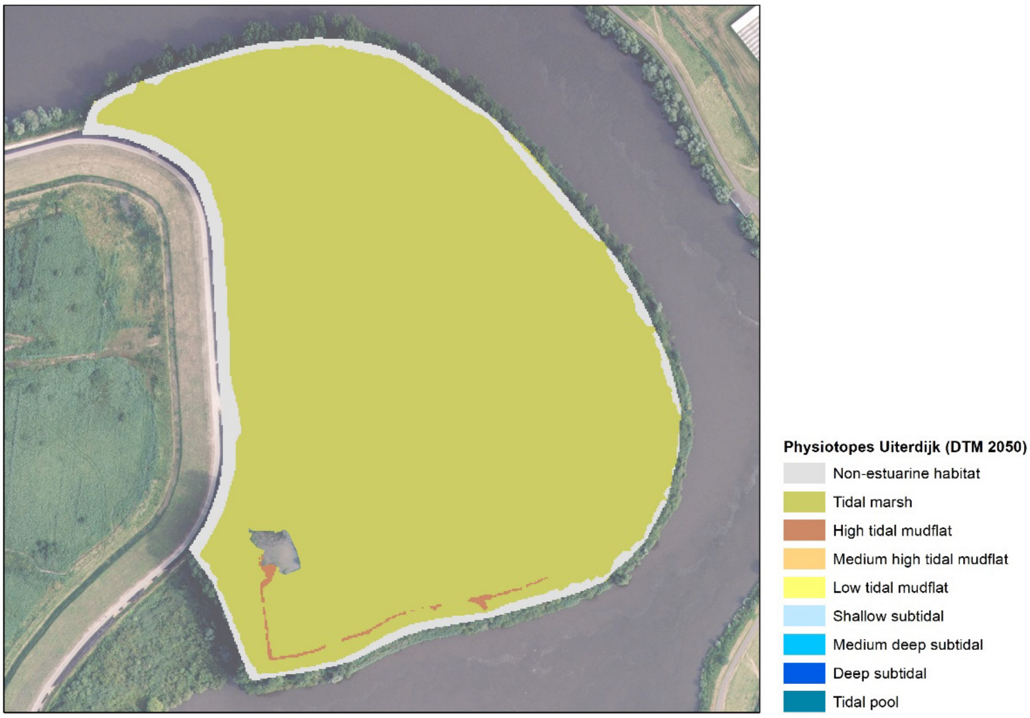

Figure 42 - Physiotope map of the LIFE Sparc area Uiterdijk based on a simulated DTM of 2050 taking in account 25 years of sedimentation.

6.3.3 Physiotope maps of the LIFE Sparc FCA-CRT's

Three LIFE Sparc study areas will be transformed into so-called flood control areas with reduced tides (FCA-CRT's). Apart from an overflow levee, these areas include a sluice system allowing a limited amount of water to flow into the area through a high inlet at high tide. At low tide, the water slowly flows back into the river through a low outlet sluice. In order to trigger the desired development of estuarine nature, the aim is for a FCA-CRT to be flooded for about 20% of its surface at (mean) neap tide and for about 85% at (mean) spring tide (Maris *et al*. 2020).

In the 'habitat model' developed at the Research Institute for Nature and Forest, 80% of tidal marsh and 20% of tidal mudflat was used as the general habitat proportioning occurring within FCA-CRT's (Van Braeckel *et al*. 2019). Based on the results of our physiotope mapping, however, the current LIFE Sparc FCA-CRT settings do not seem to meet this general objective.

Study area De Bunt for example is classified as non-estuarine for about 45% of its surface, followed by high tidal mudflat (37%) and tidal marsh (14%) (Figure 43). Clearly, allowing more water to flow into the area would result in a higher proportion of estuarine versus non-estuarine physiotopes.

The FCA-CRT Vlassenbroek should, based on the delivered 4QN+QE water levels, mostly evolve to shallow subtidal (58%), added with a relatively small share of tidal mudflats (20%) and only 5% of tidal marshes. Non-estuarine habitat takes in about 17%, mostly due to the fact that the wide new Sigma dykes are included in the area's perimeter (Figure 44). At Vlassenbroek, smaller water volumes flowing into the area would result in a more desirable proportion of estuarine habitats.

For Wal & Zwijn, the current combination between the DTM of 2022 and the 4QN+QE water levels does create an interesting and wide mix of estuarine habitats, with 20% of shallow subtidal, 29% of mudflats and 28% of tidal marsh (Figure 45). Considering both areas separately, however, the share of tidal marsh (in favour of shallow subtidal and tidal mudflats) in the subarea Zwijn is very limited, while almost no mudflats occur in the subarea Grote Wal. Here also, some further finetuning of the FCA-CRT settings seems to be needed.

Physiotope surface areas expected to develop within the LIFE Sparc FCA-CRT's are further summarised in Figure 46.

