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LIFE SPARC – action C10: Transfer to other estuaries (Replicability & Transferability)

Sub report 2
Detailed models for the hydrodynamics in the 8 selected locations

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Flanders Hydraulics Research

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Abstract

In the framework of the project LIFE-SPARC, one of the important goals is to investigate the effects of various engineering measures, such as de-embankments and flood control areas, in order to prepare the Scheldt estuary against climate change. There are eight project areas, including five de-embankments and three FCA-CRT areas, defined in the project. For assessing their influences on the hydrodynamics and evaluating the safety against flooding, a detailed 3D model is built based on the existing Scaldis 2013 model, with necessary mesh refinements and updates of bathymetry. Two different scenarios are studied, a normal scenario with average tide and upstream discharges, and a storm surge scenario from the event of Sinterklaas storm, in order to have the full picture of the possible effects from these measures.

In nature, the de-embankments and the FCA-CRT areas will silt up. In order to understand the long-term evolution of these areas, an empirical sedimentation model is set up, with its inputs derived from the numerical model.

The results show that the eight project areas are effective in the protection of the estuary against flooding, and can reduce the high water level significantly in a storm surge event. The sedimentation rates estimated by the empirical model suggest that it will take several decades before these areas silt up. Therefore, they are capable of being in operation until 2050 and likely many years after that.

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1 Abbreviations

Abbreviation	Meaning
ADCP	Acoustic Doppler Current Profiler
ANB	Agentschap voor Natuur en Bos
CRT	Controlled Reduced Tide
FCA	Flood Control Area
RMSE	Root Mean Square Error
SPARC	Space for Adaptating the River Scheldt to Climate Change
TDM	Tons of Dry Matter
ZUNO	Zuidelijke Noordzee model (model of the Southern North Sea)

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. Specific objectives for the priority area Climate Change Adaptation are:

(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 31/08/2022.

The project partners are:

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

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 estuary 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 Project Areas

The specific actions (C1 until C8) are all located in the area where the most critical water levels occurred during the last dangerous storm (6/12/2013).

Table 1 – 8 project areas of Life Sparc

Name	Type	Area [ha]
Uiterdijk	Depoldering	11
Groot Schoor Hamme	Depoldering	26
Groot Schoor Bornem	Depoldering	23
Groot Broek	Depoldering	58
Klein Broek	Depoldering	38
Vlassenbroek	Flood Control Area with Controlled Reduced Tide (FCA-CRT)	91
Wal Zwijn	FCA-CRT	148
De Bunt	FCA-CRT	67

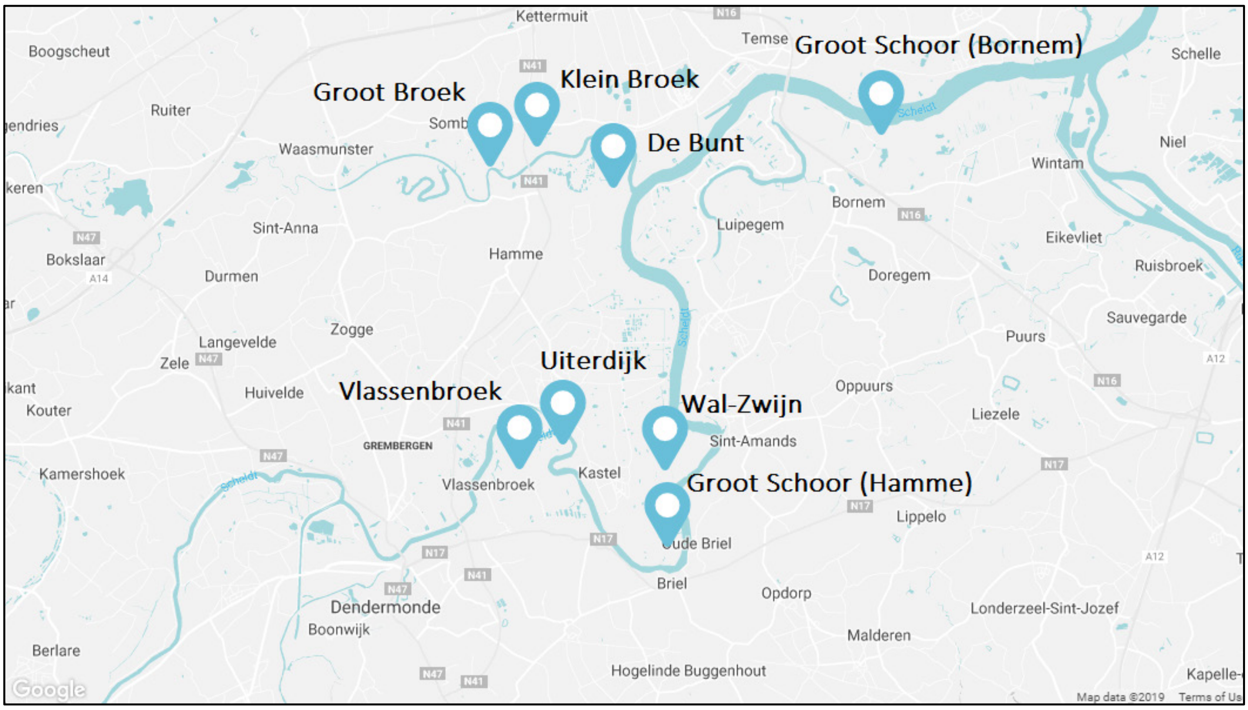

Figure 1 – Location of the 8 project areas. Source: https://life-sparc.eu/

2.3 Action C10: Transfer to other estuaries (Replicability & Transferability)

The core concept of combining Flood Control Areas (FCA) and Areas with a Controlled Reduced Tide (CRT) to give "Space to the River" is an original idea that has been developed, implemented and monitored in a pilot project in Flanders, Belgium. The experience gained at the pilot site Lippenbroek (a CRT studied during the LIFE project MARS) combined with the development of 8 additional realizations during this project (actions C1- C8), complemented with additional knowledge gained in this action will be used to assess the applicability of the core concept in other European Estuaries.

2.3.1 CRT Technique

One of the measures in the Sigmaplan is to build a set of Flood Control Areas (FCAs). To this end, specific polders along the tidal river Scheldt are selected which have an elevation below mean high tide level. As a first construction step, a sufficiently high ring dike surrounding the polder needs to be built. Secondly, the existing levee between the polder and the river needs to be lowered, in order to create an overflow dike. During storm surges, water can overtop the overflow dike and be stored in the FCA, thus damping the tidal wave in the river and mitigating the flooding of nearby valuable areas. To drain the water from the FCA when the water level in the river is sufficiently low again, outlet sluices are included within the overflow dike (Figure 2, left). The corresponding culverts are equipped with flap gates on the river side. On average, such a FCA is flooded once or twice a year.

An FCA-CRT is a variant of an FCA. It combines the safety role of a flood area with the restoration of rare tidal nature. Waterflows into and out of an FCA-CRT twice a day to the rhythm of the tides. The area is flooded at each high tide. A limited amount of water flows in through the inlet sluice. In this way the tide is "reduced". When the tide ebbs, the water flows back into the river through the outlet sluice. The natural action of a tidal river is thus mimicked. The area effectively becomes part of the Scheldt ecosystem and a system of tidal marshes can develop.

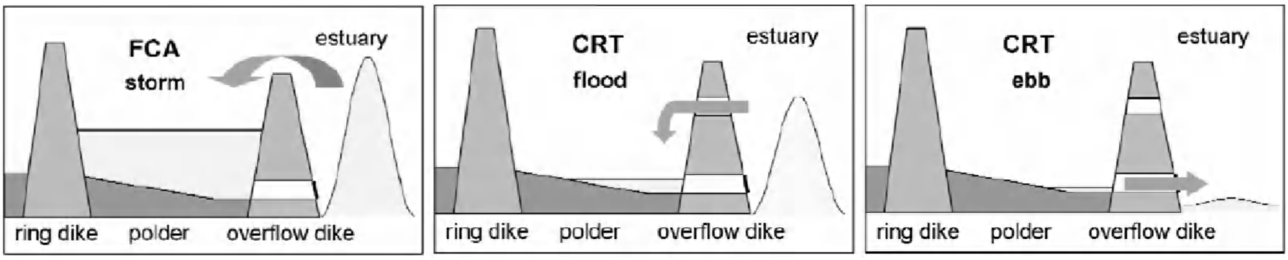

Figure 2 – Operational principle of a Flood Control Area (FCA) without (left panel) and with (middle and right panels) a Controlled Reduced Tide (CRT) (De Mulder et al., 2013)

The CRT technique is often unknown in the other EU member states but can also be used in other estuaries, especially under the following conditions:

- Available space is very limited, which means maximum storage capacity is required when the peak of the storm surge hits.
- If the relative altitude of adjacent land is unfavourable in relation to the river, development of a CRT van be an alternative to the development of which prevents tidal mudflats and tidal marshes through depoldering.
- The embankment alongside the river needs to be retained and kept accessible.

- Large tidal fluctuations are undesirable in floodplains for ecological reasons.
- Large depoldering operations are undesirable because the fairway is left without sufficient water at times

For the CRT system to function properly, a carefully dimensioned culvert construction with combined inlet and outfall has to be placed at a specific height within the tidal window. This is the only way to secure an appropriate neap-spring tidal variation, which is crucial for the development of mudflats and tidal marshes in the area.

2.3.2 Modelling of eight realizations in the Scheldt

In order to facilitate knowledge transfer, the latest state-of-the-art modelling tools will be applied to describe the hydrodynamics and expected siltation for the 8 realizations (actions C1 – C8).

The SCALDIS model is an extensively calibrated 3D TELEMAC model for the Scheldt estuary (Vanlede et al., 2015). It will be locally refined in order to describe the detailed hydrodynamics in the selected locations and calibrated and validated using the in-situ data from the project-monitoring (D1).

Sedimentation in the 8 project areas is estimated using a calibrated empirical approach (Vandenbruwaene et al., 2011). This methodology is explained further in section 3.3.

Subsequently, habitat mapping can be done based on the modelling results using the methodology established by INBO (Van Braeckel et al, 2015).

3 Methodology

3.1 Research Question

The main research question addressed in this report is what the expected effect is of the eight realizations, including 5 depoldered areas and 3 FCA-CRT areas that will be developed in the Life SPARC project both on the Scheldt estuary and on the local dynamics in the project areas. The idea is to apply the latest state-of-the art 3D modelling tools to investigate these questions for the Scheldt estuary.

The effect will be evaluated from 3 aspects: the impact on the hydrodynamics, the sedimentation on the 8 project areas and the influence on the ecotope mapping.

3.2 Hydraulic Modelling

3.2.1 The SCALDIS model

In this study, the hydrodynamics is modelled using the SCALDIS model for the Scheldt. The SCALDIS model is an extensively calibrated 3D model of the entire Scheldt estuary, with sufficient resolution and accuracy in the upstream part of the Scheldt estuary (Vanlede et al., 2015).

The SCALDIS model was developed within the framework of the project "Integrated Plan for Upper Sea Scheldt". It was developed using the TELEMAC modelling suite, which is based on the finite element method. This allows it to use an unstructured mesh that has the advantage to be very flexible in changing mesh resolution in specified areas of interest.

The model has been calibrated for the year 2013 (SCALDIS 2013). An overview is provided in this report, while the detailed descriptions of the model can be found in Smolders et al. (2016).

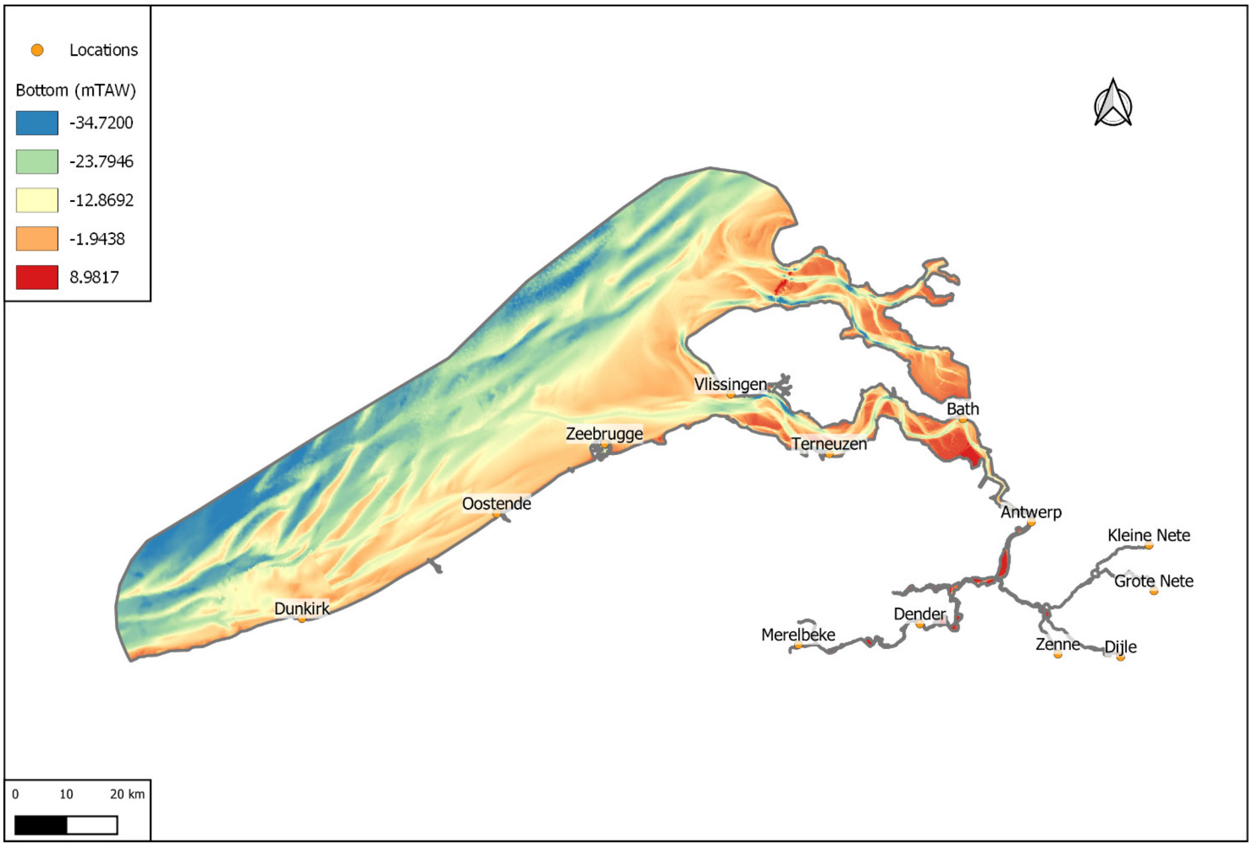

Figure 3 – SCALDIS model domain (Vanlede et al., 2015)

The model grid

The computational grid includes the Belgian coastal zone, extended to Dunkirk in France and Westenschouwen in the Netherlands. The grid includes the Eastern Scheldt as well. The mesh resolution varies between 400 and 150 m in this part of the model.

In the Western Scheldt and estuary mouth area the grid resolution increases towards 120 to 80 m. The grid also includes all tributaries reaching as far as the tidal influence. The grid resolution keeps increasing all the way till the upstream boundary in Merelbeke where it is 5-7 m. All flood control areas of the Sigma Plan that are active in 2013 are included in the grid. The 2D grid consists of 459,692 nodes.

The 3D mesh consists of prisms and is automatically constructed from the 2D mesh. A sigma transformation is used for the vertical location of these 5 interfaces. Interface 1 is the bottom layer and the following layers are situated on 0.12, 0.30, 0.60 and 1.00 fraction of the water depth. The bathymetry is interpolated from measured data from 2013 (or the closest date available).

The open boundaries

There are 9 open boundaries defined in the SCALDIS model, containing one downstream sea boundary and eight upstream tributaries. The downstream boundary is located in the North Sea. Time series of water levels is imposed at each node of the downstream boundary. These time series are extracted from the regional ZUNO model (Maximova et al. 2015) of the southern North Sea. There are 8 upstream liquid boundaries with prescribed fresh water discharges, including 6 upstream tributaries, i.e. Merelbeke, Dender, Zenne, Dijle, Kleine Nete, and Grote Nete, and 2 inland channels at Ghent – Terneuzen and Bath (for the locations, see Figure 3.

Physical processes in the model

Turbulent mixing is modelled with 2 different schemes, one for horizontal and the other one for the vertical. The Smagorinski model is used for modelling the horizontal turbulence. It belongs to the category of sub-grid turbulence models and it is an recommended scheme for the large-scale models. The vertical turbulent mixing is captured by the mixing-length model, which relates the turbulent viscosity as a function of the mean velocity gradient and the mixing length based on the Prandtl's theory.

Salinity effect is included in the model. Salinity acts as an active tracer, which can influence the density of water. A salinity map, derived from interpolated measurements, is used as part of the initial conditions. Besides, the time serie of salinity level is also prescribed at each open boundary.

Wind influence is not considered in the hydrodynamic model, since the SCALDIS model used for the project mainly focused on the Upper Sea Scheldt, the wind effects is less important in the region.

The quality of the model

The SCALDIS model used in the project "Integrated Plan for Upper Sea Scheldt" has been calibrated against the measurements for the year 2013. The model is calibrated by comparison of the model results and measured water levels, discharges, and velocity measurements in multiple stations along the Scheldt estuary in both deep water and shallow zones. The model performance is indicated by a cost function that quantifies the differences between the model results and measurements for the all the available stations.

The final calibrated model is proven to reliable and it can reproduce accurate hydrodynamics in the Scheldt estuary. The total RMSE of high, low waters and complete water level time series is 12 to 14 cm in the Upper Sea Scheldt. The absolute value of the bias of water levels is smaller than 10 cm at most stations. The average RMSE of velocity magnitude for all the analysed transects in the Upper Sea Scheldt is 16 cm/s. The harmonic analysis of water levels was also done for varying the quality of the model. The M2 harmonic component is dominant in the zone of interest. In Upper Sea Scheldt the difference in M2 amplitude between the observation and model results is -2 to 1 cm. The difference in M2 phase is only -3 to 3 degrees (Smolders et al. 2016).

3.2.2 Scenarios (different boundary conditions)

The depoldered areas and FCAs/FCA-CRTs are designed as a nature-based solution to reduce flood risk and restore habitats. The FCAs/FCA-CRTs collect excessive water during storms, while the depoldered areas help reduce the strength of the tides, as well as the pressure on the levees by allowing the tides to flow in and out of the area.

For the normal situation, water can flow into and out of the depoldered areas and FCA-CRTs, but rarely the FCAs. When the tidal river does not reach the critical storm surge water levels, there will be no overflow in the FCAs, hence they will not be activated and the effects can be limited. These measures will show significant effects when the water level becomes much higher, e.g. during the storm period.

In order to thoroughly evaluate the effects and influences of the 8 project areas, two scenarios are defined in this study, the normal scenario and the storm surge scenario. Each scenario consists of a set of new (as compared to the calibrated SCALDIS model) boundary conditions derived from the ZUNO model and field observations (Smolders et al. 2016). The rest of model parameter settings remain the same.

Normal scenario

The normal scenario simulates a period without storm surge. The water levels in the tidal river changes within an average range between spring and neap tide. In this case, the boundary conditions used in the original calibrated SCALDIS model were kept. Instead of using the entire boundary conditions of 3 months, a 6-day period is selected, from 2013-09-13 00:00:00 to 2013-09-19 00:00:00, i.e. the first six days after the spin-up period. At the downstream boundary, water level and salinity are prescribed, while at the upstream tributaries the daily averaged discharges (in total varying between 51 to 82.6 m^3/s in the selected 6 days) are imposed. An example of timeseries of water level imposed at the sea boundary (node 107987) is shown in Figure 5. Its location is indicated in Figure 4.

