CENTRE OF EXPERTISE
DELTA TECHNOLOGY

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PERKPOLDER
TIDAL RESTORATION

ONE YEAR AFTER REALISATION
DRAFT PROGRESS REPORT

CENTRE OF EXPERTISE DELTA TECHNOLOGY
NOVEMBER 2016

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TIDAL RESTORATION

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DATE	LOCATION	VERSION AND STATUS
November 27, 2016	Vlissingen, Utrecht, Yerseke	V2, draft

Photo on cover: Edwin Paree, HZ University of Applied Sciences/Rijkswaterstaat CIV

DELTA ACADEMY
WAGENINGEN UNIVERSITY & RESEARCH
Deltares Enabling Delta Life
NIOZ Royal Netherlands Institute for Sea Research
Rijkswaterstaat Ministerie van Infrastructuur en Milieu

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1 INTRODUCTION

1.1 PLAN PERKPOLDER

Starting from 2003 the ferry between Kruiningen (Zuid-Beveland) and Perkpolder (Zeeuws-Vlaanderen) became out of service, which was caused by the opening of the Western Scheldt tunnel. This fact was a starting point for the development of *Plan Perkpolder* to prompt the social-economic development of the area. This plan combines the development of real estate, recreational facilities and nature restoration. The regional development plan utilized the concepts developed within the EU project titled *ComCoast* (Interreg IIIb North Sea; Hamer, 2007). The site of Perkpolder was one of the ten pilot locations along the North Sea, and aimed to develop a safe and sustainable coastal zone attractive for living, doing business and recreational activities. The plan includes the following climate adaptation concepts developed within the C*omCoast* project: (1) an elevated former ferry platform, high enough to provide safety for the next 200 years with a rising sea level; (2) the newly developed salt march that acts as a natural buffer to lower the wave load on the dyke. Figure 1.1 offers an impression of the plan at Perkpolder. The former ferry terminal platform is elevated and transformed into a small village (No. 1). A salt-water tidal area will develop on the southeast side (No. 2). On the west side of the village an area designated for a golf course and housing is planned (No. 3), and the former ferry port will be transformed into a marina (No. 4).

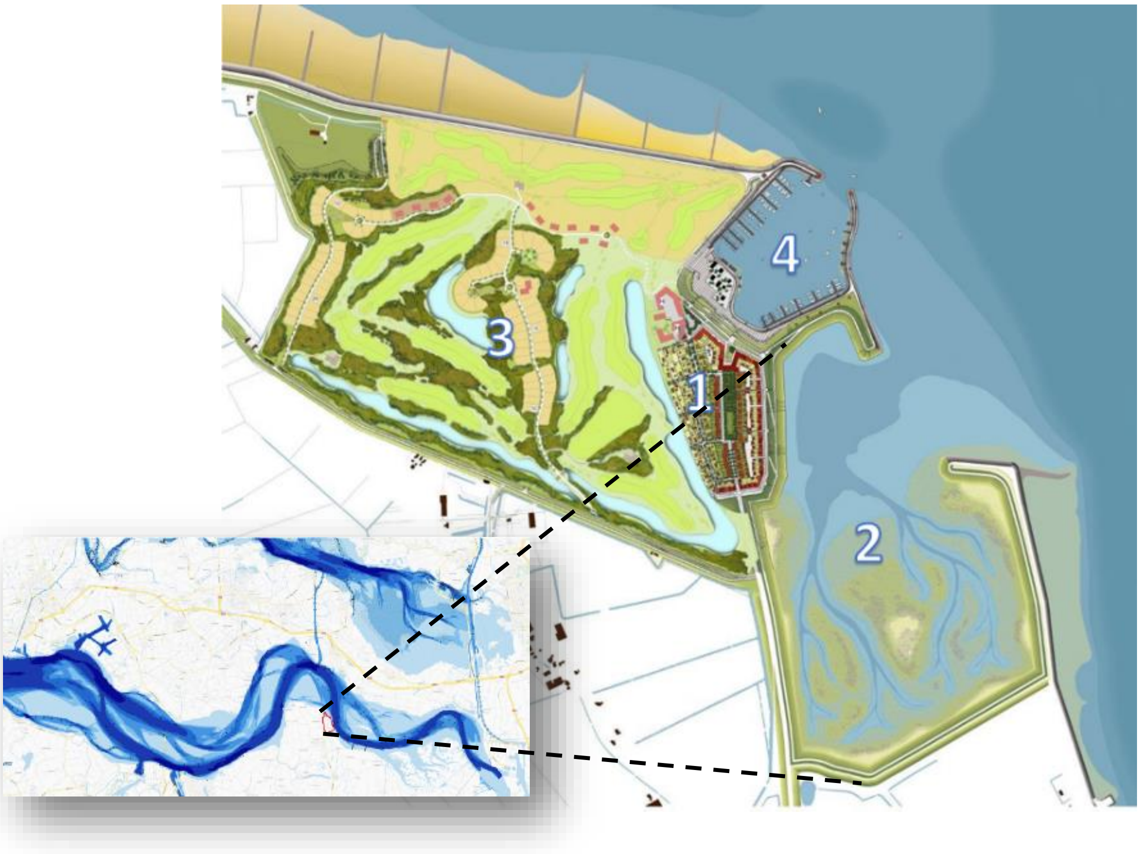

Figure 1.1. Plan Perkpolder, village on former ferry platform (No.1), natural tidal area (No.2), recreational housing with gulf course (No.3), and marina (No.4), (source: Bureau Lubbers)