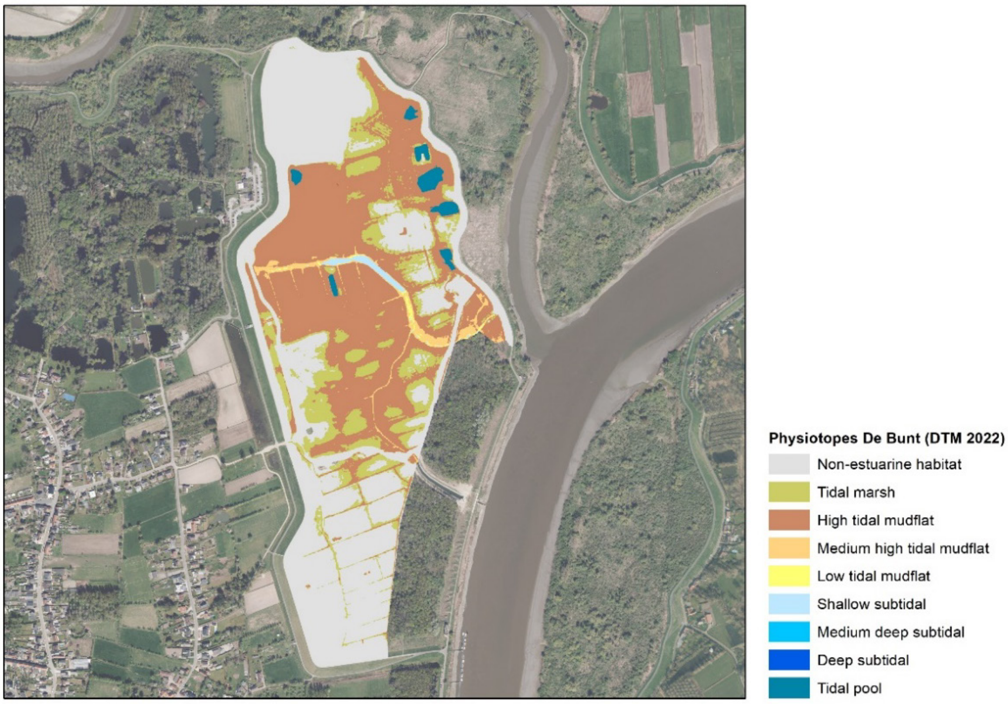

Figure 43 - Physiotope map of the LIFE Sparc FCA-CRT De Bunt based on the DTM of 2022 and 4QN+QE water levels.

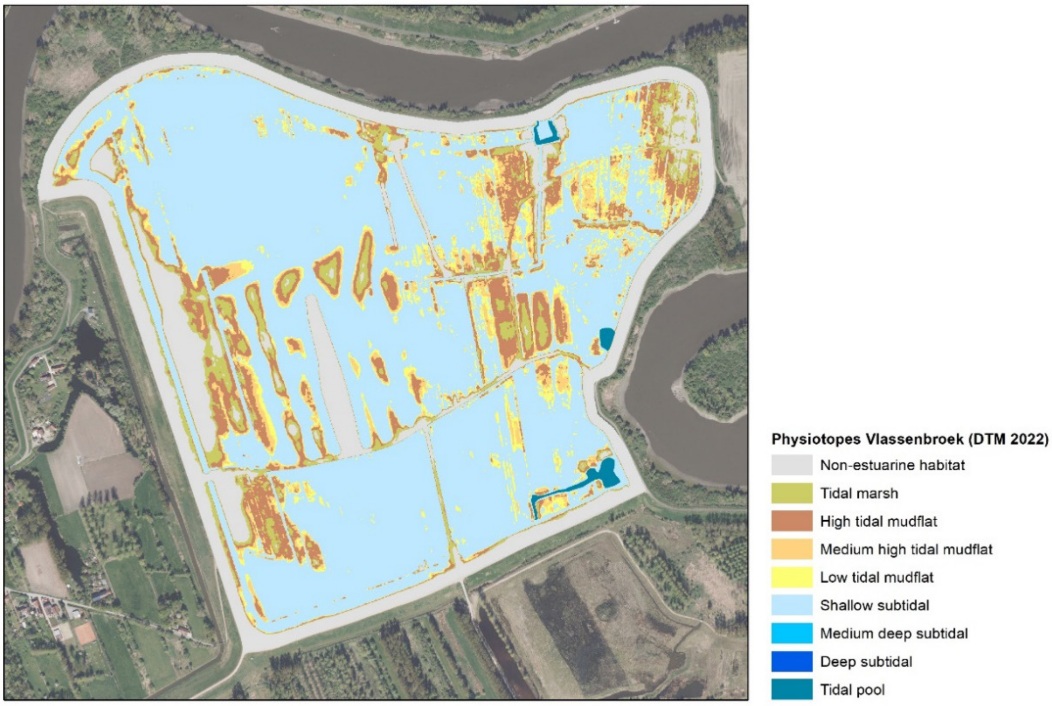

Figure 44 - Physiotope map of the LIFE Sparc FCA-CRT Vlassenbroek based on the DTM of 2022 and 4QN+QE water levels.