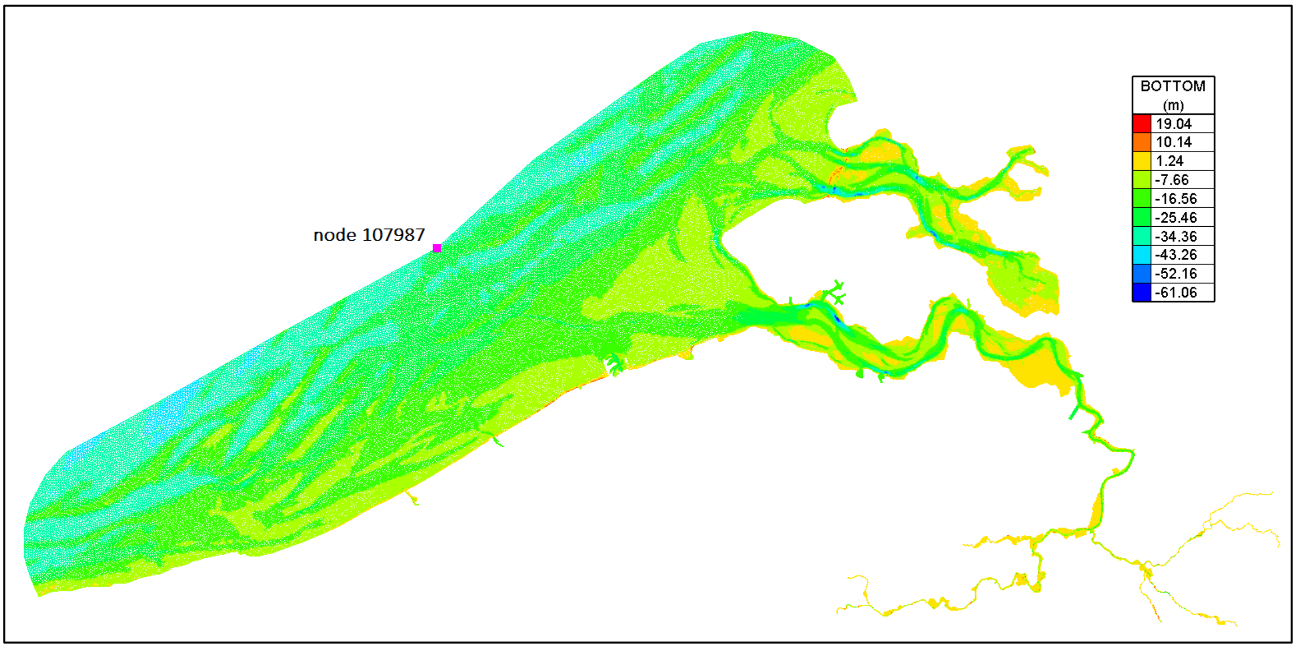

Figure 4 – Location of the node at the seaward boundary

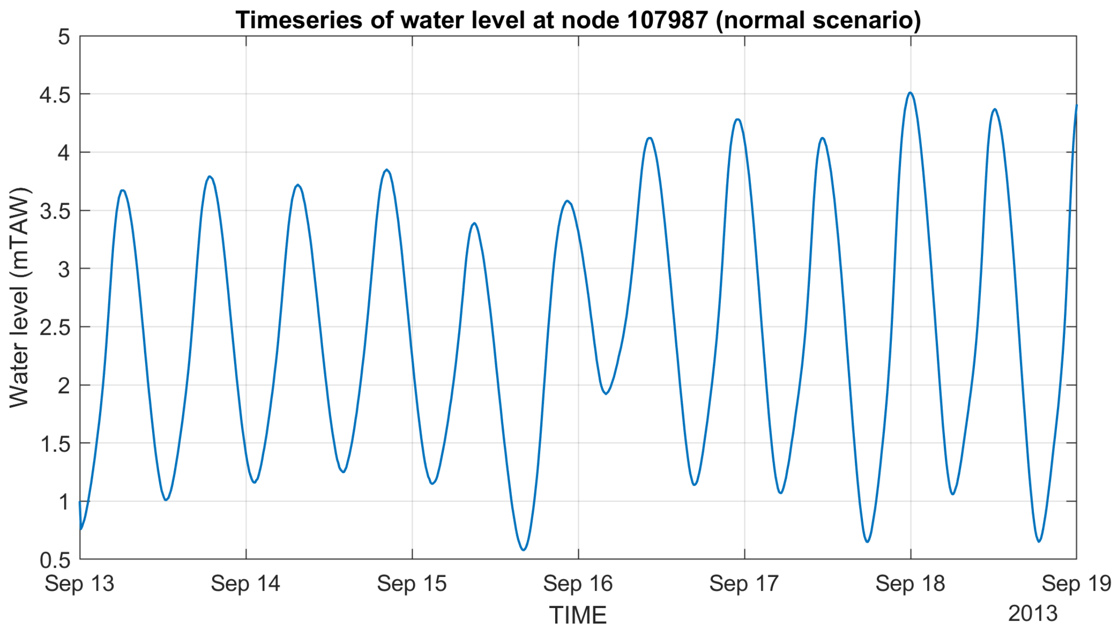

Figure 5 – The timeseries of water level at node 107987 (normal scenario)

Storm surge scenario

The storm surge scenario is a period with a storm event. The Sinterklaas storm happened in the year of 2013. It was a heavy storm that swept across Northern Europe on December 5 and 6, 2013. Ostend suffered the highest water level since the Flood of 1953. This storm event is then chosen for representing this extreme scenario, the simulation period is from 2013-12-03 00:00:00 to 2013-12-09 00:00:00. At the downstream boundary, water level and salinity are forced, while at the upstream tributaries the daily averaged discharges (in total varying between 42.3 to 64.4 m^3/s in 6 days) are imposed. An example of timeseries of water level imposed at the sea boundary (node 107987) is shown in Figure 6.

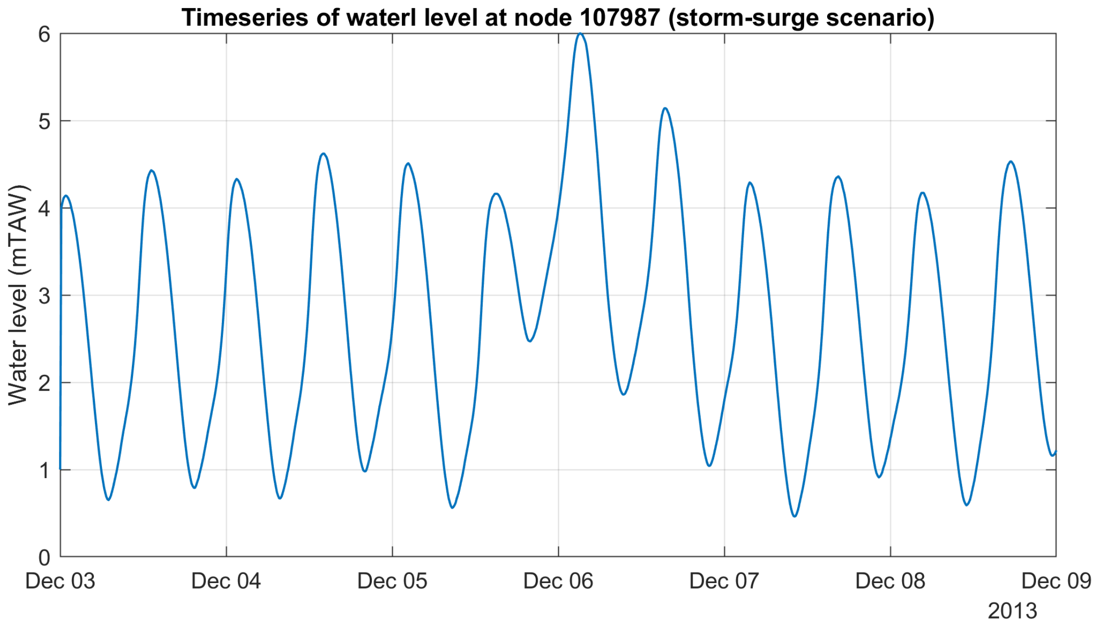

Figure 6 – The timeseries of water level at node 107987 (storm surge scenario)

3.2.3 List of the model runs

Based on the proposed scenarios, 4 model runs are defined. Two runs are performed with the normal scenario:

- the reference run 2013_Normal_0R without the implementation of the 8 project areas;
- the run 2013_normal_8R with the implementation of the 8 project areas (the dikes between the tidal river and the depoldered areas are breached).

Similarly, the other two runs are performed with the storm surge scenario. The overview of the model runs can be seen in Table 2.

Table 2 – List of the model runs

Name	Boundary conditions	FCA-CRT areas	Depoldered areas
2013_Normal_0R	Normal scenario	Not implemented	Not implemented
2013_Normal_8R	Normal scenario	Implemented	Implemented
2013_Sinterklaas_0R	Storm surge scenario	Not implemented	Not implemented
2013_Sinterklaas_8R	Storm surge scenario	Implemented	Implemented

In the runs 2013_Normal_0R and 2013_Sinterklaas_0R, there are no depoldered or flood control areas. In the runs 2013_normal_8R and 2013_Sinterklaas_8R, only the 8 project areas are implemented. By comparing those model runs, we then show the effects of the project areas without other interferences.

3.3 Effects on habitats

One of the important objectives in the LIFE-SPARC project is to restore habitats to make the ecosystem more resilient to the climate change, and enable tidal mud flats and freshwater tidal marshes to develop in line with the Habitats Directive. This requires the assessment of the hydrodynamic conditions on the 8 project areas, or the ecotope analysis. The analysed results can then be used for further evaluation of the effects on the habitats. Several indexes are computed to show the hydrodynamic characteristics on the 8 project areas:

The inundation frequency is an important index for evaluating the ecological influence on the floodplain, especially for the floodplain vegetation. In this report, the inundation frequency is computed from the model results according to the definition:

$$f_{inundation}(x, y) = \frac{T_{wet}(x, y)}{T_{total}(x, y)} \quad (1)$$

in which, T_{wet} is the duration of the point being wet in the domain, T_{total} is the duration of the analysed period. (x, y) represents the location of each point in the domain.

The frequency of the flow velocity that exceeds 0.65 m/s can be computed in a similar way:

$$f_{u>0.65}(x, y) = \frac{T_{u>0,65}(x, y)}{T_{total}(x, y)} \quad (2)$$

This gives an indication about the flow strength in the inundated areas, which is important for estimate the ecological impacts.

The frequency of the bed shear stress that exceeds 1 Pa is used as an indication for evaluating the morphological stability of the area:

$$f_{\tau>1.0}(x, y) = \frac{T_{\tau>1.0}(x, y)}{T_{total}(x, y)} \quad (3)$$

When the bed shear stress is small, deposition could occur and the bottom elevation tends to increase. When it is large, the area is likely to be eroded due to high shear stress.

Moreover, the maximum water depth, velocity and bed shear stress are also computed during the simulation period.

Note that the effect on habitats is only computed for the normal scenario, which means only the runs 2013_Normal_0R and 2013_Normal_8R are included in the analysis.

Note that the 8 areas are opened 'as-is', in the sense that the bathymetries after opening are kept identical to the present bathymetry. Possibly local changes are made to the bathymetry during the process of preparing these areas for opening that are not included in these preliminary results.

3.4 Expected sedimentation in the 8 project areas by 2050

3.4.1 Introduction

The updated Sigmaplan contains numerous measures to diminish the risk of flooding along the Sea Scheldt and its tidal tributaries. One of these measures is the construction of flood control areas. These areas will buffer water and reduce water levels upstream when extreme high water levels occur. Two types of these flood control areas exist. The first type is the flood control area (FCA) that buffers water when extreme water levels in the river are reached. This area has an outlet structure to release the buffered water when lower water levels are again reached in the tidal river. The second type has the same function as the first one, but has also inlet structures to let water enter these areas at normal tides, creating a reduced tide (CRT = controlled reduced tide) in the area to create tidal nature (Cox et al., 2006; Maris et al., 2007). The FCA with CRT function imports sediments with the water on a daily basis. On the long term this will increase the bed level of the polder.

Next to the flood control areas with and without CRT function, de-embankments are made, giving more space to the river. These de-embankments will also flood daily and tend to trap sediments. The bed level of these areas will also increase on the long term. Different methods are available to describe the long term evolution of a platform or bed level. Here we will describe the methods used in this report. We differentiate between de-embankments and FCA's with CRT.

3.4.2 De-embankments

De-embankments are created by breaching an existing dike. The land behind the dike needs to have a bed level that is high enough to get a tidal regime like that of natural intertidal areas. Just after the breaching of the dike, the land will flood frequently and the sedimentation speed and increase in bed level will be high. Eventually this speed will decrease as the bed level rises. The flooding frequency will decrease and the sedimentation rate or the speed at which the bed level increases will decrease. Due to this process the elevation of the platform or bed level over time is asymptotic. This is comparable to the elevation in platform of natural marshes (e.g., Temmerman et al., 2003).

Many types of models can be used to simulate the long term elevation of platform level of marshes (e.g., Temmerman et al., 2004; Vandenbruwaene et al., 2011). We will choose the empiric elevation model of Vandenbruwaene et al. (2011) that was developed to describe the long term elevation of the platform of the FCA with CRT Lippenbroek. Vandenbruwaene developed this model further within a project on the Hedwige-Prosperpolder to account for natural intertidal areas and de-embankments (not for FCA with CRT). The model was calibrated based on the long term elevation of platform level of the Land of Saeftinghe. This model took into account the suspended matter and could differentiate the elevation speed between vegetated and non-vegetated land (Vandenbruwaene et al., 2015).

The empirical model for estimating the change of the platform mass and the sedimentation rate in de-embankments area is

$$\Delta M = \Delta E \cdot A \cdot \rho_b \cdot 10^{-3} \quad (1)$$

$$\Delta E = C_{SPM} C_j a h \quad (2)$$

$$h = \frac{1}{k}\sum_{j=1}^{k} \max\left((H_j - z_j), 0\right) \quad (3)$$

$$z_j = z_0 + \Delta E \quad (4)$$

With:

ΔM = the changing rate of mass on the platform [tons of dry matter (TDM) / year]

ΔE = the elevation rate of the platform [m / year]

A = area of the platform [m^2]

ρ_b = bulk density of the platform material [kg/m^3]

C_{SPM} = $SSC_{de\text{-}embankment}/SSC_{saeftinge}$, correction for the difference in SPM between the de-embankments and Saeftinge [-]

C_j = calibration factor [-]

a = the linear empirical relationship for the elevation of Saeftinge over 32 years [1 / year]

h = the mean water depth [m]

k = the number of tidal cycles in a synthetic year (4QN+QE)

H_j = the high water (HW) level for the tidal cycle j [m]

z_j = the platform elevation for the tidal cycle j [m]

z_0 = the initial platform elevation [m]

The empirical parameters that will be used further are shown in the table below:

Table 3 – parameters used in the empirical model for depoldered areas

Parameter [unit]	Value
a [1/year]	1,13 (vegetated growth); 0,42 (non-vegetated growth)
C_j [-]	1,36 (vegetated growth); 0,94 (non-vegetated growth)
C_{SPM} [-]	variable depending on locations

The vegetated platform will grow faster than the non-vegetated platform, because the vegetation will trap sediment. The model further assumes that vegetation starts to develop once the platform height rises above the level of Mean High Water Neap.

These parameters were calibrated with field observations and hence can be used here to calculate the long term (from the year in operation to 2050) elevation of the different de-embankments along the Scheldt estuary. The input data of the model will be described in one of the next paragraphs.

3.4.3 FCA's with CRT function

A FCA with CRT function is a flood control area with inlet and outlet structures that allow water to enter the polder in a reduced way (the amount of water coming in is dependent on the dimensions of the inlet structure). So inside the polder the land is flooded with every tide, simulating flooding conditions of natural marshes (e.g., Cox et al., 2006; Maris et al., 2007). In this way estuarine nature can develop inside the polder area. This is the ecological function of such an area (besides its safety function when extreme high water levels occur in the estuary).

Like de-embankments and natural marshes the bed level of these polders will elevate due to sedimentation of suspended particulate matter (SPM) present in the entering tidal water. Such a polder is a closed system which receives a determined amount of water every tide (controlled by the inlet construction). The sediments get trapped inside the polder, which will elevate the bed level inside the polder. The bed level elevation of CRT areas in 2050 is estimated based on the water volumes and SPM entering these areas. A comparable exercise was already done for CRT Lippenbroek and this was based on detailed monitoring data near the in- and outlet structure of this CRT (Peeters et al., 2009). Here we will follow this approach and make some basic assumptions to estimate the amount of tons of dry matter (TDM) present in the FCA's with CRT by 2050:

$$TDM = V_{sn}\, c_{SPM}\, TE\, m\, n\, 10^{-3} \qquad (5)$$

with:

V_{sn} total volume of water entering the CRT over a spring-neap tidal cycle [m³]

c_{SPM} Scheldt surface SPM concentration near the CRT area during the last phase of flood tide (representative for average tidal conditions and upstream discharge [kg/m³]

TE Trapping Efficiency (= TDM deposited / TDM entering) [-]

m the number of spring neap tidal cycles per annum = 365days / 14.75 days per cycle

n number of years (from the year of opening until 2050)

Based on the number of TDM, the bulk density and the surface area of the FCA with CRT, the average elevation of the bed level can be calculated using the following formula:

$$z_{2050} = z_0 + \frac{TDM}{A\,\rho_b} \qquad (6)$$

with:

z_{2050} Average bed level of CRT in 2050 [m]

z_0 Average bed level of CRT in the year from where we start the calculation [m]

A Surface area of CRT area [m²]

ρ_b Bulk density of bottom [kg/m³]

The trapping efficiency is the ratio of the amount of TDM deposited in a flood area to the amount of TDM that flows into the area. In Peeters et al. (2009) an annual trapping efficiency of 0.64-0.75 (average conditions) was calculated for the Lippenbroek FCA-CRT based on sediment monitoring at the inlet and outlet sluices. Based on these values, a value of 0.75 was used in this memo for all FCA-CRT areas.

3.4.4 Model run for a synthetic year

The hydrodynamic simulations described in §3.2.2 only run for a short period (6 days). However, for the estimation of long-term sedimentation in both de-embankments and FCA-CRTs, information of hydrodynamics, e.g. water levels at different locations and volume entering specific areas, is needed. Moreover, the methodology stated in §3.4.2 and §3.4.3 is based on the records of HW levels in a full year and water volume at least during a spring-neap tidal cycle, which demands longer period of model simulations.

To tackle the issue above, another set of model runs are created based on the methodology proposed in the project "Integral Plan for the Upper Sea Scheldt". The new set of runs simulate a full year with the use of synthetic boundary conditions derived from the statistical analysis of history data. Hence, it is more suitable to be used for long-term studies. The other model inputs, e.g. bathymetry, implementation of the project areas, and other physical parameters, remain the same as in the runs in §3.2.2. In other words, only the boundary conditions and simulation periods are changed.

The new simulations consist of two parts (scenarios), a normal scenario (QN) that lasts about 3 months and an events discharge scenarios combined with storm surge signals (QE) for about 20 days. The modelled results in the end will be assembled as 4xQN plus QE in order to derive the hydrodynamic information that can represent a full year. The synthetic boundary conditions are described in detail in the following sections.

Normal scenario (QN)

Downstream boundary is a harmonic boundary without storm surge (derived from the DCSMv6-ZUNOv4 instead of DCSMv5-ZUNOv3). Upstream boundary is a synthetic discharge boundary containing evens with a return period equal to or smaller than 1/6 year. The simulation period is 3 months from 29/07/2013 22:20 to 01/11/2013 22:20. The first three days in this period will be used for the spin up of the model.

As done in the project "Integral Plan for the Upper Sea Scheldt", 3 months' timeseries of the harmonic tide without storm surge is used as the downstream boundary condition. 3 months discharge time series are used as the upstream boundary conditions (Figure 7).

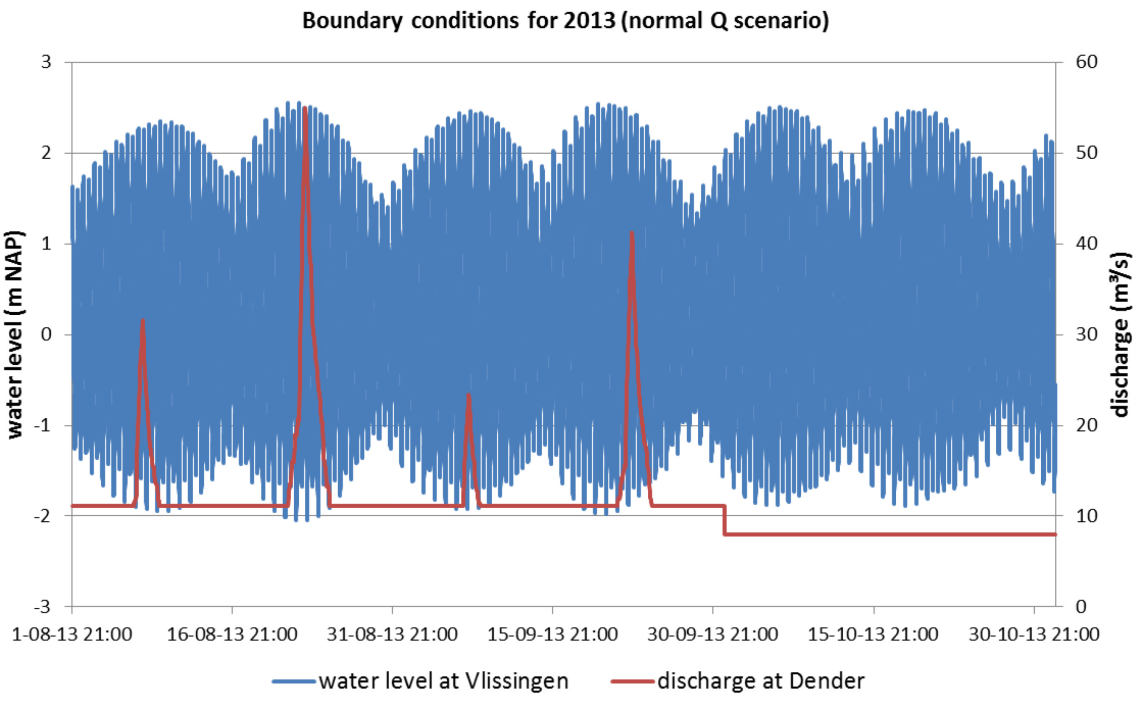

Figure 7 – Combination of the time series for the current state (for QN scenario)

The maximum discharge at Dender (the second peak in the time series in Figure 7) is put 15 hours after the maximum high water at Vlissingen. The maximum high water is selected based on the analysis of 1 year harmonic time series for 2013. Different spring-neap cycles are observed during the selected 3 months. Therefore, some of these tides represent average astronomical tide.

Events discharge scenario (QE)

The downstream boundary is a harmonic signal plus a storm surge signal. The typical storm surge was determined in a statistical way in IMDC (2015). The upstream boundary is a discharge time series that contain 2 discharge events with return periods of 1 year and 1/2 year. The simulation period is about 2 weeks (or a few days longer depending on the combination of the boundary condition upstream and downstream).

Downstream boundary condition

The water level at Vlissingen calculated in the harmonic ZUNO run is analyzed for the entire year 2013 (or 2050) and the maximum high water is found. The peak of each storm surge (T1, T1/2, T1/3) should coincide with high water (conservative approach). The time series of the T1 surge is shifted so that the peak of T1 surge coincides with the highest high water at Vlissingen (23/08/2013 03:20).

The time series of the surges with return periods T1/3 and T1/2 are made to coincide with high waters too. The surges are combined so that there are about 4.5 days between their peaks (figure 8). To decrease the simulation period we let surges overlap for a limited time. When they overlap, the highest surge is taken for the calculation. The surge signal will be added to the harmonic water levels to get the downstream boundary of the SCALDIS2019 model.

Upstream boundary condition

In total 14 days of discharge time series are available (7 days for T1 and 7 days for T1/2 return periods). The maximum discharge at Dender is expected 15 hours after the maximum surge at Vlissingen (IMDC, pers. comm.). The peak of discharge T1 is therefore put 15 hours after the peak of surge T1 ; the peak of discharge T1/2 is put 15 hours after the peak of surge T1/2. When no discharge is available (between Q T1 and Q T1/2) a constant average discharge is used upstream.

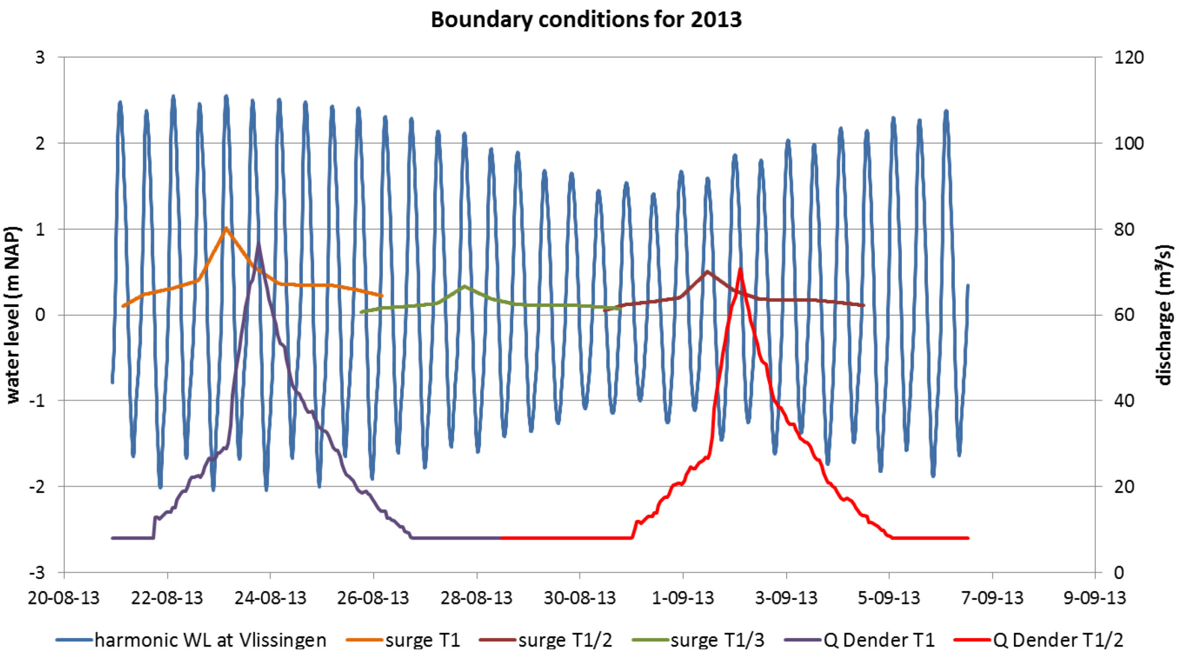

Figure 8 – Combination of the time series for the current state (for QE scenario)

The simulation period for the QE scenario is as follows: from 17/08/2013 22:20 to 06/09/2013 22:20. The first 3 days will be used for the model spin up.

List of the model runs (4QN plus QE)

An overview of the addition runs are listed in Table 4.

Table 4 – List of the model runs representing a full synthetic year

Name	Boundary conditions	FCA-CRT areas	Depoldered areas	Simulation period
2013_QN_8R	Normal scenario	Implemented	Implemented	29/07/2013 22:20 to 01/11/2013 22:20
2013_QE_8R	Events discharge scenario	Implemented	Implemented	17/08/2013 22:20 to 06/09/2013 22:20

3.4.5 Input data

Initial elevation and area of the platform

To determine the initial elevation (bed level) of the de-embankments and the FCA's with CRT the dataset DTM Vlaanderen from 2004 was used (5x5 m resolution). This older dataset was chosen over more recent ones because the last years a lot of building activity and excavation has happened in the de-embankment and CRT areas. Some of the CRT areas are already functioning and a recent DTM cannot be used to determine the original polder bed level. The area of the platform is computed from the GIS data with the contours of each project site. Table 5 and Table 6 give an overview of the initial bed level and area of the de-embankments and CRT areas, respectively.

High water level

For the estimation of the sedimentation in the de-embankments, high water (HW) levels is one of the important input data required by the empirical model. It is preferred to have a full year record of HW levels at the project areas. As mentioned in §3.4.2, such records of HW levels can be obtained from a 4QN plus QE simulation forced by a set of synthetic boundary conditions that statistically represent a full year including a storm surge period. An example of the HW levels used in the empirical sedimentation model is shown in Figure 9. The mean high water during neap tide (MHW Neap) and mean high water during spring tide (MHW Spring) are also derived from the simulation results. The MHW Neap is used to determine the growth type of the platform, that is to say, non-vegetated growth if platform elevation is below the MHW Neap, or vegetated growth when it is above the MHW Neap.

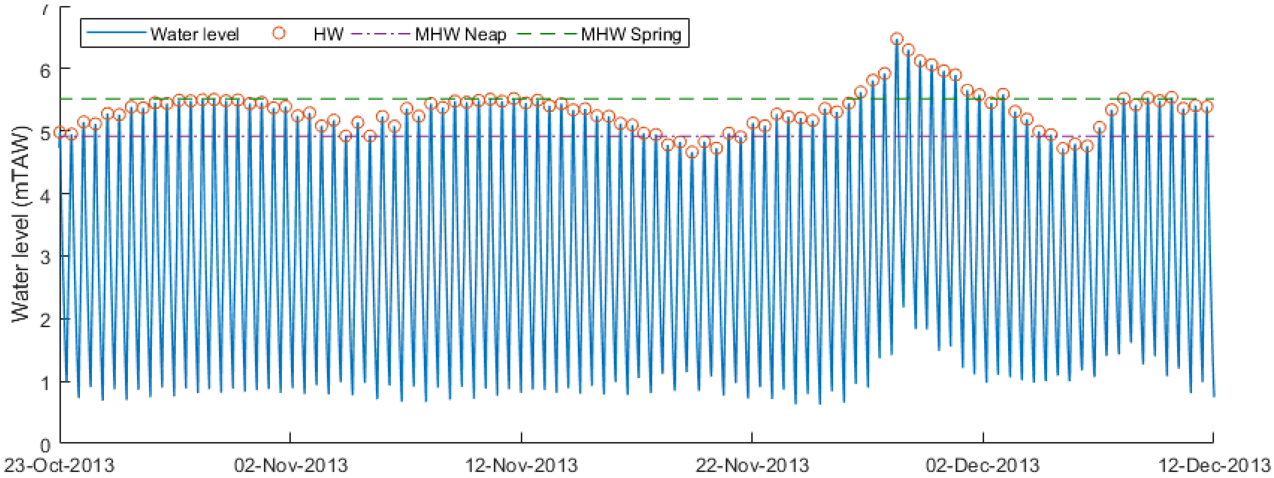

Figure 9 – Example of water level taken in the main channel near the de-embankment Uiterdijk (blue line) and the HW data points (read circle) used in the empirical sedimentation model. The storm surge period is near the end of the full-year simulation.

Evolution of the high waters

For the de-embankments, the influence of sea level rise and the morphological evolution of the estuary is also taken into account in the empirical model for the estimation of long-term sedimentation. Each de-embankment is assigned with a value of the evolution in the high waters, which was based on calculations made by Levy et al. (2014). They calculated a linear increase in water levels caused by sea level rise at a series of gauge stations along the Scheldt estuary and its tributaries, over the period 1901-2012. These sea level rise values are then used to adjust the HW levels from the first year of operation until 2050 (see Table 5).

For the FCA-CRT areas, due to the fact that the water entering and leaving is regulated by hydraulic structures, the sea level rise has limited effects, hence, it is not considered there.

Volume entering the project area

The volume of water entering the project area during a spring-neap cycle (14.75 days) is required for estimating the sedimentation in the FCA-CRTs. The entering volume is also computed based on the simulation result from the 4QN plus QE run. The following formula is used in the calculation.

$$V_{sn} = \sum_{t=t_1}^{t_2} \sum_{i=1}^{n} \max\big(0, H(t,i) - H(t-1,i)\big)\, A(t,i) \tag{7}$$

where V_{sn} is the entering volume in the project area, *t* is time, t_1 and t_2 are the starting and end of a spring-neap cycle, *i* is the node index and *n* is the total number of the nodes in the project area, H is water depth of and A is nodal area (discretized area assigned to each node following the same algorithm in Telemac-3D). Note that the volume leaving the area is excluded according to the methodology. A trapping efficiency parameter is applied to the entering volume for estimating the mass that could stay in the area due to sedimentation.

Surface SPM

A FCA-CRT/de-embankment will be submerged during the last part of the flood phase. To get an idea of the amount of sediment flowing into the flood zone, it is important to know the surface SPM concentration of the river during the last part of the flood phase. This will vary depending on the location along the estuary.

Due to the fact that the simulations performed without adding sediment to the model, the SPM data will be taken from field measurements.

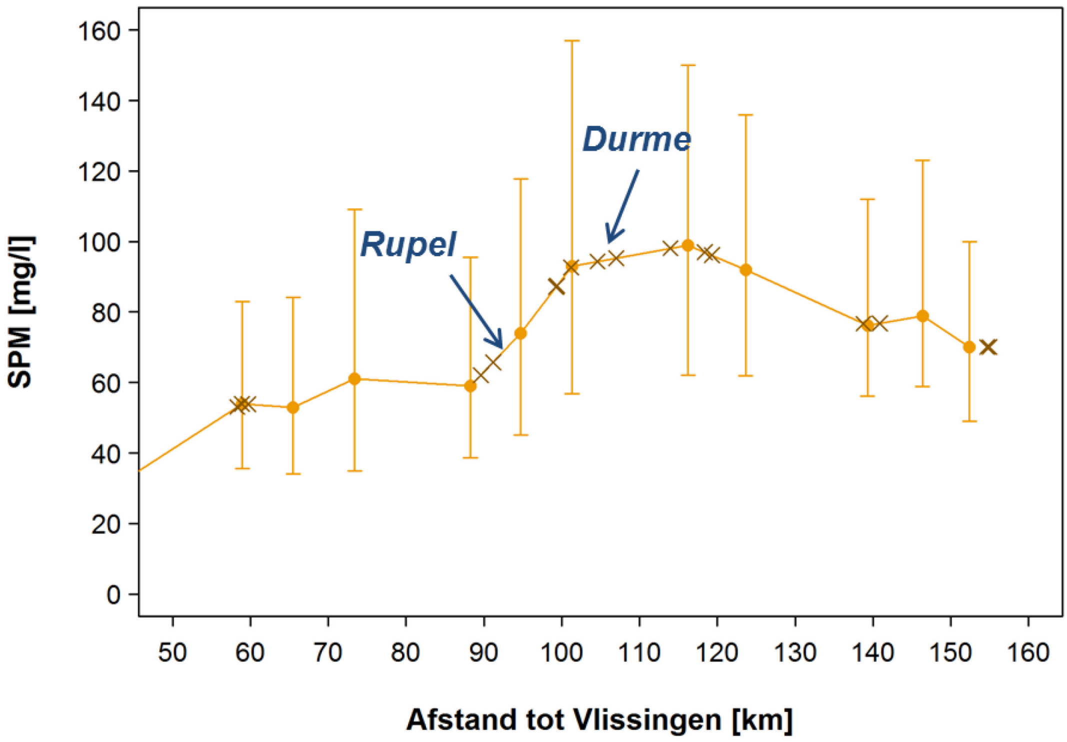

Figure 10 – Variation in surface SPM along the Sea Scheldt during the last part of the flood phase (Vandenbruwaene et al., 2015)

In the Sea Scheldt sediment balance project, the time of HW was assigned to a dataset of tidal-independent surface SPM measurements (Vandenbruwaene et al., 2015). The dataset includes measurements performed at various locations along the Sea Scheldt, with a measurement frequency of approximately 3 weeks since 1995.

From the surface SPM dataset, the measurements during the last part of the flood phase were selected (i.e. from 120 min before HW to 60 min after HW). In this way, the SPM concentrations are retained that are representative of flooding from a FCA-CRT/de-embankment. Subsequently, the distance to Vlissingen was determined for each measurement location and the locations were divided into clusters of 10 km. The median distance to Vlissingen and the median SPM concentration were determined for each cluster, for all measurements from 1995 to recent years. Then a linearly interpolation was performed in order to get the surface SPM concentration for each project area (Figure 10).

Because the sediment transport is not modelled in this study, we assume that the surface SPM concentration will stay at a similar level after these areas being in operation. This is based on the fact that the total area of depoldering is relatively small and it has limited effect on the sediment concentration in the main channel.

Overview of the input data

The processed input data for the empirical sedimentation model is summarized in Table 5 and Table 6.

Table 5 – Overview of the parameters used to calculate the bed level elevation of the de-embankments

De-embankment	River	X [km]	t_0 [Yr]	z_0 [mTAW]	A [m²]	SPM [mg/l]	SPM factor	Evolution of the high waters [cm/yr]	$GHWD_0$ [mTAW]
Groot Schoor Bornem	Scheldt	99.4	2025	2.98	229957	106	2.5	0.88	4.99
Groot Schoor Hamme	Scheldt	101.2	2021	5.00	267032	113	2.7	0.88	5.04
Uiterdijk	Scheldt	118.4	2022	5.09	116911	115	2.7	0.88	4.91
Groot Broek	Durme	n/a	2025	4.84	572424	95	2.3	1.00	5.04
Klein Broek	Durme	n/a	2025	5.11	404971	95	2.3	1.00	5.03

Table 6– Overview of the parameters used to calculate the bed level elevation of the CRT areas

FCA with CRT	River	X [km]	t_0 [Yr]	z_0 [mTAW]	A [m²]	SPM [mg/l]	V_{sd} [m³]
Zwijn	Scheldt	112.6	2025	2.39	700575	97.5	3 604 401
Wal	Scheldt	114	2025	2.90	607859	98.1	2 375 845
Vlassenbroek	Scheldt	119.3	2025	2.58	942440	113.9	2 595 302
De Bunt	Durme	n/a	2025	3.06	670000	94.6	2 351 258

4 Implementation of the project areas

In this study, the calibrated SCALDIS model for the year 2013 is used as the basis for the detailed modelling of the 8 realization areas. For evaluating the effects of the nature-based solutions (de-embankment, FCA and CRT), 8 project areas (actions C1 – C8, see Table 1) have to be implemented in the SCALDIS model.

These 8 realizations can be categorized into two types:

- The first type is the flood control area (FCA) with controlled reduced tide (CRT). It buffers water when extreme water levels in the river are reached. This type of area has an outlet structure to release the buffered water when lower water levels are again reached in the tidal river, it also has inlet structures to let water enter these areas at normal tides, creating a reduced tide in the area to create tidal nature.
- The second type is the de-embankment or depoldering area, which is made for giving more space back to the river. De-embankments are created by breaching an existing dike. The land behind the dike needs to have a bed level that is high enough to get a tidal regime like that of natural intertidal areas. These de-embankments will be flooded daily and tend to trap sediments.

The FCA-CRT areas can be modelled with the culvert functionality that is available in Telemac-3D, while the de-embankments (breaching of the dikes and depoldering of the nearby area) can be modelled by altering the bathymetry. This normally requires mesh refinements in the corresponding area.

For better resolving the hydrodynamics in the 8 realization areas in the Upper Sea Scheldt, the SCALDIS model is adapted. The original calibrated SCALDIS model for the year 2013 has a relatively coarse grid in the 8 project areas (Figure 11).

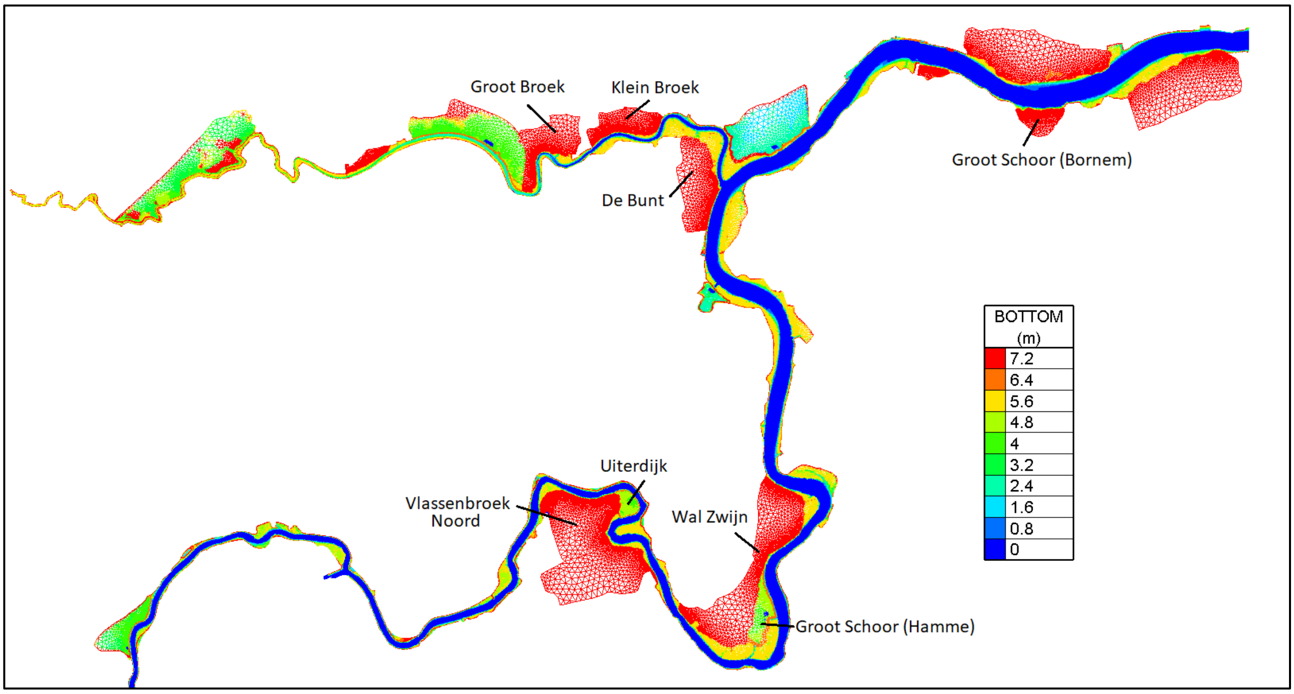

Figure 11 – The original mesh in the SCALDIS 2013 model

In this project, three major adaptations have been made to the SCALDIS model:

- local refinement of the model grid;
- update of the bathymetric data;
- implementation of depoldered areas by breaching the dykes;
- implementation of FCA-CRT functional areas.

The 5 depoldered areas are modelled in more detail by refining the grid and altering the local bathymetry, while the 3 FCA-CRT areas not only need the local grid refinement and bathymetry update, but also the culvert function parameters for modelling in-outflow under tidal influence properly.