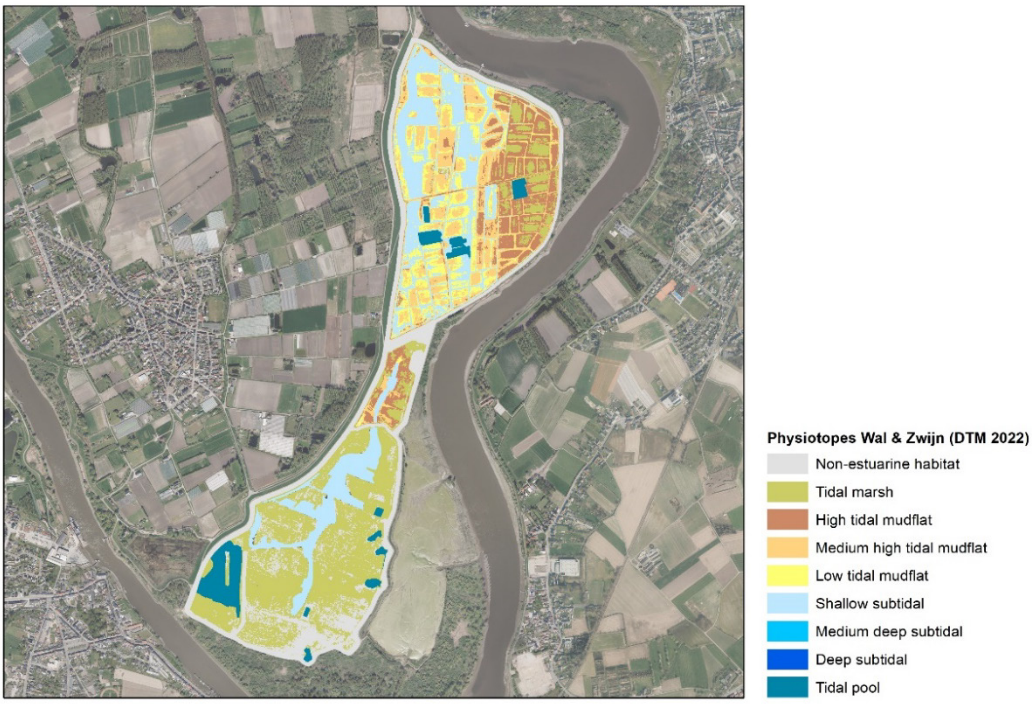

Figure 45 - Physiotope map of the LIFE Sparc FCA-CRT Wal & Zwijn based on the DTM of 2022 and 4QN+QE water levels; the area can be split up in subareas Zwijn (north), Kleine Wal (middle) and Grote Wal (south).

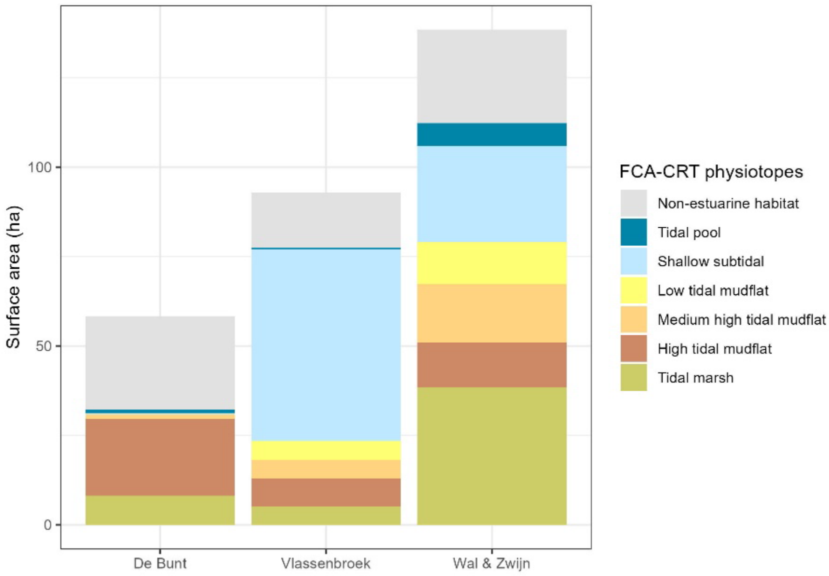

Figure 46 - Summary of the expected physiotope surface areas (ha) in 2022 for the FCA-CRT's De Bunt, Vlassenbroek and Wal & Zwijn.

Note that mean water depth is the sole explanatory variable in our 1D sedimentation model, while the modelled water volumes do not seem to reflect the volumes that will actually be flowing into the FCA-CRT's after implementation. Further complicating any attempt to predict sedimentation is the fact that the sinusoidal tidal pattern inside a FCA-CRT is determined not only by the water volumes but also by the area's height profile. It was therefore concluded that there was little sense in trying to predict sedimentation for these three areas.