4.1 Bathymetry data

In the framework of "LIFE-SPARC", new bathymetric survey data is collected and processed. There are three main data sources (Vanlede et al. 2020):

- The Digital Height Model (DHM) derived from the most recent LiDAR survey carried out in 2016. This DHM is supplied by Maritime Access division, and it includes the elevation of the land area for entire Upper Sea Scheldt, Durme and Rupel basin;
- The general bathymetric data that Maritime Access division has compiled from surveys of the different zones in the rivers and channels in the Upper Sea Scheldt. The field campaigns were all conducted in the first half of January 2018;
- The latest bathymetry data of the Durme dating from 12 March 2018, supplied by the Vlaamse Waterweg NV;
- The latest bathymetry of De Bunt provided by the Vlaamse Waterweg NV.

The data was then processed and merged into a high-quality bathymetric dataset, which covers the 8 project areas in the Upper Sea Scheldt. It is only used for updating the bathymetry in the 8 project areas in the SCALDIS model, while the rest of the domain remain unchanged. The updated bathymetry is shown in the Figure 12 - Figure 16.

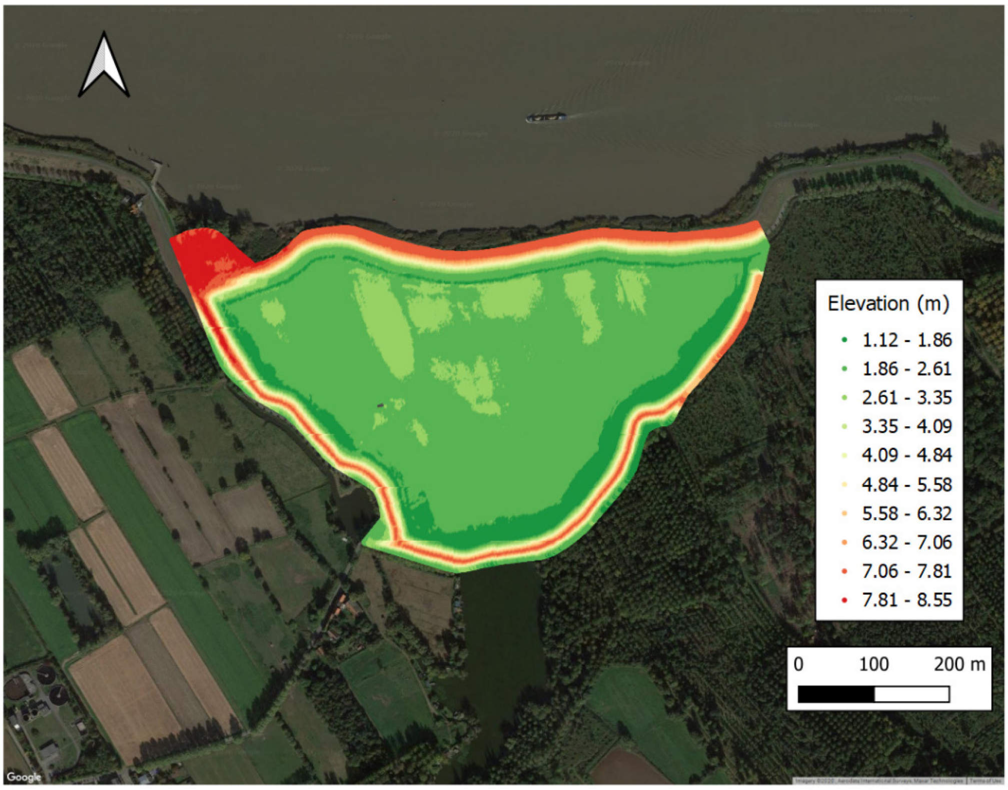

Figure 12 – The latest bathymetric data of Groot Schoor Hingene (Bornem)

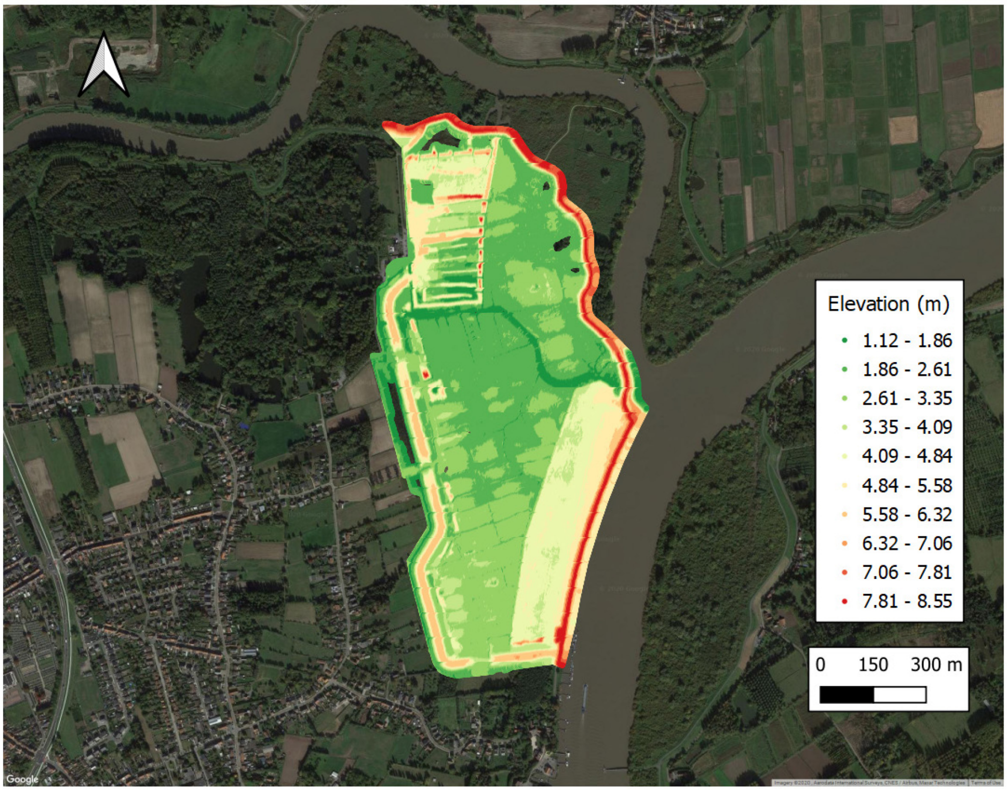

Figure 13 – The latest bathymetric data of De Bunt

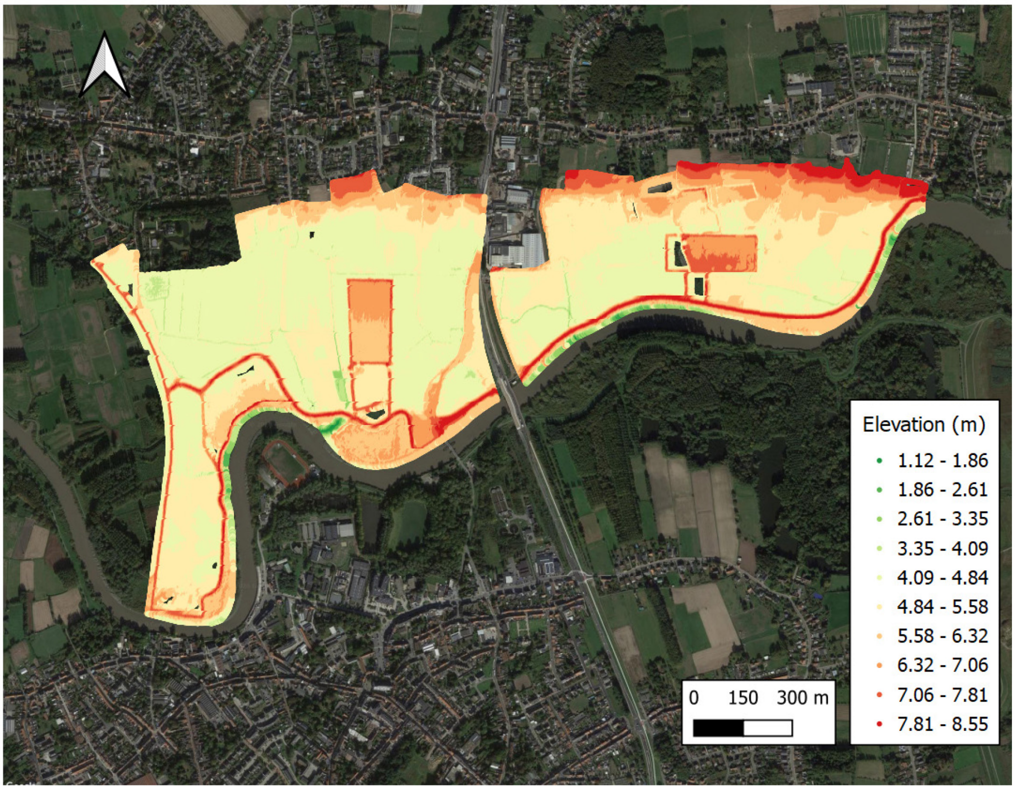

Figure 14 – The latest bathymetric data of Groot Broek and Klein Broek

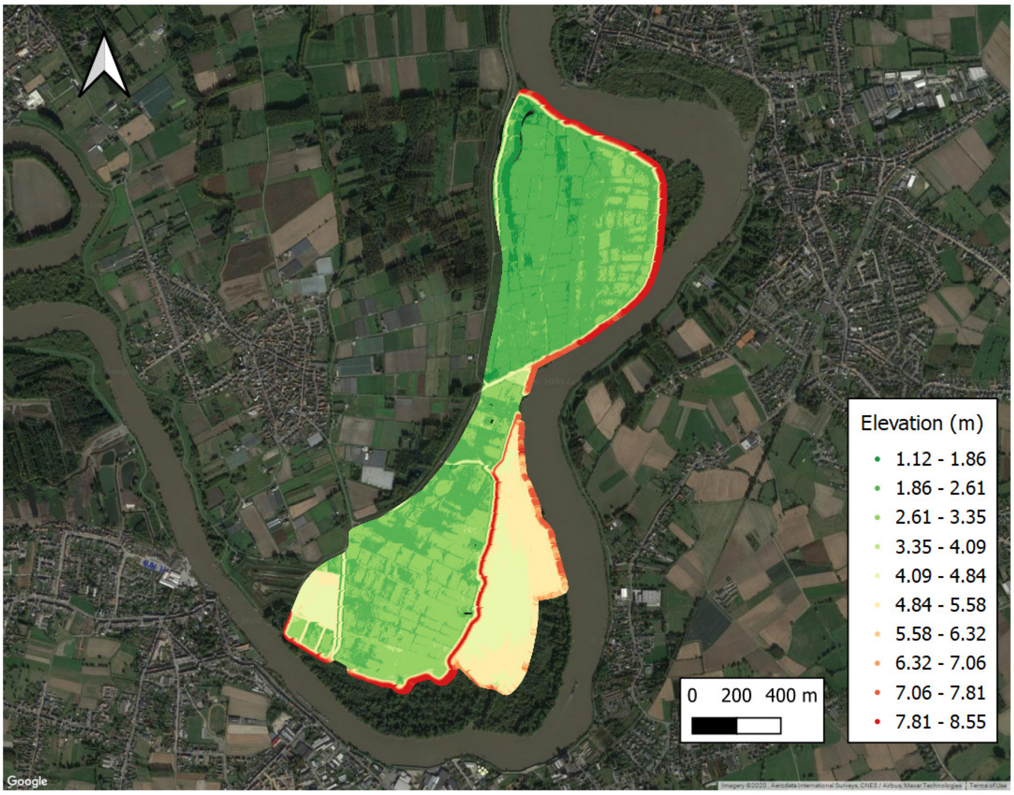

Figure 15 – The latest bathymetric data of Wal Zwijn and Groot Schoor (Hamme)

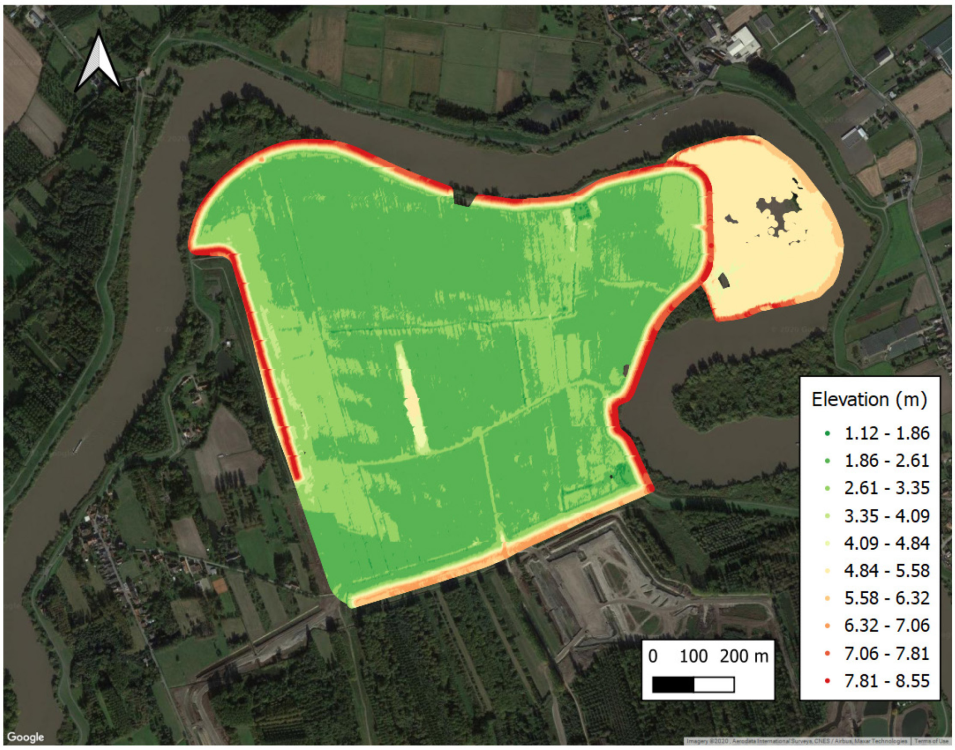

Figure 16 – The latest bathymetric data of Vlassenbroek Noord and Uiterdijk

4.2 Local mesh refinement and bathymetry update

Before updating the bathymetry of the 8 project areas in the SCALDIS model, the grid resolutions in those areas is optimized (refined) in order to capture the necessary details of the terrain, e.g. the relatively thin dikes around the depoldered areas and flood control areas (Figure 12 - Figure 16).

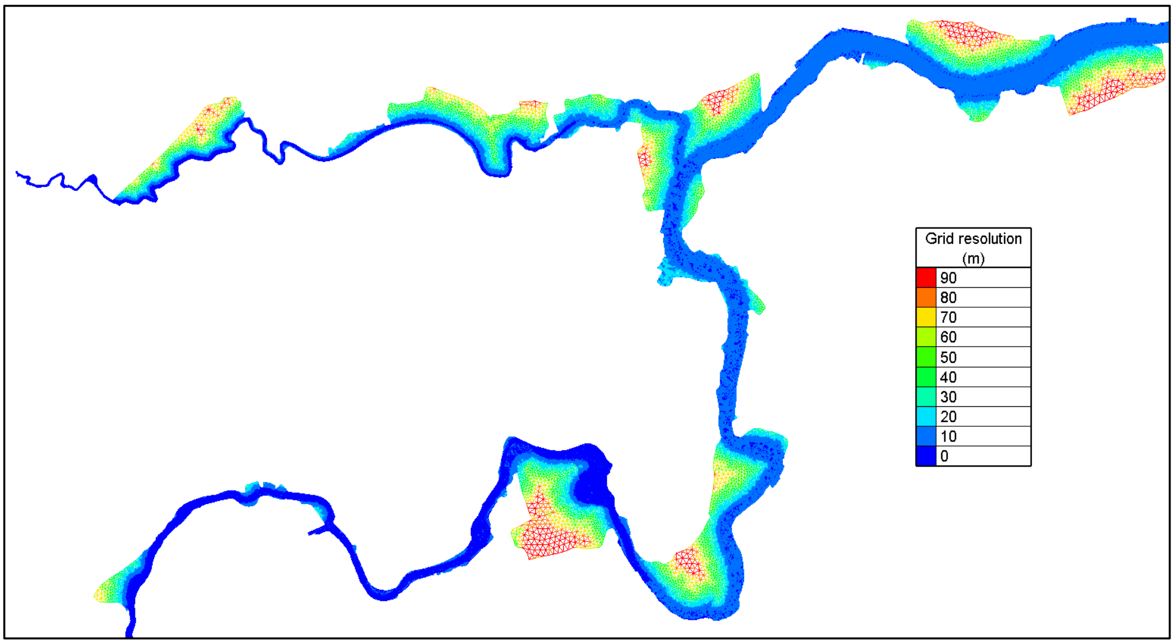

Figure 17 – The original grid resolution in the SCALDIS model

In the original SCALDIS model, the grid resolution in the 8 project areas ranges from 30 to 90 m (Figure 17). These structures can only be modelled by mapping the bathymetry onto a very fine grid. Hence, the SCALDIS grid in the 8 project areas was refined to a much finer resolution about 10 m. The refinement of the grid results in a new mesh with 523,233 nodes, which is about 10.76% more than the original mesh.

After the local mesh refinement, the updated bathymetry of the 8 project areas is mapped to the new grid. The refined grid and the updated bathymetry are shown in Figure 18, Figure 19 and Figure 20. Note that the updated bathymetry still includes the ring dykes around the depoldered areas. In the next step, these dykes are breached in order to create a connection to the main river.

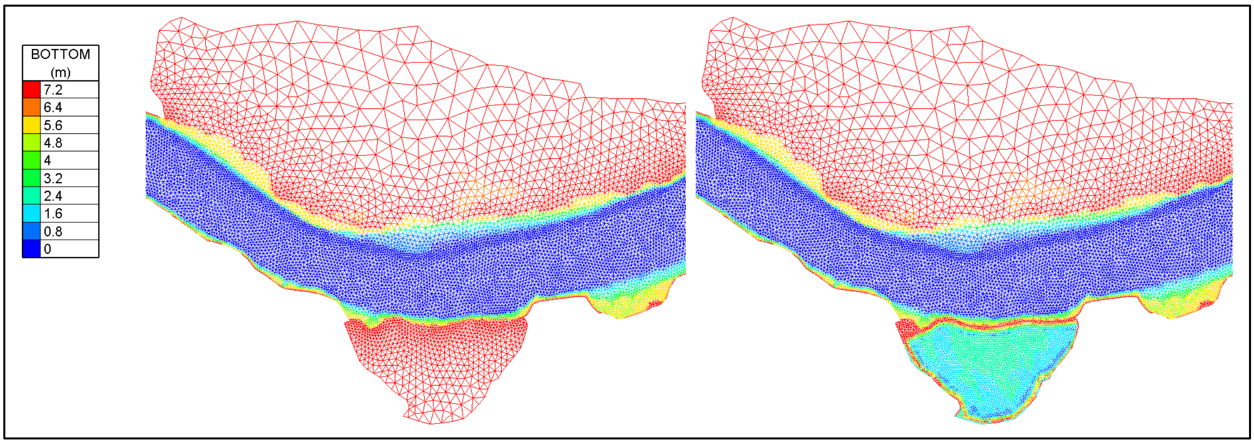

Figure 18 – The original grid (left) and the refined grid (right) of Groot Schoor Hingene (Bornem)

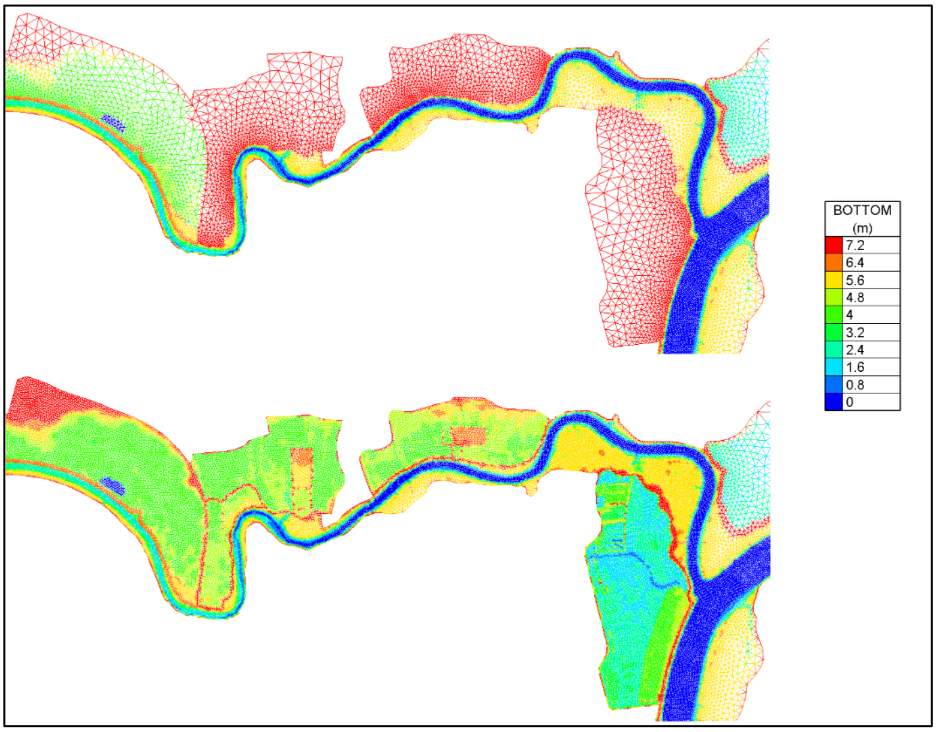

Figure 19 – The original grid (upper) and the refined grid (lower) of Groot Broek, Klein Broek and De Bunt

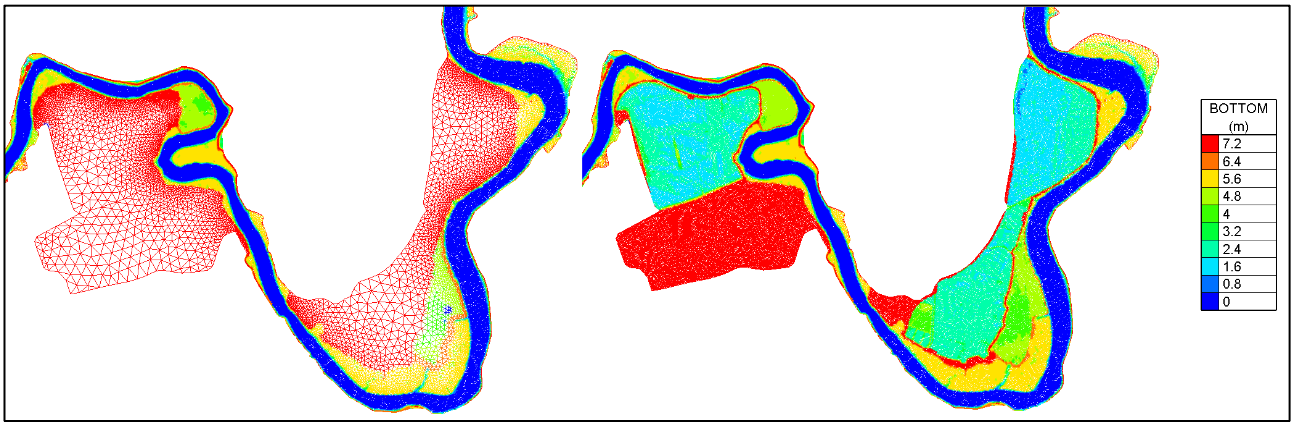

Figure 20 – The original grid (left) and the refined grid (right) of Wal Zwijn, Groot Schoor (Hamme), Vlassenbroek and Uiterdijk

4.3 Implementation of the depoldered areas

The implementation of the depoldered area can be done by altering the bathymetry locally. As mentioned above, the latest bathymetry of the 5 depoldered areas are mapped to the refined grid. In this step, the dikes in front of the 5 depoldered areas in Groot Schoor (Bornem), Groot Broek, Klein Broek, Groot Schoor (Hamme) and Uiterdijk are breached, in order to allow overflow in the these areas during flood and ebb. The comparisons of the bathymetry before and after breaching the dike are shown in Figure 21 - Figure 24.

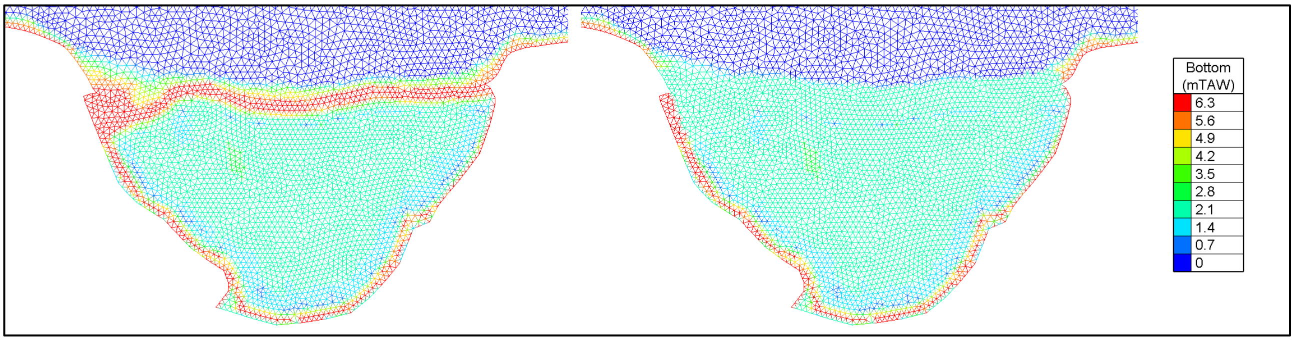

Figure 21 – The refined grid of Groot Schoor (Bornem)
with the updated bathymetry (left) and the bathymertry after breaching the dike (right).

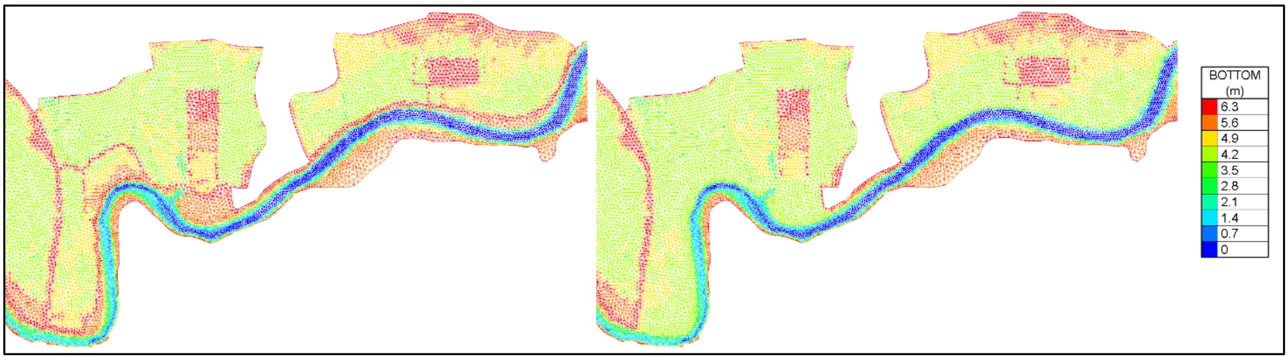

Figure 22 – The refined grid of Groot Broek and Klein Broek
with the updated bathymetry (left) and the bathymertry after breaching the dike (right).

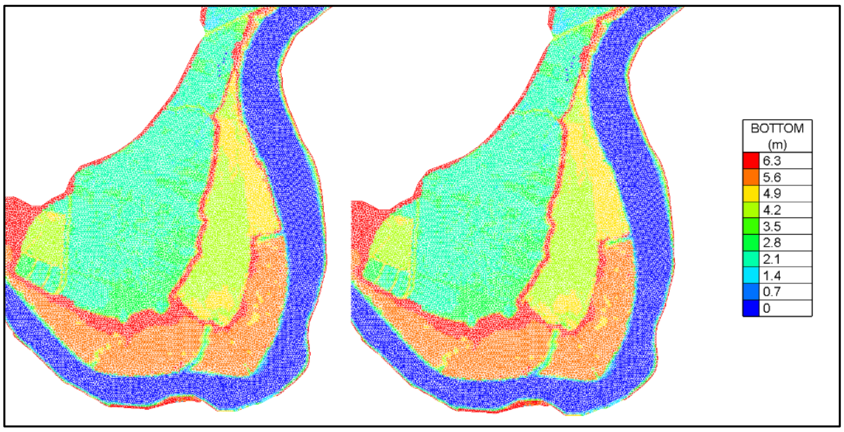

Figure 23 – The refined grid of Groot Schoor (Hamme)
with the updated bathymetry (left) and the bathymetry after breaching the dike (right).

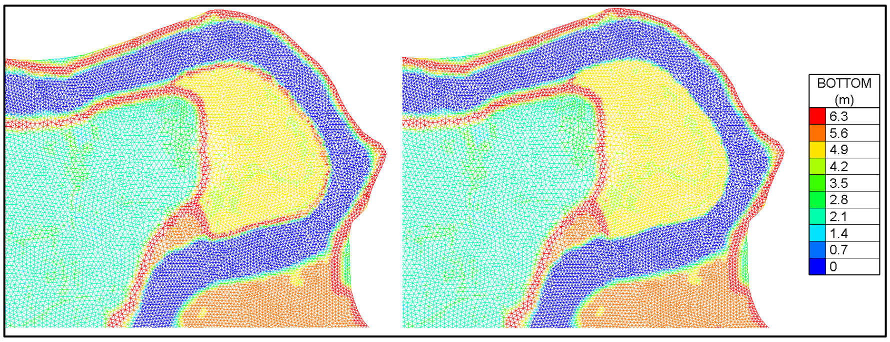

Figure 24 – The refined grid of Uiterdijk.
with the updated bathymetry (left) and the bathymetry after breaching the dike (right).

4.4 Implementation of FCA-CRT areas

There are three FCA-CRT areas planned in the Upper Sea Scheldt in this study, namely De Bunt, Wal-Zwijn and Vlassenbroek Noord. These areas are surrounded by the ring dikes in the updated bathymetry. Culverts will be defined as hydraulic structures to allow water flow in and out of the FCA-CRT areas.

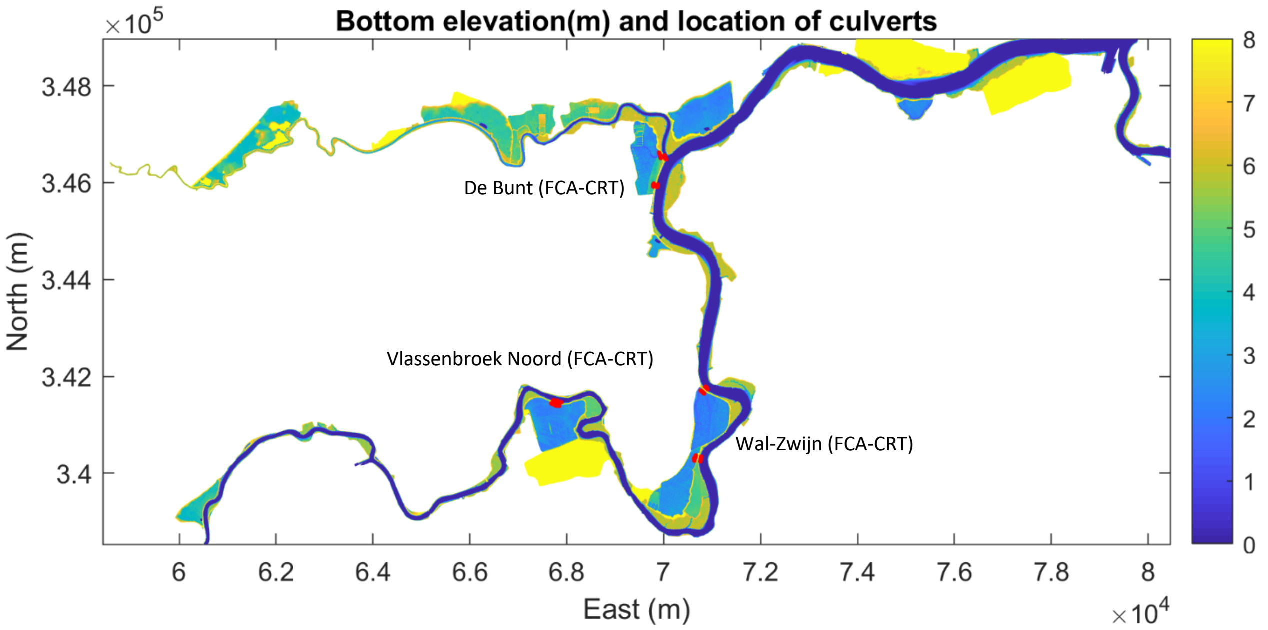

Figure 25 – The locations of the culverts in the FCA-CRT areas

4.4.1 De Bunt

De Bunt is operated as an FCA with CRT function, which means water can enter the area during most tidal cycles. The bathymetry is updated and the FCA-CRT is modelled with culverts defined based on the design in 2008 (Figure 26). More specifically, 6 outlets are grouped with 3 inlets placed in the north, while 2 outlets with 3 inlets in the south. The configurations of the culverts, i.e. dimensions and other characteristics of the overflow dike and hydraulic structures for the in- and outflow, are shown in Table 7. The location of the culverts are indicated in Figure 26.

Table 7 – The dimensions and characteristics of the FCA-CRT area in De Bunt

Overflow dike:	920 m long	crest level = 6.8 m TAW
Outflow:	8 culverts:	bottom level =0.5 + 2.78 m TAW dimensions = 3 m wide x 2.2 m high length = 18 m non return valves present trash screen present
Inflow:	5 culverts:	bottom level = 4.2 m TAW dimensions = 3 m wide x 2.2 m high length = 18 m height of weir = 0.2 + 0.4 m trash screen present

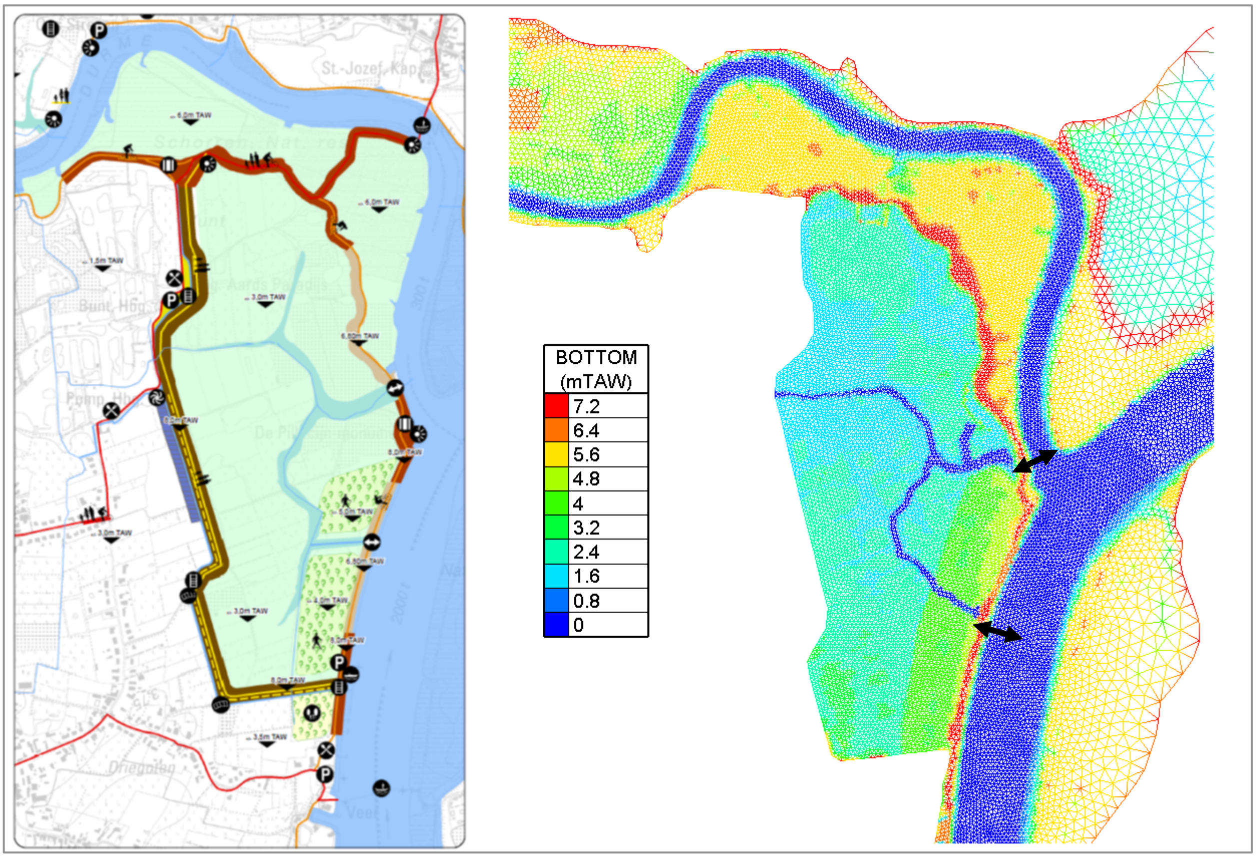

Figure 26 – Design of May 2008 of the FCA/CRT De Bunt (left) and implementation in the model (right).
(Map taken from: Rivierherstelproject Durmevallei Stapsgewijze realisatie van het GGG De Bunt: Schetsontwerp. versie Mei 2008)

4.4.2 Wal-Zwijn

Wal-Zwijn has the largest area among the three areas and will be operated as an FCA-CRT area. According to the design, there are two locations having the in- and outflow culverts, one in Zwijn, and the other one in Kleine Wal (Figure 27). The configurations of the FCA-CRT Wal-Zwijn are shown in Table 8.

Table 8 – The dimensions and characteristics of the FCA-CRT area in Wal Zwijn

Zwijn	**Overflow dike:**	2*360 m long	crest level 6.7 TAW
	Outflow:	6 culverts:	bottom level =1,5 m TAW dimensions = 3 m wide x 2,2 m high length = 18 m non return valves present trash screen present
	Inflow	4 culverts:	Bottom level = 4,0 mTAW Dimensions = 3 m wide x (2,2 – schotbalken) m 1 * 0.3 m schotbalk 2 * 0.6 m schotbalk 1 * 0.8 m schotbalk Length = 20 m

Kleine Wal	**Overflow dike:**	245 m long	crest level 6.7 m TAW
	Outflow:	6 culverts:	bottom level =1,5 m TAW dimensions = 3 m wide x 2,2 m high length = 18 m non return valves present trash screen present
	Inflow:	3 culverts:	Bottom level = 4,0 mTAW Dimensions = 3 m wide x (2,2 – schotbalken) m 1 * 0.3 m schotbalk 1 * 0.5 m schotbalk 1 * 0.6 m schotbalk Length = 20 m
Compartimenteringsdijk Grote Wal – Kleine Wal		160 m	Crest level ~ +2,5 m TAW + profile
Grote Wal	**Overflow dike:**	1850 m long	crest level 6.7 to 6.9 m TAW

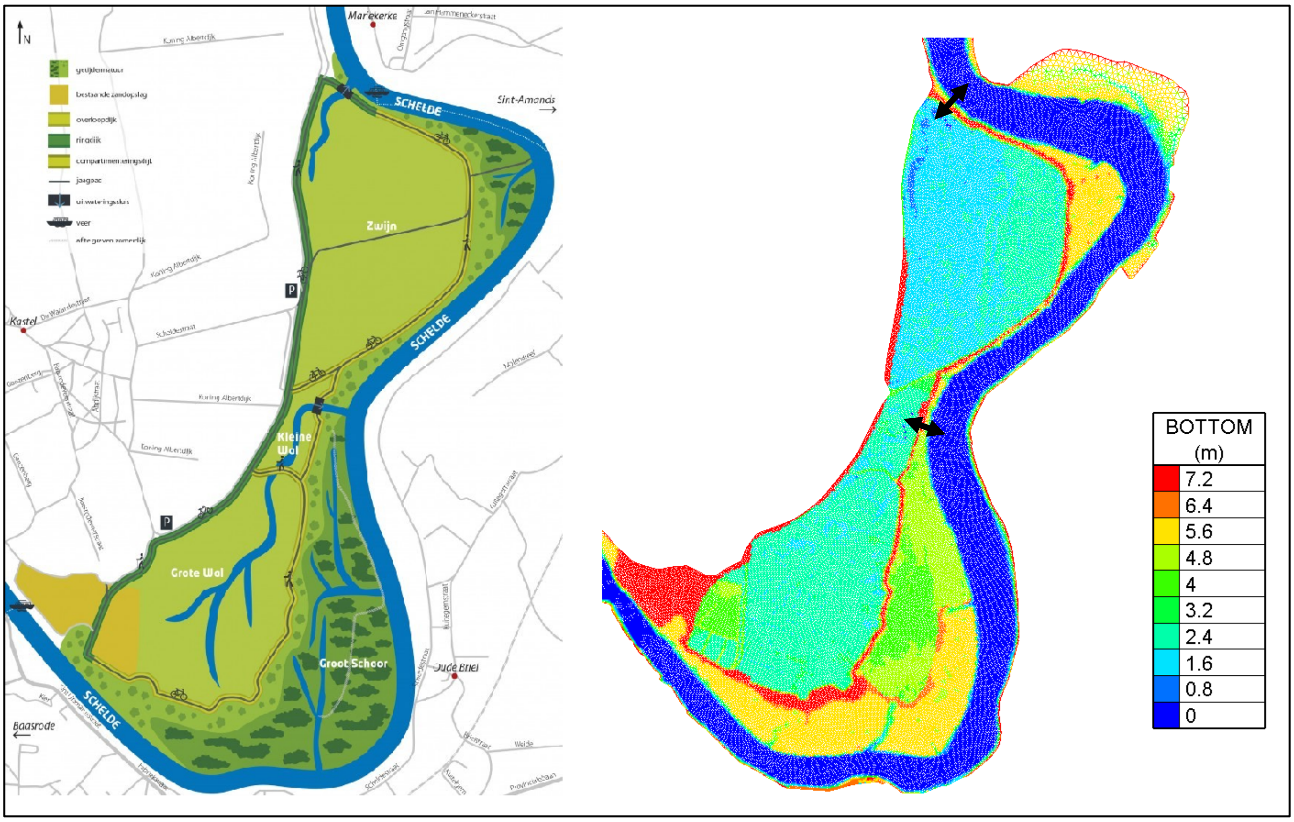

Figure 27 – The designed plan from 2019 for FCA-CRT Wal Zwijn (left) and the implementation in the model (right).
(Map taken from: https://sigmaplan.be/nl/projecten/wal-zwijn/deelprojecten/grote-wal-kleine-wal-en-zwijn%20/).