6.4 Discussion

In this study we aimed to produce estuarine habitat maps for all eight LIFE Sparc areas, for the current (reference) situation as well as the expected situation in 2050, taking in account 25 year of sedimentation and assuming no sea level rise. Hence, the 2050 physiotope maps as generated in this study are the result of (modelled) sedimentation processes only, and not the result of an interplay between sedimentation and evolutions in sea level.

Including all LIFE Sparc areas in the estuarine system of the Upper Sea Scheldt would create roughly 360 ha of additional estuarine nature, which would imply a major step forward in the Natura 2000 objective to create and sustain 500 ha of tidal mudflats and 1500 ha of tidal marshes across the tidal Sea Scheldt in Flanders.

De-embankments would account for about 140 ha of estuarine nature. Over a period of 25 years and due to sedimentation, the surface area of tidal marshes within the LIFE Sparc zones is expected to increase from 47 to 126 ha. Meanwhile the extent of mudflats should decrease from 93 to only 13 ha.

Unfortunately, the physiotopes maps and the resulting proportion of estuarine habitats (totalling 220 ha) in the planned FCA-CRT's are considered to be unreliable. This is due to an insufficient calibration of the (modelled) water volumes entering these areas. This for example results in an unrealistically high proportion of shallow subtidal in the Vlassenbroek FCA-CRT. While in fact, the general objective is to trigger the development of a mosaic of (mostly) tidal mudflats and marshes. Therefore we propose to perform an update of the physiotope mapping once the actual sluice settings (and resulting water levels inside the FCA-CRT's) are available.

To reliably generate physiotope maps as a base for future monitoring, we further strongly advise on targeted drone flights generating DTM's reflecting the areas' situation shortly after implementation. In this study, we used DTM's of three years old for six out of eight study areas. These DTM's, however, still include the (old) dykes and certain local elevations (cfr. Groot Broek), while they do not yet include Sigma dykes nor creek onsets. Importantly, Sigma dykes often tend to be very wide, possibly taking in unexpectedly large surface areas of the potential estuarine habitats as reported above.

The sedimentation model as applied in this study needs some minor adjustments. For instance, we should not allow the simulated DTM to drop below the reference DTM. Also we plan to update the sedimentation model with data from recent de-embankments (i.e. Groot Schoor Hamme & Klein Broek) as well as new DTM's of the currently included areas. Importantly, we will look for a way to deal with the issue of negative sedimentation values in case of low mean high water depths, which is especially relevant when considering sedimentation in FCA-CRT's. Considering the latter, adaptive sluice management is a crucial aspect in order to reach the objectives regarding the development and maintenance of estuarine habitats (Maris *et al*. 2020). This implies that in the course of time, the water volumes allowed to flow into the area might need adjustment, in turn affecting the water depths occurring inside the area. Since mean high water depth is the only explanatory variable in our sedimentation model, it was regarded as unfeasible to present predictions on sedimentation rates for the three LIFE Sparc FCA-CRT's based on our 1D sedimentation model, and propose to turn to the results reported by Bi *et al*. (2022).

7 Long Term Monitoring (OMES)

The OMES program conducts Research on Environmental Effects within the framework of the Sigma Plan (in Dutch: Onderzoek naar de MilieuEffecten in het kader van het Sigmaplan). In addition to monitoring the pelagic ecology (ecology in the water column) of the Sea Scheldt, OMES also follows up on several newly created intertidal areas. All measurement results are submitted to VLIZ, which manages the OMES database.

Over time, the CRT areas that are developed in LIFE Sparc (Vlassenbroek, Wal Zwijn and De Bunt) will become part of this monitoring plan (see §7.2). At present, no results are available yet, but in the following paragraphs we present the measuring methodology, and the lessons learnt so far from monitoring the existing CRT areas.

7.1 Lessons learnt so far from existing CRT's

The monitoring in Lippenbroek has been ongoing for more than 15 years. In preparation for the construction of areas with controlled reduced tides (CRT), the pilot project Lippenbroek became active in 2006: the very first controlled flooding area with controlled reduced tides (FCA-CRT). Through research monitoring, the abiotic and ecological development is closely followed. The data from Lippenbroek is used in chapter 5 to estimate the expected ecosystem services of the LIFE Sparc areas by means of extrapolation from existing data.

Monitoring results from the past years indicate that all CRT areas are developing within the expected evolution margins. Sedimentation occurs everywhere, which is relatively limited and manageable. This leads to the anticipated flattening of the area, causing slight shifts in the flooding patterns within the area. If these flooding patterns deviate too far from the initially set goals, the sluices can be easily adjusted (e.g., with stop logs). For now, this is not necessary anywhere in the existing CRT's. With minor adjustments to the sluices, the tides and thus the ecological development can be controlled (Maris et al., 2023).

Proper maintenance of the culverts of the CRT's is essential for the development of the areas. Data from Lippenbroek in 2022 shows that debris accumulation at the gates can impede the inflow or outflow, with direct consequences for ecology and potentially also safety. It is also important that after a temporary closure of CRT sluices (e.g. during an emergency), the gates are quickly reopened with the same settings as before.

Vegetation development is closely monitored. Over time, succession in the fresh water CRT areas will lead to (willow) floodplain forest. Europe-wide, 99.5 per cent of alluvial willow and tamarisk forests have been lost.

7.2 Monitoring plan (Project monitoring)

In newly created CRT's monitoring is required for the first few years: project monitoring. Starting up a CRT requires detailed monitoring of the tides to choose the desired configuration of the stop logs. Additionally, basic monitoring of sedimentation and erosion, vegetation, and fish (the latter being conducted by INBO) is necessary, in view of the specific objectives of each CRT.

With a program for project monitoring, it is possible to determine to what extent the area meets the set expectations and whether it is evolving in a favourable direction. Quick detection of potential problems allows for adaptive management and adjustments. Project monitoring is an appropriate instrument for this. In addition to regular system monitoring, project monitoring is carried out to measure certain parameters with increased frequency, limited in time and space. During this period, the evolution of the area is continuously evaluated. If everything goes as planned, project monitoring can be phased out, and the area will be included in the regular system monitoring.

Attention is focused on sedimentation and erosion processes. Based on detailed measurements, a prognosis of the area's morphological evolution is made. Detailed surveys of several fixed transects and sedimentation are conducted to map the morphological changes. Vegetation is also monitored (dVW, 2024).

Table 14 shows the typical project monitoring planning for ths first nine years. The different types of measurement are explained in the paragraphs below.

Table 14 - Proposed temporal monitoring plan for CRT's in the first nine years (dVW, 2024)

	T0	T1	T2	T3	T4	T5	T6	T7	T8	T9
Tide	Ctu	Ctu	Ctu	Ctu	Ctu	Ctu	Ctu	Ctu	Ctu	Ctu
Topo SET	4x/yr	4x/yr	4x/yr	4x/yr	4x/yr	4x/yr	4x/yr	4x/yr	4x/yr	4x/yr
Topo MH	1x/yr	1x/yr	1x/yr	1x/yr	-	-	1x/yr	-	-	1x/yr
Topo Transects	1x/yr	1x/yr		1x/yr	-	-	1x/yr	-	-	1x/yr
Topo Creeks	1x/yr	1x/yr	-	1x/yr	-	-	1x/yr	-	-	1x/yr
Vegetation	1x/yr full	1x/yr full	1x/yr limited	1x/yr full	1x/yr limited	1x/yr limited	1x/yr full	1x/yr limited	1x/yr limited	1x/yr full
Sediment	1x/yr	1x/yr	1x/yr	1x/yr	-	-	1x/yr	-	-	1x/yr
Rapportage	limited	full	limited	full	Limited	limited	full	limited	limited	full

Table 15 lists the proposed measurement extent (number of stations, number of transects) in each of the LIFE Sparc areas for project monitoring.

Table 15 - Proposed monitoring plan for the three CRT's developed within LIFE Sparc (dVW, 2024)

Area	# Tidal stations	Topo SET	Topo MH	Topo transects	Topo creeks	Vegetation mapping	Bottom
Vlassenbroek	5	-	20	4	8	x	4
De Bunt	4	-	15	3	6	x	2
Wal-Zwijn	10	4	40	7	-	x	4

7.3 Monitoring of tide

The tide is the driving factor in a CRT. A good spring tide-neap tide variation is essential for a rich and diverse intertidal ecosystem. When problems arise, such as unwanted developments in sedimentation (e.g. too high) or vegetation (e.g. dying off) or the appearance of invasive species, a tidal analysis can often explain much.

Therefore, monitoring of tides is essential. Permanent monitoring stations will be set up in all CRT's, which record the water level at least every 10 minutes. These measurements in the existing areas will continue, and the network will be further maintained. Some of these tide meters are managed by Flanders Hydraulics, and the data from these stations is available via www.waterinfo.vlaanderen.be.

7.4 Morphological changes

Sedimentation is desired for the ecological development of the area. The input of fresh sediment helps build a typical salt marsh morphology (including creek ridges) and the typical marsh soil. These promote the establishment of estuarine vegetation and benthic fauna. Different organisms live in hard polder clay compared to a well-developed marsh soil. In such marsh soil, numerous processes take place that are important for the functioning of the Scheldt ecosystem, such as the nitrogen or silicon cycle.

Due to the safety function in the controlled reduced tide (CRT) areas, excessive sedimentation must be avoided. This could lead to a loss of water storage capacity, thereby compromising flood protection. Rapid sedimentation is also not advisable for ecological reasons in CRT areas.

It is therefore essential to keep track of sedimentation and erosion processes and to monitor the morphological changes in relation to the safety function and the ecological development of the areas.

7.4.1 SET (Surface Elevation Table)

SET's are widely used in the scientific community to accurately and non-destructively measure relative changes in the height of the surface (or platform) over the long term. This portable measuring device is mounted in the same fixed location. The precision of this method is very high, capable of recording height changes up to 2 mm. SET's provide information on both surface and subsurface processes. Surface processes include sedimentation, erosion, and compaction of newly deposited sediment, while subsurface processes encompass root growth, decomposition, pore water flux, and compaction of underlying layers.