4.4.3 Vlassenbroek Noord

Vlassenbroek is operated as a FCA area with CRT function. Currently only the northern part (Vlassenbroek Noord) is activated in the model. The southern part is planned as a FCA but not finished at the moment. It is also not included in the LIFE SPARC project. In this study, only Vlassenbroek Noord is implemented in the model. The structure for in- and outflow is located in the north of the area (Figure 28). The dimensions of the culverts and other characteristics of the overflow dike are shown in Table 9.

Table 9 – The dimensions and characteristics of the FCA-CRT area in Vlassenbroek

Overflow dike:	- 2400 m long	- crest level = 6.5 to 6.9 m TAW
Water outflow:	- 8 culverts:	bottom level =0.5 m TAW dimensions = 3 m wide x 2.2 m high length = 18 m non return valves present trash screen present
Water inflow:	- 6 culverts:	bottom level = 4.2 m TAW dimensions = 3 m wide x 2.2 m high length = 18 m height of weir = 0.0 m trash screen present

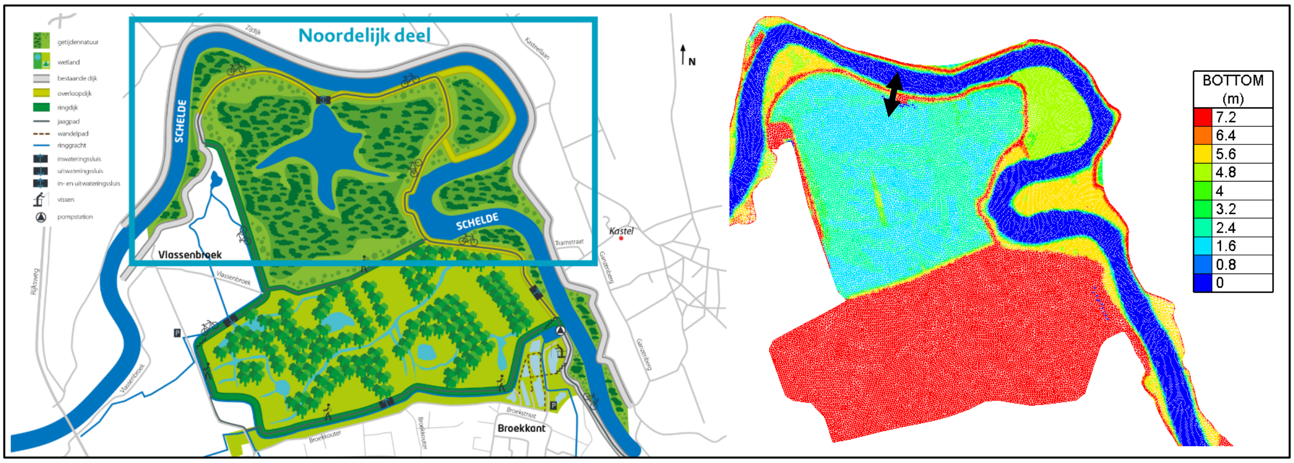

Figure 28 – The designed plan from 2019 for FCA-CRT Vlassenbroek Noord (left) and the implementation in the model (right).
(Map taken from: https://sigmaplan.be/nl/projecten/vlassenbroek/deelprojecten/noordelijk-deel%20/).

5 Results

5.1 Hydraulic Modelling

5.1.1 Reducing the flood risk

Ensuring the safety of the estuary and reducing the flood risk is an important goal of deploying the depoldered areas and FCA-CRTs in the Upper Sea Scheldt. By implementing the 8 project areas, it is expected to have more volume stored in those areas during the high water, thus, the maximum high water level in the tidal river can be reduced.

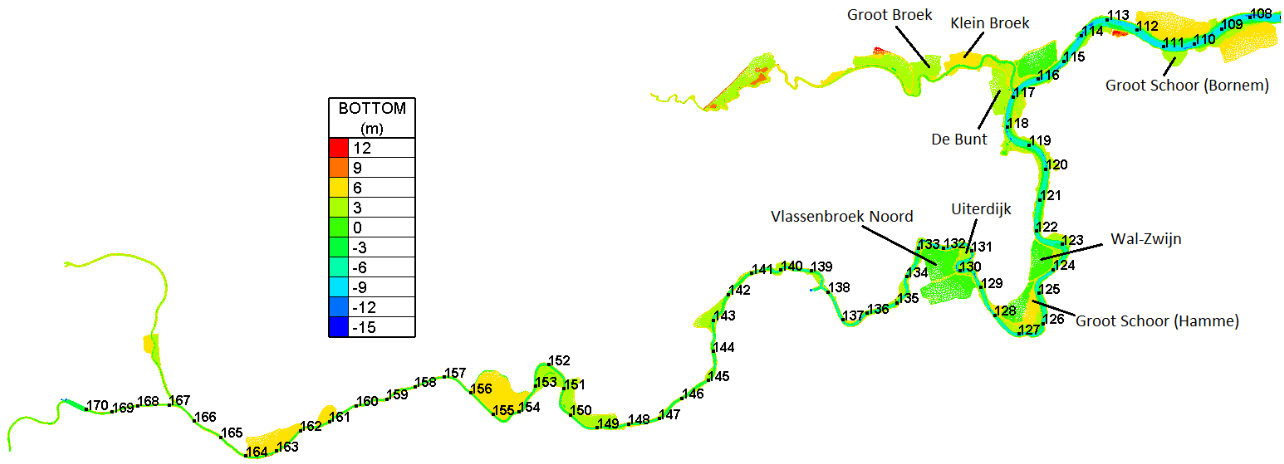

Figure 29 – The Upper Sea Scheldt with the indication of the distance (km) from Vlissingen

For evaluating the effect on reducing the flood risk, the maximum water levels along the Scheldt are compared between different model runs. The time series of water levels are extracted at the thalweg points along the main navigation channel (Figure 29). Then the maximum values at each point during the simulation period are taken to show the variation over the thalweg. By comparing the maximum water levels along the Scheldt between the model runs, the effects of the 8 project areas in terms of reducing the flood risk can be revealed.

Normal scenario

Under the normal situation, the 8 project areas already show a significant effect on the high water level in the Scheldt. By breaching the dikes and activating both the depoldered and FCA/FCA-CRT areas in the model, the high waters in the main channel are reduced in general. The effect extends further upstream and downstream, starting from 75 km to 170 km.

In the region from 118 km to 130 km, the largest effect is observed. The maximum reduction is about 10.6 cm at 124 km, where the FCA-CRT area Wal-Zwijn and depoldered area Groot Schoor (Hamme) are located. The maximum water level during slack tide in the transition from flood to ebb becomes slightly higher from 160 km to 167 km, with the maximum increase of 1.6 cm. This is due to the fact that the extra water volume stored in the project areas is released during ebb, given the same upstream discharge, the water level tends to rise slightly higher in the main channel in this region because of the extra volume. It becomes opposite during flood when the volume is stored in the project areas, hence the water level in the main channel becomes lower (Figure 31).

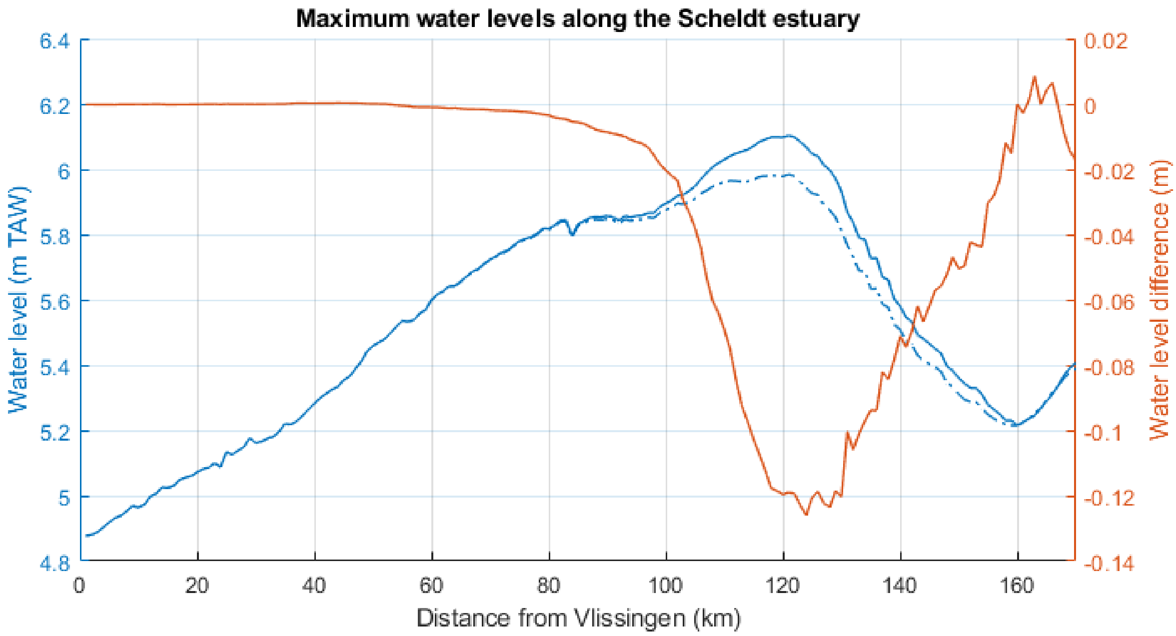

Figure 30 – Comparison of maximum water level along the Scheldt under the normal scenario
(solid lines represents the reference situation,
dot-dash lines represents the situation with the implementation of the 8 project areas)

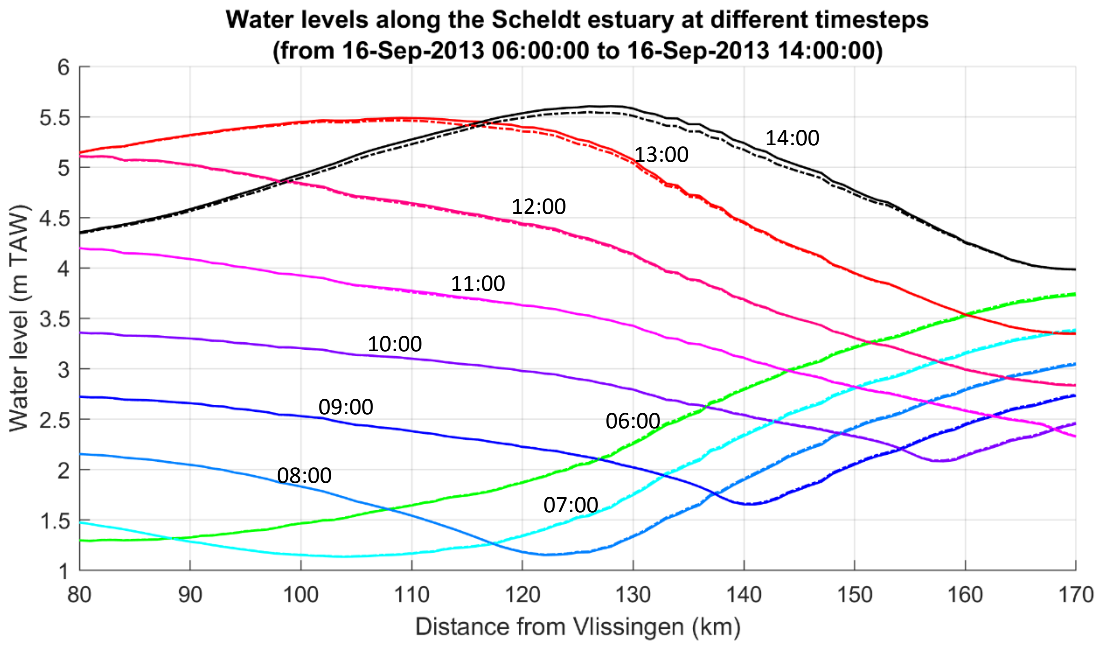

Figure 31 – Comparison of water levels in the Upper Sea Scheldt on 16-Sep-2013 under normal situation.
(solid lines represents 2013_Normal_0R, dot-dash lines represents 2013_Normal_8R)

Storm surge scenario

In the event of Sinterklaas storm, the water level can reach up to 7.42 mTAW in the Upper Sea Scheldt at 122 km from Vlissingen if the 8 project areas are not implemented as in the reference run. It is worth noting that the minimum value of high waters along the thalweg is about 6.2 mTAW. This is much higher than the normal scenario.

After activating the depoldered and FCA/FCA-CRT areas, the maximum water level in the Scheldt is significantly reduced. The maximum reduction is about 24.7 cm at 130 km. The effect is extended further, from 70 km to 170 km. There is slight increase of maximum water level from 165 km to 175 km. It can be seen that the maximum water level reaches the peak at 122 km before. But after implementing the measures, this peak is smoothed and lowered. It also can be seen that the water level is reduced during flood and increased during ebb. The largest increase and the largest reduction both happen in the same region (Figure 33).

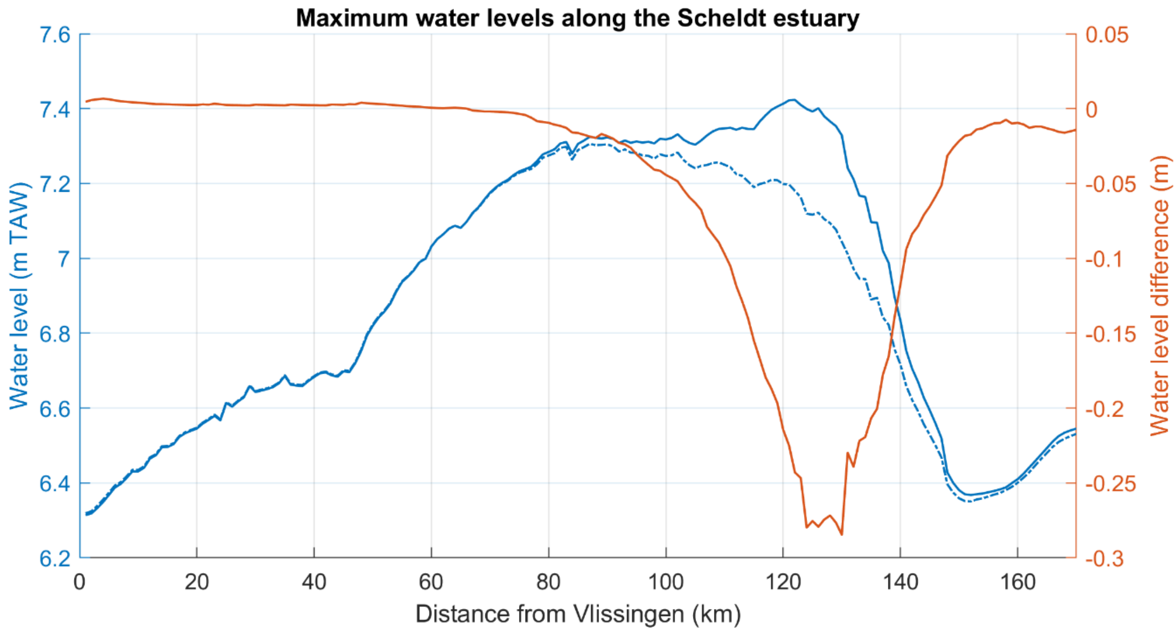

Figure 32 – Comparison of maximum water level along the Scheldt under the storm surge scenario

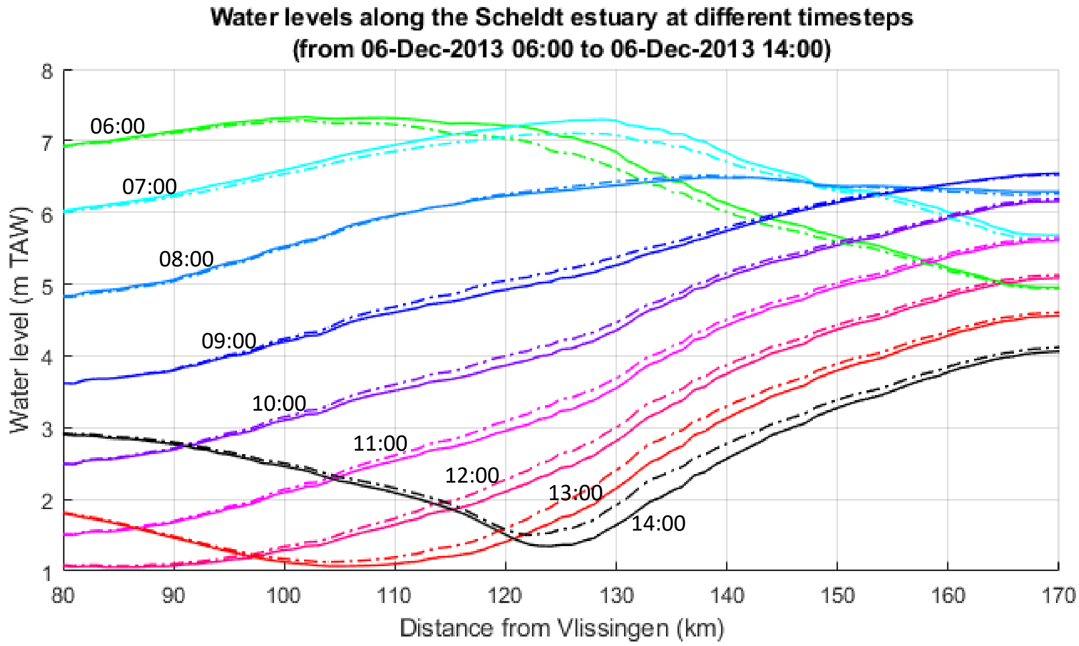

Figure 33 – Comparison of water levels in the Upper Sea Scheldt on 16-Sep-2013 under storm surge situation. (solid lines represents 2013_Sinterklaas_0R, dot-dash lines represents 2013_Sinterklaas_8R)

During the writing of the project proposal of LIFE SPARC, some exploratory runs were performed with a 1D hydrodynamic model. These runs also showed the effect of realising the 8 areas. The 1D model simulated several standard storm surge scenarios with different return periods.

Despite the differences between the 1D model and the 3D model used in this study, it is still useful to compare the results from both models in order to gain more confidence in the simulated effects. The 1D model result with T10 storm surge scenario is used for the comparison because the return period of the Sinterklaas storm is closest to this one.

It can be seen from Figure 34 that the maximum water level is also significantly reduced in the 1D model after implementing the measures. The maximum reduction is about 36 cm observed at 130 km, which is larger than the 3D model but the location of the maximum value is the same. Another major difference is that, in the 1D result, the region from 145 km to 165 km also shows significant reduction of maximum water level, which suggests there are additional measures implemented in the area, while in the 3D model there are only 8 project areas located between 110 km to 134 km. This explains the similarity of the effects predicted by both models from 70 km to 145 km, but not in the region from 145 km to 165 km. It is reasonable for the 3D model to have less reduction of the maximum water level with less incorporated measures. But at least the magnitude is similar, and the location of the maximum reduction is the same.