Figure 47 - SET measurements in Bazel CRT (Maris et al, 2023)

7.4.2 MH (Marker Horizons)

Marker Horizons (MH) allow for the monitoring of soil changes, but with much lower accuracy than SET. MH only measures surface processes, such as sedimentation, erosion, and compaction of newly deposited sediment, whereas the outcomes of SET measurements also include subsurface processes such as root growth, decomposition, pore water flux, and compaction of the underlying layers. Marker Horizons are initially measured annually during the same period as the SET.

Figure 48 - Marker Horizon using a white kaolin clay layer (Maris et al, 2023)

7.4.3 Transects

For the transect measurements, the survey starts from a fixed starting point and proceeds in a straight line to the endpoint. Every few meters, the height of the ground surface is measured with an RTK-GPS to an accuracy of approximately one centimeter. If there are significant changes in ground surface elevation, such as a creek cutting through the area, the measurement points are placed closer together, down to a minimum distance of 5 cm in the steepest sections. For project monitoring, this is done in the following years: T0, T1, T3, T6, T9, and T12 (see also Table 14).

Figure 49 - Transect measurement at Bergenmeersen (Maris et al, 2023)

7.4.4 Creeks

Mudflats and salt marshes in tidal areas are very dynamic environments. The inflowing and receding water leads to the formation of creeks and gullies in the CRT areas. The proper formation of a well-draining creek system is important for the irrigation and drainage of the mudflats and salt marshes and the associated fauna and flora.

In selected areas, a series of creek transects are measured. Only creeks with a minimum depth of 20 cm (height difference with the ground level) and a minimum length of 10 m are included. These creek transects, like the other transects, have a fixed starting and ending point. Both points are located on the respective banks and are positioned so that the transect stands perpendicular to the creek. Between these points, the height of the ground surface is measured every 20 cm with an RTK-GPS or Total Station. If there are significant vertical differences between the successive points (such as at a creek edge), the points are taken closer together, up to a maximum distance of 5 cm from each other.

7.5 Vegetation mapping

Comprehensive vegetation mapping is carried out between June 15 and October 15 (preferably between July 1 and October 1).

The first year of the opening of the CRT (T0), the area is mapped for the first time. This mapping indicates which vegetation is present when the tide is introduced. The mapping can be just before or just after the sluices are opened, as the mapping is always done in the summer; the opening of a CRT can theoretically happen year-round.

In the first and third years after the start of the area (T1 and T3), comprehensive mapping is also carried out. After the third year, the area is monitored during the sixth year after the start (T6) and the ninth year after the start (T9), after which the areas are included in the regular six-year monitoring under the auspices of MONEOS (INBO). The next comprehensive mapping would then take place in T15, T21,...

Detailed monitoring during the first and third years (T1, T3) after the start of the CRT is crucial to quickly detect any unwanted developments and adjust the management of the area if necessary. Once the areas have been active for several years, sudden changes in vegetation are not expected to occur, so after T3, T6, and T9, the frequency of monitoring is reduced to every six years, and the area can be included in the regular MONEOS monitoring conducted by INBO.

To follow up in the intervening years, a limited, simplified mapping is carried out for T2, T4, T5, T7, and T8 (see Table 14). If the interim mapping (or other field observations) indicates that development is not going as expected, an additional mapping may be conducted.

7.6 Sediment characteristics

Soil samples are collected in the fall, preferably between mid-September and mid-October. The soil is monitored in T0, T1, T2, and T3. From then on, sampling occurs every three years in T6 and T9. After T9, the monitoring of benthos is included in the soil sampling by INBO (see Table 14).

7.6.1 Grain size

Soil samples for determining the grain size and organic matter content are composite samples taken with a narrow gouge (diameter 1 cm), up to a depth of 15 cm. At each sampling location, five to ten subsamples are taken within a radius of approximately three meters around a central point. The subsamples are transferred to a container and kept cool and dark, awaiting further processing in the lab. The number of sampling locations per area and the number of reference locations are shown in Table 15.

In the lab, the composite samples are homogenized by thoroughly stirring them. The grain size distribution of the homogenized sediment samples is determined (e.g., with a laser diffraction analyzer). In addition to the "volume weighted mean grain size," the median grain size and the percentages of sediment particles belonging to the clay (≤ 4 µm), silt (4-63 µm), and sand (> 63 µm) fractions are also reported. The organic matter content is determined after ashing.

7.6.2 Bulk density and water content

Soil samples for determining bulk density and volumetric moisture content are collected using Kopecky rings. The Kopecky rings used are stainless steel cylinders with a height of 5.2 cm, a diameter of 4.6 cm, and a volume of 100 cm^3. Three soil samples are taken at each sampling location using the Kopecky rings, within a radius of approximately 3 meters around a central point.