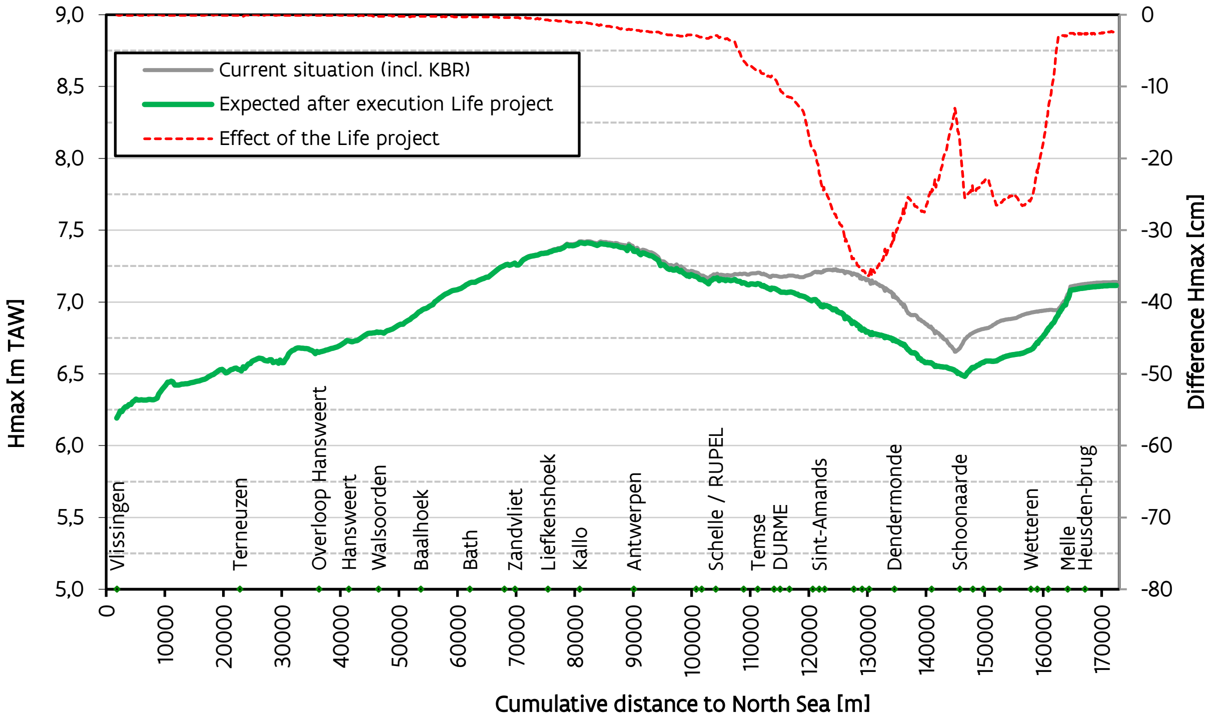

Figure 34 – Profile view of Expected Maximum High Water Levels along the Estuary during a T10 storm (Coen, 2019)

5.1.2 Effects on habitats

Normal scenario

In the normal scenario, the maps of maximum water depth, velocity and bed shear stress during the simulation period are computed and shown in Figure 35, Figure 36 and Figure 37. It can be seen that there is no water in the project areas in the run 2013_Normal_0R. After implementing the depoldered and FCA/FCA-CRT areas in the run 2013_normal_8R, water can flow in and out of these areas during flood and ebb, respectively.

All the 5 depoldered areas can be flooded in the run 2013_normal_8R. The highest water depth is observed in the Groot Schoor (Bornem) because the bathymetry in the area is the lowest. For the other 4 depoldered areas, the maximum water depth is around 1.0 to 1.6 m. The maximum water depth in the 3 FCA/FCA-CRT areas is relatively lower, less than 1.0 m in general. Because the in- and outflow rate is determined by the water level in the main channel, when it is not high enough as in the normal scenario, it is expected to have less water entering the FCA/FCA-CRT areas.

The maximum depth-averaged velocity in the 8 project areas is about 0.5 to 0.6 m/s, rarely exceeding 0.65 m/s. This is also consistent with the fact that the maximum bed shear stress is less than 2.0 Pa in most of the areas.

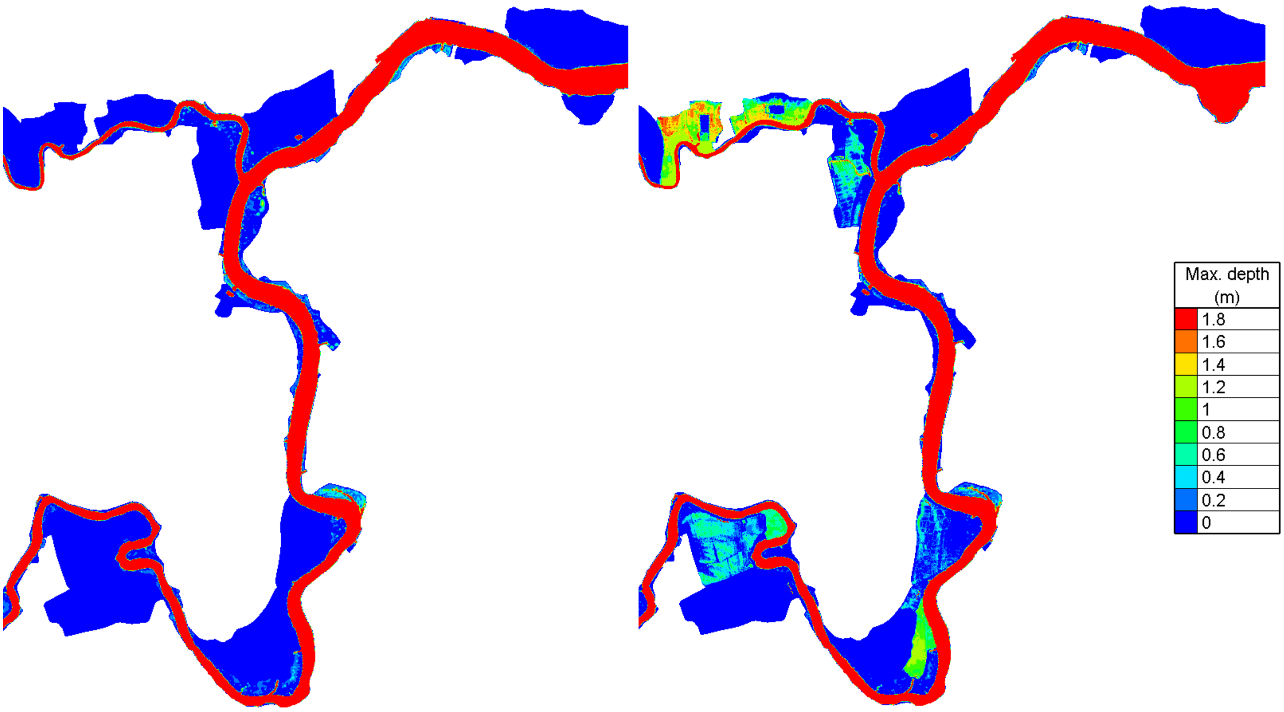

Figure 35 – Comparison of maximum water depth (left: 2013_Normal_0R, right: 2013_normal_8R)

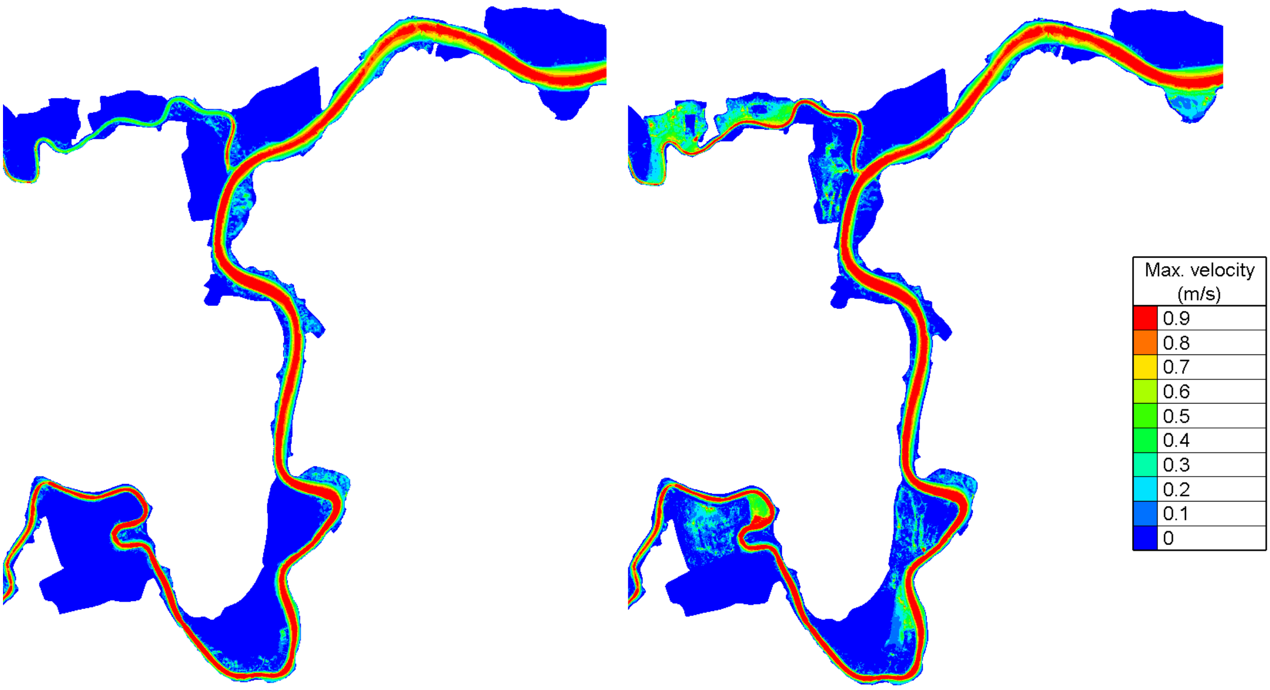

Figure 36 – Comparison of maximum velocity (left: 2013_Normal_0R, right: 2013_normal_8R)

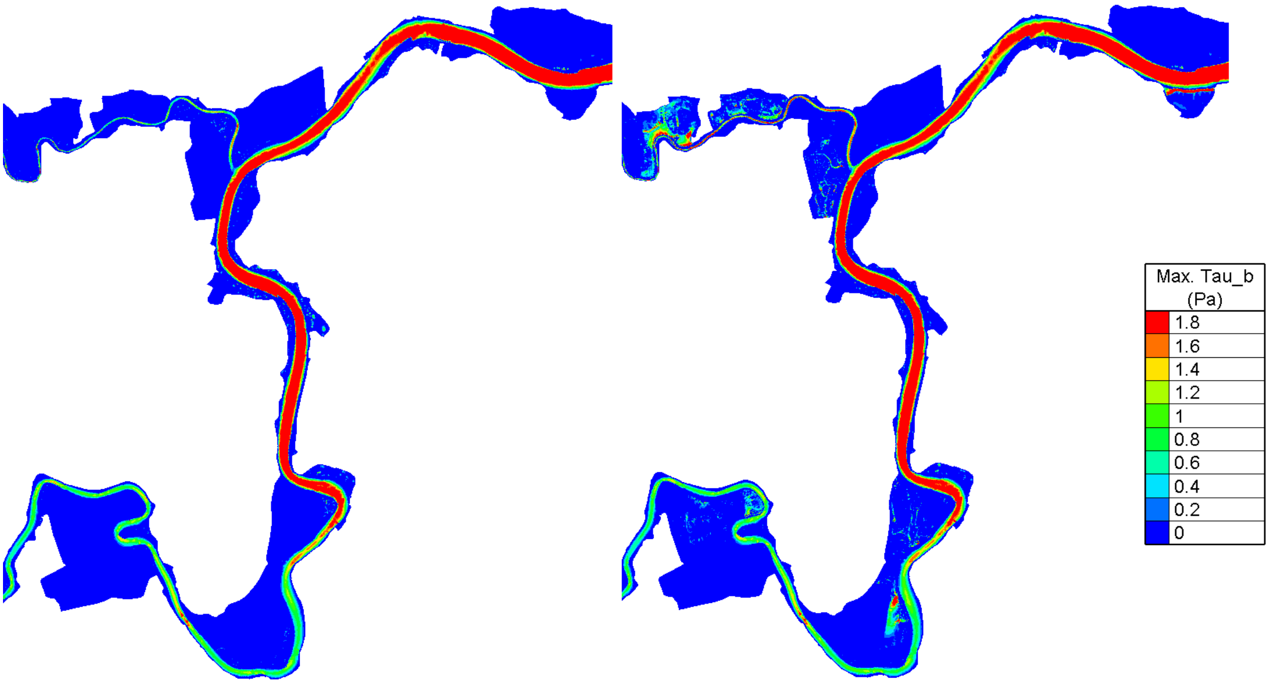

Figure 37 – Comparison of maximum bed shear stress (left: 2013_Normal_0R, right: 2013_normal_8R)

Beside of the maximum water depth, velocity and bed shear stress, the inundation frequency map, the frequency map of velocity exceeding 0.65 m/s and the frequency map of bed shear stress exceeding 1.0 Pa are computed. The formulas used to calculate these maps are given in §3.3.

Here we only show the results from the run 2013_normal_8R, since there is no water in the project areas in the run 2013_Normal_0R. The results are shown in Figure 38, Figure 39 and Figure 40.

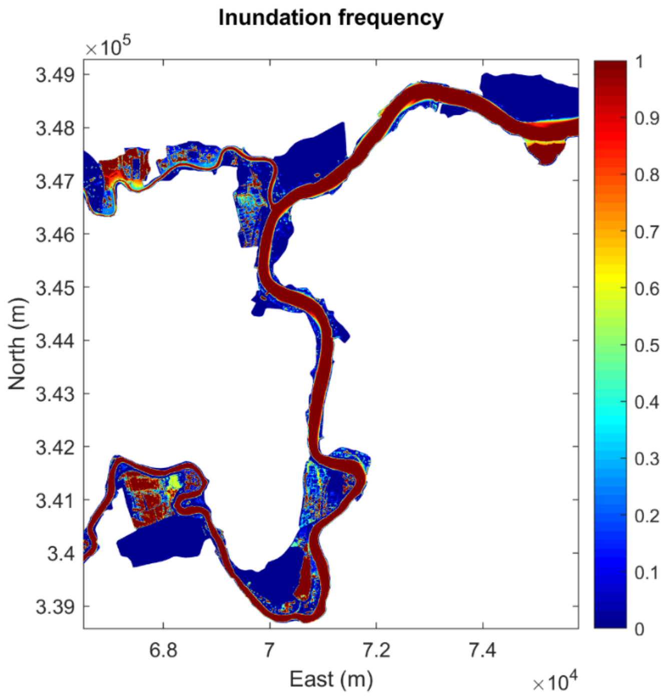

Figure 38 – Inundation frequency map (2013_normal_8R)

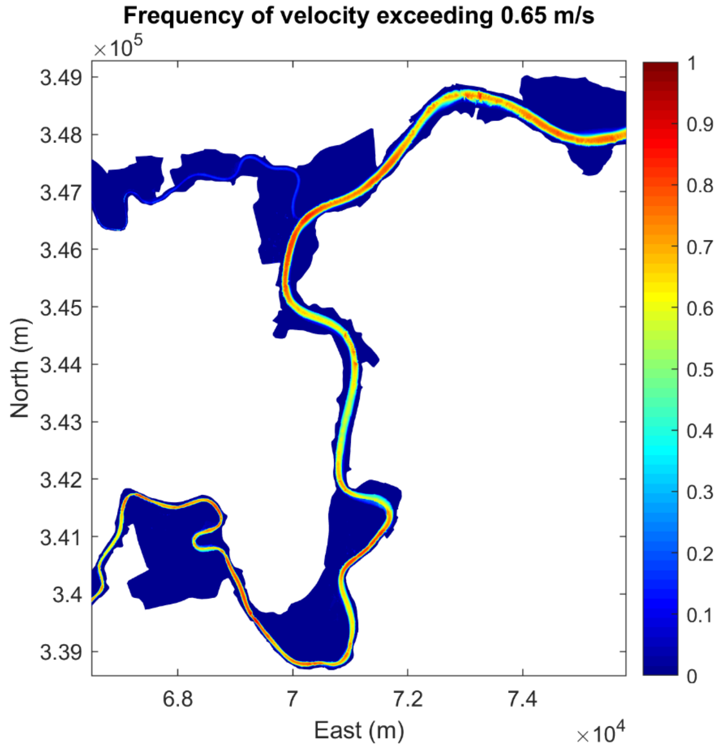

Figure 39 – Frequency map of velocity exceeding 0.65 m/s (2013_normal_8R)

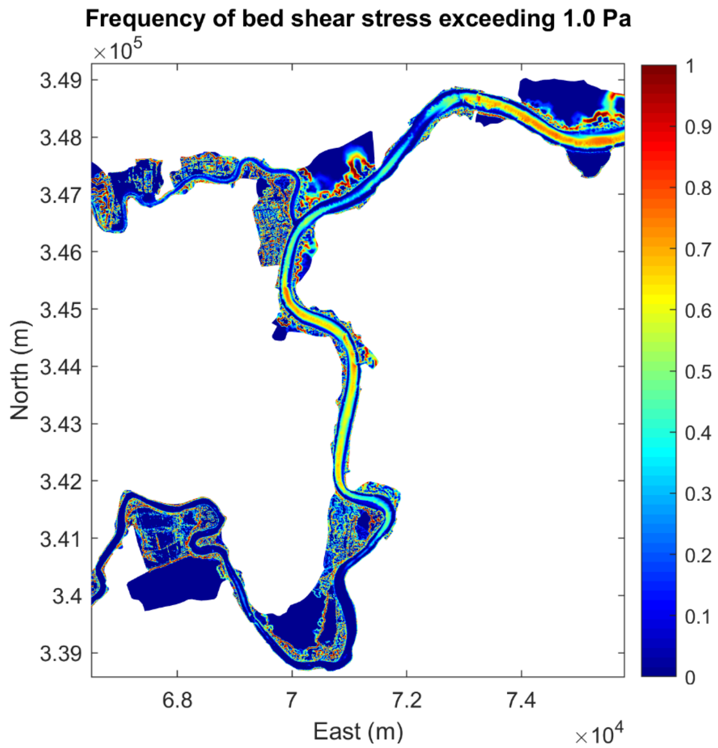

Figure 40 – Frequency map of bed shear stress exceeding 1.0 Pa (2013_normal_8R)

It is worth mentioning that due to the limitation of the model, it is difficult to have accurate bottom shear stress in the shallow areas, e.g. on the tidal flats with drying/wetting process.

5.2 Expected sedimentation in the project areas by 2050

As described in §3.4, an empirical method based on field observations is used in this study for estimating the long-term sedimentation in the 8 project areas after being in operation until the year 2050. The results are discussed in the following sections.

5.2.1 De-embankments

The estimated sedimentation rates in the five de-embankment areas are shown in Table 10. The empirical methodology presented in this study takes into account the change of water depth as the platform rises, as well as the sea level rise in the HW signals. It predicts non-linear growth of the platform, and the growth rate in general decreases over time. The figures of platform elevation over time can be seen in Appendix I. Estimated sedimentation in the de-embankments.

Table 10 – Overview of the average bed level (Z_0) of the de-embankment and the estimated bed level in 2050 (Z_{2050})

De-embankment	T0 [Yr]	Z_0 [cm TAW]	Z_{2050} [cm TAW]	ΔZ [cm]	Sedimentation rate [cm/Yr]
Groot Schoor Bornem	2025	298.0	434.7	136.7	5.5
Groot Schoor Hamme	2021	500.0	565.8	65.8	2.3
Uiterdijk	2022	509.0	553.7	44.7	1.6
Groot Broek	2025	484.0	519.6	35.6	1.4
Klein Broek	2025	511.0	561.5	50.5	2.0

The results show that the largest increase of platform elevation (136.7 cm until 2050) is expected in Groot Schoor Bornem. This is mainly because the initial elevation is much lower than MHW Neap at this location (Figure 45), hence more sediment can deposit each tidal cycle. In the upstream of the Scheldt, Groot Schoor Hamme and Uiterdijk have less sedimentation because their initial elevations are higher. The elevation of Groot Schoor Hamme initially is lower than the MHW Neap, as the platform increases, it becomes higher that the MHW Neap at the year 2030, meaning that area will favour the growth of vegetation since then. This will change the growth type of the platform from the non-vegetated growth to vegetated growth afterwards (Figure 46). Uiterdijk is initially higher than the MHW Neap, therefore it is vegetated growth from the start of operation (Figure 47). Groot Schoor Hamme and Uiterdijk increase by 65.8 cm and 44.7 cm respectively until 2050.

In the Durme branch, Klein Broek is similar to Uiterdijk in terms of both growth type and growth rate (Figure 48), while the Groot Broek is always below the MHW Neap until 2050 (Figure 49). The increases of the platform are 50.5 cm and 35.6 cm for the Klein Broek and Groot Broek respectively.

The sedimentation in the five areas is also summarized in Figure 41 and Figure 42. The latter shows converts the changes of platform elevations into Tons of Dry Matter (TDM) by taking into account the area of the de-embankments.

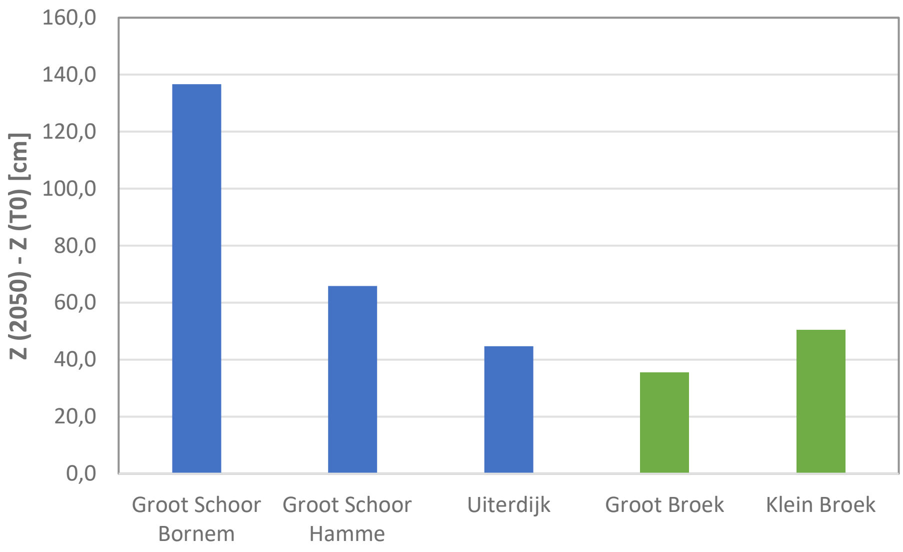

Figure 41 – Change in elevation of the de-embanked sites.
De-embankments along the Scheldt are given in blue, along the Durme are given in green.

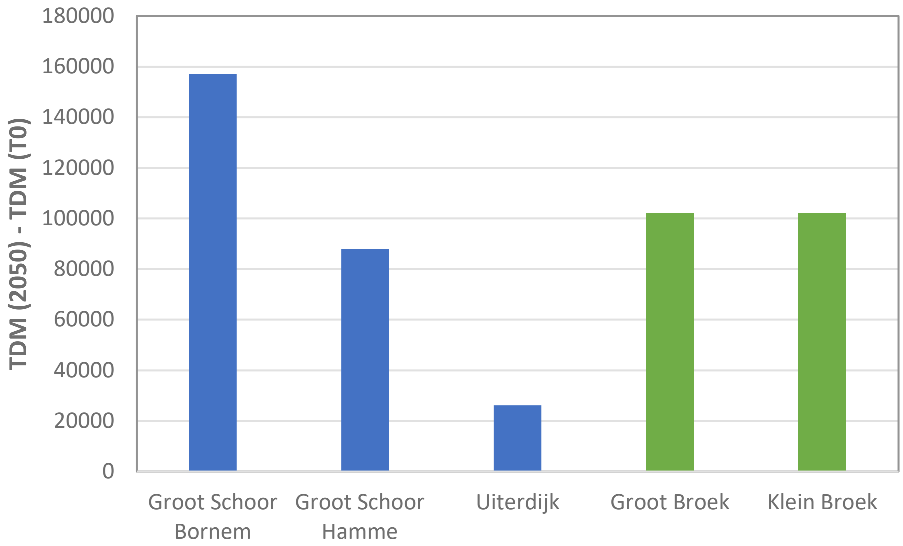

Figure 42 – Tons of dry matter (TDM) deposited on the de-embankment between the time of operation (T0) and 2050.
TDM of De-embankments along the Scheldt are given in blue, along the Durme in green.

5.2.2 FCA-CRTs

The sedimentation in the FCA-CRTs is estimated according to the methodology described in §3.4.3. Because the water entering the FCA-CRT is in principal regulated, the influence of sea level rise is not considered here. In fact, a constant growth rate of the platform is assumed in all the areas.

Table 11 – Overview of the average bed level (Z_0) of the CRT areas and the modelled bed level in 2050 (Z_{2050})

FCA-CRT	T0 [Yr]	Z_0 [cm TAW]	TDM [Ton]	Z_{2050} [cm TAW]	ΔZ [cm]
Zwijn	2025	239.0	163057	285.5	46.5
Wal	2025	290.0	108141	325.6	35.6
Vlassenbroek	2025	258.0	137156	287.1	29.1
De Bunt	2025	306.0	103203	336.8	30.8

Table 11 shows the estimated sedimentation in the FCA-CRTs by 2050. Figure 43 shows the comparison of the platform elevation changes by 2050. The results show that the sedimentation rates in the FCA-CRTs are generally lower compared to those in the de-embankment areas. The main reason is that the overflow in the FCA-CRTs is regulated by the culverts. The largest increase of the platform elevation is 46.5 cm found in Zwijn by 2050, while the smallest increase is 29.1 cm in Vlassenbroek. The deposited sediment mass is computed based on the platform increase and the area of the project site. The TDM is estimated in each project area can be seen in Figure 43.

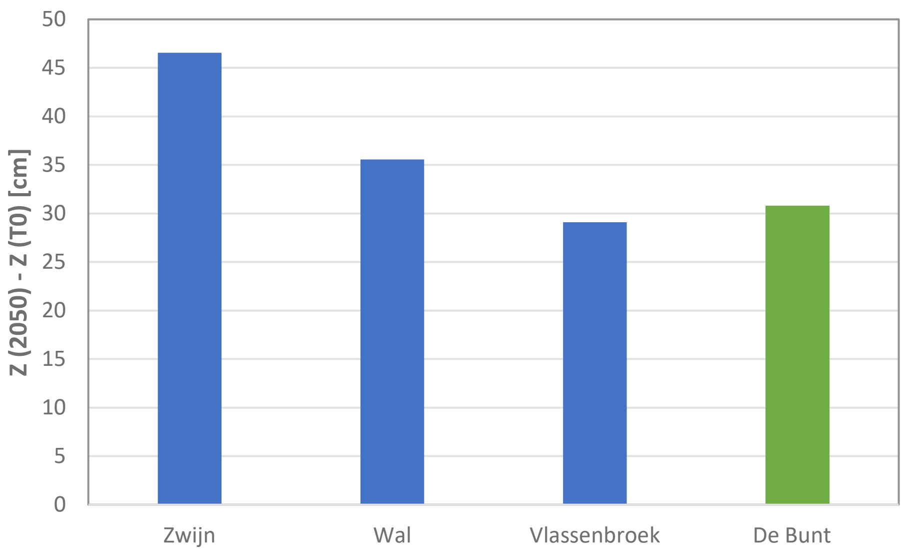

Figure 43 – Change in bed level of the FCA-CRT area between the time the CRT became active and 2050.
The results for FCA-CRT areas along the Scheldt are given in blue, along the Durme in green.

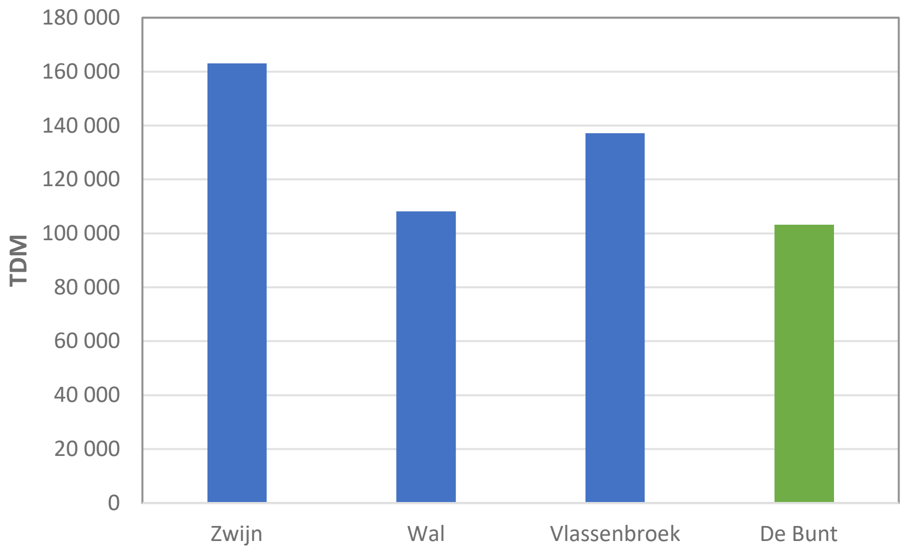

Figure 44 – Tons of dry matter (TDM) deposited in the FCA-CRT areas between the time of operation and 2050.
TDM of FCA-CRT areas along the Scheldt are given in blue, along the Durme in green.

6 Conclusions

In this study, a detailed model for the Scheldt estuary 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. The following conclusions can be drown.

- In the normal scenario, the implementation of the eight project areas already shows a moderate reduction on the high water level. The maximum reduction is about 10.6 cm at 124 km, where the FCA-CRT area Wal-Zwijn and depoldered area Groot Schoor (Hamme) are located.
- In the storm surge scenario, 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 about 24.7 cm at 130 km.
- 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.

Estimation of long-term sedimentation in the project areas is another important goal in this study. This can give an idea about the sustainability of these engineering measures and how often a maintenance would be required. For achieving this task, an empirical sedimentation model is set up, that takes its input from the hydrodynamic model. The sedimentation model estimates the sedimentation rate from the (estimated) year of starting operation until 2050. The main results are:

- Among the five de-embankments, Groot Schoor (Bornem) has the largest siltation rate of 5.5 cm/yr. This is mainly due to its low initial elevation, which results in large sedimentation rates. The rest of the de-embankments has moderate sedimentation rates ranging from 1.4 cm/yr to 2.3 cm/yr.
- For the de-embankments, the sea level rise is considered and the estimated sedimentation rate changes temporally. It is faster at the beginning and slightly decreases over time. This is because the increase of the platform elevation will reduce the overflow in these areas, hence less sediment mass will be transported there. This feedback is taken into account in the empirical model.
- In the FCA-CRT areas, the sedimentation rates are in general smaller. The largest rise of the platform is found in Zwijn (46.5 cm) while the smallest increase in Vlassenbroek (29.1 cm). Due to the fact that the overflow in the FCA-CRTs is normally regulated by the culvert structures, the methodology assumes constant sedimentation rate, and the influence of sea level rise is thus not considered.

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Appendix I. Estimated sedimentation in the de-embankments

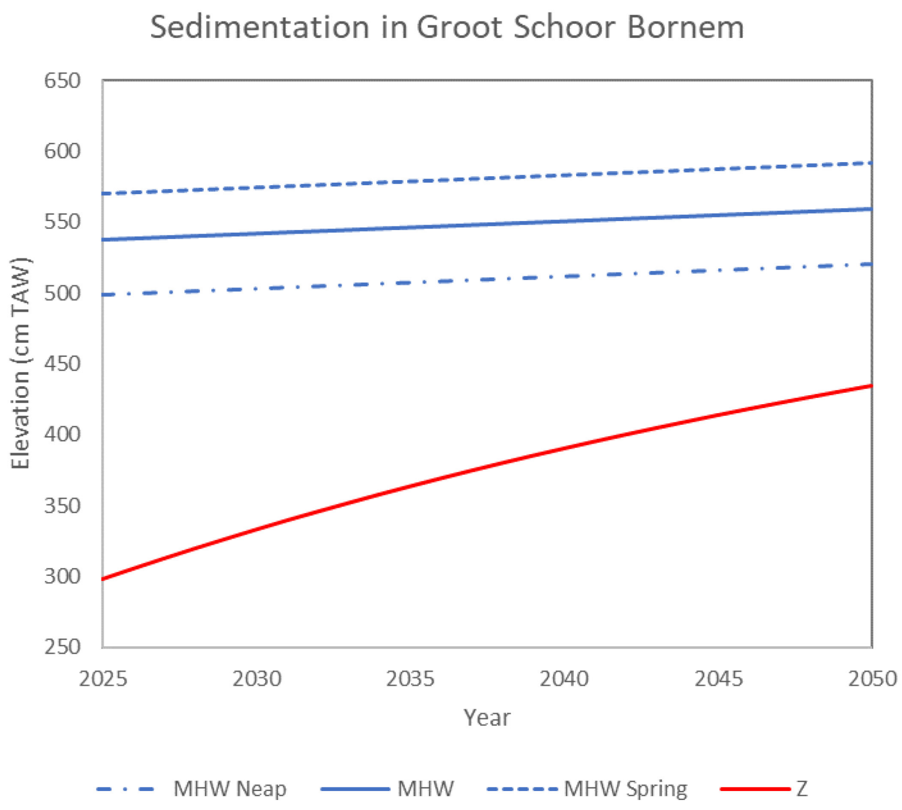

Figure 45 – Estimated sedimentation in Groot Schoor Bornem from T0 to 2050

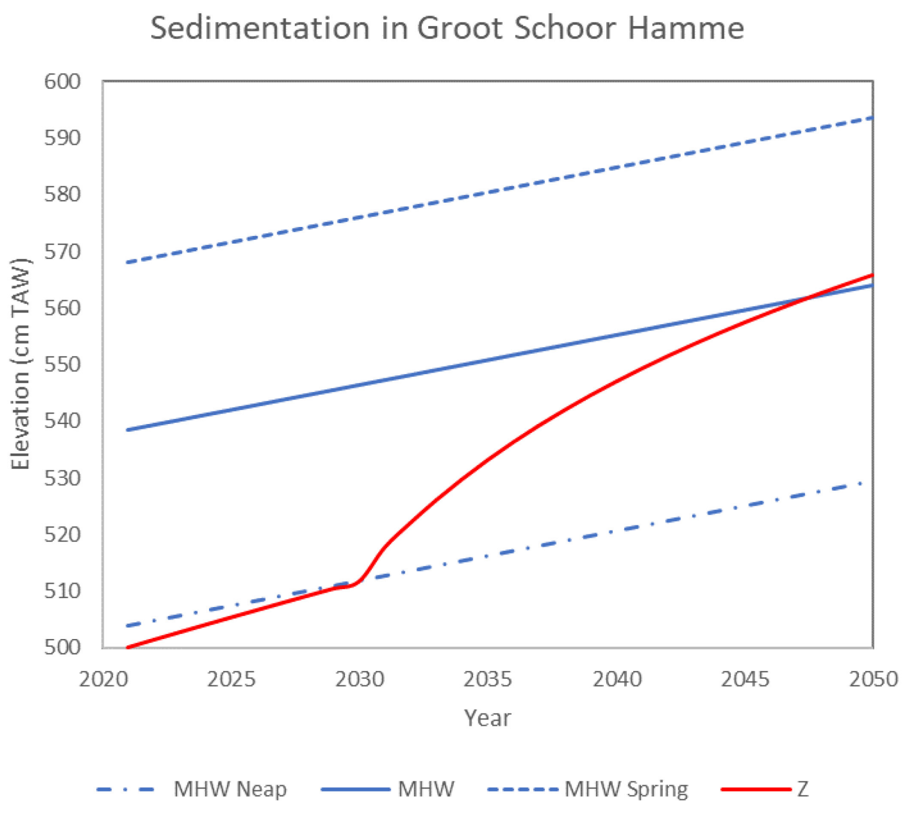

Figure 46 – Estimated sedimentation in Groot Schoor Hamme from T0 to 2050

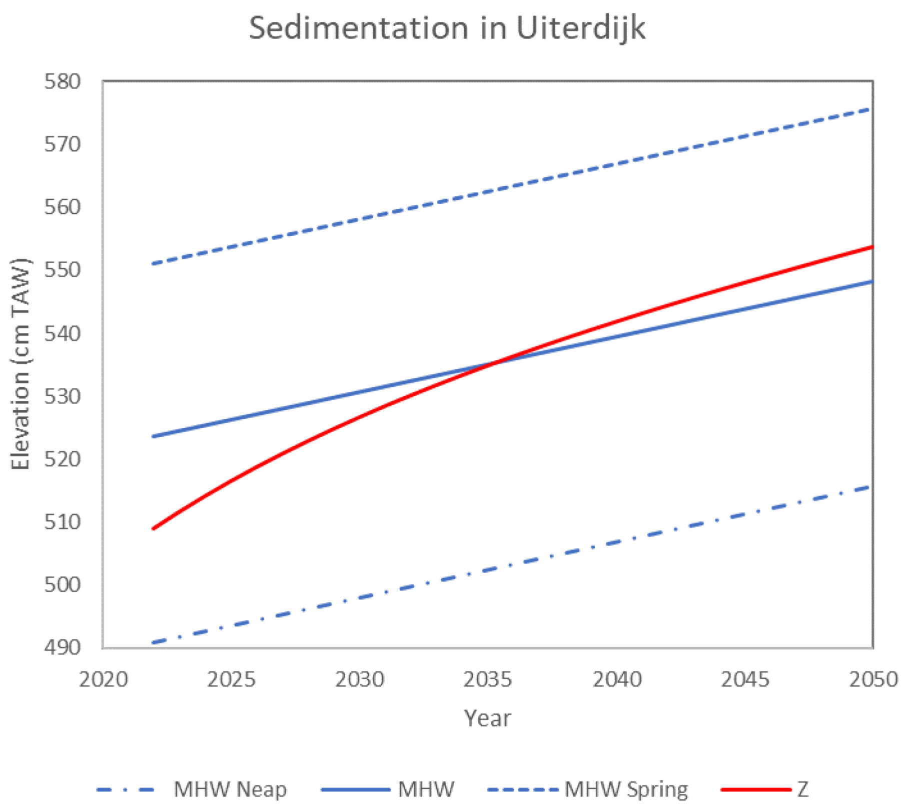

Figure 47 – Estimated sedimentation in Uiterdijk from T0 to 2050

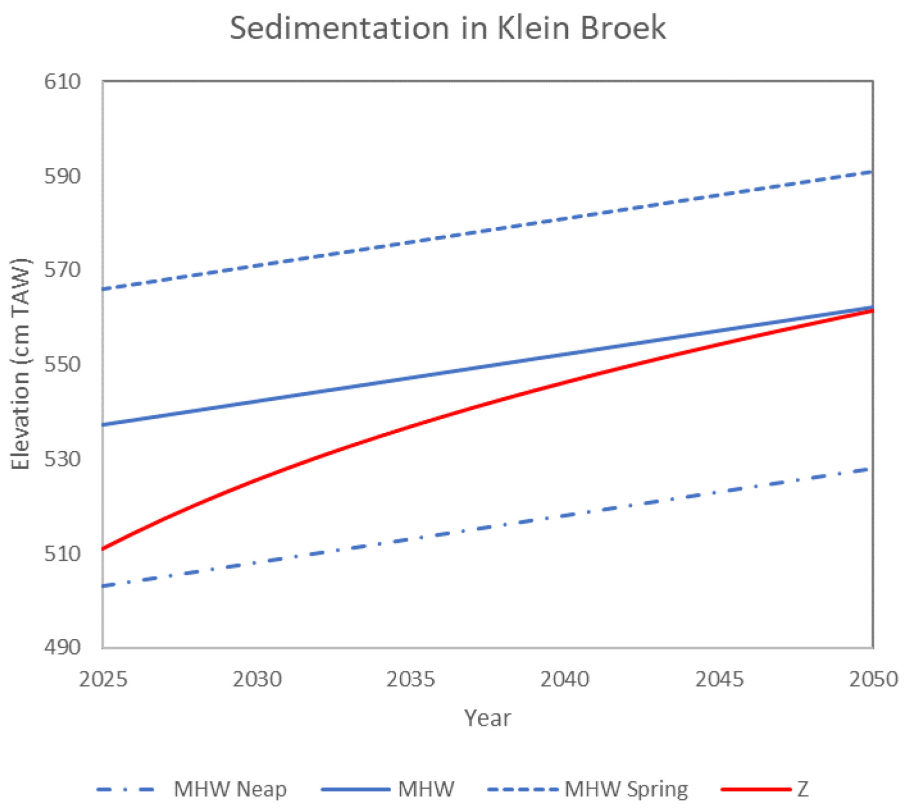

Figure 48 – Estimated sedimentation in Klein Broek from T0 to 2050

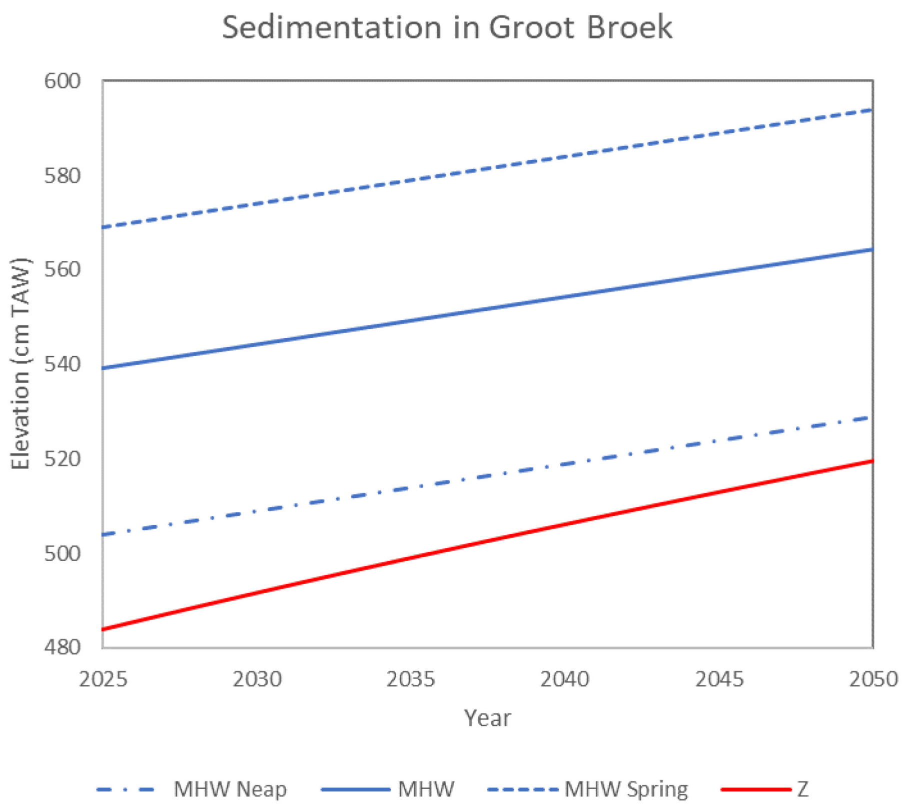

Figure 49 – Estimated sedimentation in Groot Broek from T0 to 2050

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