In the lab, the wet weight of the sediment is first determined with a precise balance. The samples are then dried in an oven at 70°C for several days. Subsequently, they are dried for a few more hours at a temperature of 105°C, after which the dry weight is determined. The bulk density (expressed in g/cm^3) is calculated by dividing the dry weight of the sediment by the volume of the Kopecky ring. The volumetric moisture content (expressed in g/cm^3) is obtained by subtracting the dry weight of the sediment from the wet weight and then dividing by the volume of the Kopecky ring.

8 Conclusions

8.1 Safety against flooding

The level of high water that is reached during a storm event (a combination of downstream surge and upstream discharge) has an obvious relation to the safety function of the LIFE Sparc areas: to provide safety against flooding.

The cumulative effect of the LIFE Sparc areas on HW ranges from -15 cm to -45 cm, depending on the severity and characteristics of the event. In all simulations, performed with two different model instruments, the LIFE Sparc areas had a net positive effect on safety against flooding, i.e. a reduction of the peak HW level.

The effect is not limited to the immediate vicinity of the areas, but rather extends ~35 km up- and downstream of the project areas, with the main effect around the project areas and a decreasing influence up- and downstream of them.

8.2 Functioning of the Durme

Three areas of LIFE Sparc are foreseen in the Durme (areas 1-3 in Figure 1). Groot Broek is a depoldering of 58 ha that became active in 2025. Klein Broek is a smaller depoldering of 38 ha that is expected in 2026. De Bunt is a FCA-CRT that will become active in 2025.

Since the measurements took place in 2019-2024, we can't see the effects of these areas reflected in the measurements described in chapter 4. The measurements do provide valuably system insight and ground truth data for the calibration/validation of numerical models that can be used for impact assessment studies.

From the four different measurement campaigns, the Durme appears consistently as a flood dominant system, with higher peak flood velocity and bed transport predominantly during the flood phase.

Performing a modelling study allows the modeler to isolate the effect of the addition of the areas from the natural variability of the environmental factors. One recent modelling study (performed by Flanders Hydraulics outside LIFE Sparc) investigated the effect of adding Klein Broek, Groot Broek and De Bunt to the Durme tributary on its daily tidal signal (Meire et al., 2024).

Activating all three Sigma areas leads to an increase in the flood volume at the mouth by 51% and 33% for the selected spring tide and neap tide, respectively. The model calculated sudden changes in the water volume in the Durme river at the inlet-outlet sluice of FCA De Bunt and at the openings of the polders Klein Broek and Groot Broek.

The implementation of the Sigma area(s) result(s) in the distortion of the tidal wave in the Durme river, with the largest effect due to the polder Groot Broek. The HW levels computed from runs with Groot Broek are lower and lag about 0.5 hour behind those of the reference case. This phase lag leads to a longer flood and shorter ebb duration. The phase shift is also observed for the case of Klein Broek, but much less pronounced. The polder Groot Broek results in lower HW in the river with the largest reduction in HW of 10 - 15 cm for the selected spring tide. Activating Klein Broek together with Groot Broek could lead to further reduction of HW along the entire river compared to the case of Groot Broek alone. A drop in HW reaches 15 cm at Waasmunster-Brug for a typical spring tide when all three Sigma areas are active (Meire et al., 2024).

A strong effect of the three Sigma areas on the current velocity was calculated downstream of the areas with higher velocity peaks. The velocity asymmetry, based on peak velocities, is flood dominated in most of the river section. Activating Klein Broek and/or Groot Broek leads to a weaker flood dominance in the middle and downstream sections of the river. The effect of Groot Broek is stronger and extends more upstream. The polder Groot Broek even alters the velocity asymmetry to ebb dominance at the river section near the mouth. In terms of sediment transport, the polder Klein Broek and Groot Broek could slow down the sedimentation process in the downstream part of the Durme river itself.

8.3 Ecosystem services

A major ecosystem service that tidal marshes provide is their beneficial effects on water quality. Marshes remove nitrogen and phosphorus from the water column, two nutrients that are presently in excess in the Scheldt and are partly responsible for eutrophication. In addition, tidal marshes provide silicon, an essential nutrient for diatoms. By removing Nitrogen (N) and Phosphorus (P) and enriching Silicon (Si) in the floodwater, salt marshes contribute to a healthier N/P/Si ratio in the water column, and thus provide an important ecosystem service to the Scheldt.

Based on knowledge gained from long-term research monitoring in the Lippenbroek area (a 10 ha demonstrator site for the concept of FCA-CRT) that has been going on since 2006, the expected effect of the Life Sparc on the ecosystem services “DSi delivery” and “Nitrogen removal” is estimated.

8.3.1 Export of dissolved silicon

The export of dissolved silicon out of tidal marshes is an important ecosystem service of these estuarine habitats. The supply of dissolved silicon (DSi) is crucial to maintain a balanced P-N-Si ratio in the estuary. This ‘good’ ratio is the ratio in which these nutrients are needed for the growth of diatoms. Diatoms form the basis of the estuarine food chain and are therefore desirable in the estuary. When DSi becomes depleted, the growth of diatoms consequently stops and green algae, which do not need DSi, take over. Green algae are less appreciated as a food source and will therefore accumulate in the estuary, leading to typical (and unwanted) eutrophication symptoms. By adding extra marsh habitat to the estuary, the DSi concentration in the estuary can be increased. DSi release is not considered as a pelagic process but rather as a bottom process, and so is independent of the tidal volume that is exchanged, but rather depends on the area of flooded surface. It is also clear that an area only starts delivering DSi after some years. For Lippenbroek this was 8 years, and this value is taken as representative of that timescale. Based on detailed HD simulations of the LIFE Sparc areas, the flooded area is known, and so the DSi delivery can be estimated once the areas become net exporters of DSi after 8 years.

The LIFE Sparc marshes can always deliver DSi, especially when DSi concentrations are low in the estuary. During winter conditions, the Sparc marshes deliver about 29 ton of DSi a month. This represents only about 3% of the estuarine DSi flux, because of the higher concentrations and discharge in the estuary. During the summer half year, and especially the months July and August, DSi peaks to 52 ton DSi when the DSi concentration in the estuary is low. The export from the marsh is between 27 and 52% of the estuarine DSi flux in Melle, and up to 40 to 85% at Dendermonde. This transect is in the middle of the tidal freshwater zone, where DSi usually reaches a minimum. When DSi is depleted in the estuary, the export out of the LIFE Sparc marshes can be more than 1000% of the estuarine flux at Melle or Dendermonde. DSi depletion typically occurs at low freshwater discharge, leading to extremely low estuarine DSi fluxes. On these moments, the Sparc marshes will make a crucial difference and avoid DSi depletion in the estuary.

8.3.2 Nitrogen removal

The Scheldt estuary does not meet the Water Framework Directive criteria for nitrogen (e.g. nitrates). It is known that marshes can remove N from the inflowing water. Here we focus on the sink function of tidal marshes for total dissolved inorganic nitrogen (TDIN). TDIN removal in “new” intertidal area is considered to be mainly a peleagic process. Larger tidal volumes ensure proportionally larger TDIN retention, while it is independent of the flooded surface. This seems contradictory to the findings in natural tidal marshes, where water purification is mainly attributed to bottom processes. However, natural tidal marshes have a very porous soil through which water can flow relatively easily. In new intertidal area, the soil might be too compacted for it to contribute to the water purification processes. This hypothesis has been confirmed for the Lippenbroek case, although more research is needed as more areas will be developed in the sigma plan. Furthermore, the flooding water in a CRT has a longer residence time compared to a natural salt marsh, which means that the pelagic processes can have a greater impact. Based on detailed HD simulations of the LIFE Sparc areas, the tidal prism is known, and so the TDIN removal is estimated separately for MR and CRT sites.

The LIFE Sparc marshes remove nitrogen, especially at spring tide. In the winter half year, TDIN removal by LIFE Sparc sites (both CRT and MR) is highest due to the higher TDIN concentration in the estuary. The impact however of LIFE Sparc on the TDIN cycling in the winter half year is considered to be very small, since this removal is very small compared to the high estuarine TDIN flux. In the summer half year, and especially in the warmer summer months (July and August), the absolute removal by the LIFE Sparc sites is less, but becomes relatively more important due to the smaller estuarine influx. We can conclude that these areas together will minimally remove 5 to 8% of the TDIN flux entering the estuary in summer. This is an important contribution to a better water quality, but not enough to achieve WFD standards.

8.4 Development of ecotopes over time

Sedimentation in the LIFE Sparc areas was estimated using a new empirical relation linking yearly sedimentation to mean water depth (related to inundation frequency for shallow points). This model is successfully applied for the de-embankments. Based on modeled inundation frequencies and High and low water levels, physiotope boundaries are established, both immediately after opening, and -in combination with the sedimentation model- in 2050.

All five depoldering areas are expected to develop to tidal marsh in a period of 25 years. De-embankments would account for about 140 ha of estuarine nature. Over a period of 25 years and due to sedimentation, the surface area of tidal marshes within the LIFE Sparc zones is expected to increase from 47 to 126 ha. Meanwhile the extent of mudflats should decrease from 93 to only 13 ha. Including all LIFE Sparc areas in the estuarine system of the Upper Sea Scheldt would create roughly 360 ha of additional estuarine nature, which would imply a major step forward in the Natura 2000 objective to create and sustain 500 ha of tidal mudflats and 1500 ha of tidal marshes across the tidal Sea Scheldt in Flanders.

The physiotope mapping for the FCA-CRT areas showed that the expected water levels inside the areas are not as they should be for optimal ecological development. This is not entirely unexpected as the typical design of a FCA-CRT is an iterative exercise where the height of the overflow dike, and the culvert design are carefully tailored to produce an desired ecological outcome. This design loop was not closed within LIFE Sparc, which serves as an important lesson that will be taken into account in follow-up projects like Sigma3.

9 References

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