1.2 ADMINISTRATIVE BACKGROUND

On January 17, 1995 the Netherlands and Flemish Region signed a treaty concerning the second extension of the waterway to the Port of Antwerp. Part of this treaty was the compensation of nature in the Western Scheldt region for the period of 1998-2008. The compensation of nature was adopted in the program titled "Natuurcompensatie Westerschelde (NCW)". In total six project locations in the Western Scheldt (category A) and a large number of projects behind the sea defense (categories B and C) became a part of this nature compensation program (NCW-eindrapportage, 2008). Perkpolder is one of the category A projects, and the executing agency of the Ministry of Infrastructure and the Environment (further mentioned as: “Rijkswaterstaat”) is responsible for the realization and monitoring of this project.

In the original agreement between the national and local governments in the Netherlands, concerning the execution of the NCW program, only the ferry port in Perkpolder was a part of the environmental compensation (total area is 10 hectares). To increase the impact on natural development the ferry terminal and the polder at the southeast site were also included in the program, which resulted in a total of 40 hectares (NCW-eindrapportage, 2008). In beginning of 2000 the local municipality of Hulst took the initiative to start an initiative for social-economic development of the region around Perkpolder. In 2004 a memorandum of understanding was signed, which became a start of *Plan Perkpolder*. In this plan the size of the natural area was increased to 75 hectares, and the port area was planned to be transformed into a marina (Figure 1.1). Out of these 75 hectares, 40 hectares are a part of the NCW-program, and 35 hectares are a part of the so-called “Natuurpakket Westerschelde (NWP)” (Verbeek, 2005). This environmental compensation package is a part of the development outline signed by the Dutch and Flemish governments, which focuses on an integrative approach to safety, accessibility to the Port of Antwerp, and natural development (Verbeek, 2005). In this outline 600 hectares of estuarine nature are to be added to the Western Scheldt by 2010.

1.3 MONITORING AND RESEARCH

Since June 25th 2015 the Perkpolder tidal basin is flooded twice a day by sea water from the Western Scheldt. The inflow of water has a direct impact on the erosion and sedimentation processes, which gives rise to morphological changes. With the inflow of water benthic macro fauna will start colonizing the area and provide the food for birds. At some point in time the vegetation will have to change in order to settle and increase the stability of the deposited sediment.

This three-year project (from 2016 to 2019) is executed by the Centre of Expertise Delta Technology called CoE-DT further on, has in this project the following partners: Rijkswaterstaat Sea and Delta, Deltares, Wageningen Marine Research, NIOZ Royal Netherlands Institute for Sea Research, and HZ University of Applied Sciences. The research focuses on the morphological and ecological developments, and the groundwater changes in the Perkpolder tidal basin. In addition to developments inside the tidal basin, the effects of saline groundwater on the surrounding agricultural areas are investigated. To reduce the impact of saline water a unique seepage discharge system is constructed around the Perkpolder tidal basin, at the landward side of the dyke. Deltares is investigating these effects and the functionality of the seepage discharge system. The research is part of the this project although it began earlier, in 2012. The monitoring and research plan is described in De Louw (2014), the monitoring and research in the Perkpolder tidal basin is described in Boersema, et al. (2015).

Figure 1.2. Perkpolder tidal basin, September 6, 2016 (Photo: Edwin Paree, RWS/HZ)

1.4 PROBLEM STATEMENT

Rijkswaterstaat has the responsibility to realize a new tidal environment at Perkpolder (NCW-eindrapportage, 2008). The goal is to create 75 hectares of low-dynamic tidal nature due to the fact that the habitat is disappearing in the Western Scheldt over the last century as caused by human interference in the Scheldt estuary. In addition, this project provides a unique opportunity to monitor and study the biotic and abiotic changes in an area, which transforms from a freshwater agricultural area to a tidal salt-water natural area. Not much is known concerning this transition, thus knowledge is very valuable in respect to future tidal restoration projects.

1.5 GOALS

Rijkswaterstaat is responsible for the realization of tidal nature in Perkpolder. The goal of current research is to determine whether the tidal environment is contributing to the Natura 2000 conservation goals for the Western Scheldt and Saeftinghe (Ontwerpbeheerplan, 2015). Added to that the newly created natural area serves as a compensation measure for the second extension of the waterway to the Port of Antwerp (NCW-eindrapportage, 2008). Rijkswaterstaat is tasked to demonstrate that the area is contributing to the development of a low-dynamic tidal nature.

The development of knowledge and the education of new delta professionals are two important goals of the CoE-DT. This project offers the opportunity to study the real development of a managed realignment site, in which an agricultural area is transformed in a salt-water natural area. This study will contribute to the ongoing research programs on the Hertogin Hedwigepolder. Students involved in this project will expand their knowledge about the modern developments in coastal management and have an opportunity to conduct field work on measuring and observing the changes that are taking place.

The goals of this project are divided into the necessary and desired outcomes as required by Rijkswaterstaat. The necessary project goals for Rijkswaterstaat are indicated by the numbers 1 to 3, while the desired ones with the numbers 4 to 6[1]. For the CoE-DT it is the opposite, the objectives 4 to 6 are focusing on the mission of the Centre of Expertise. In this regard objectives of Rijkswaterstaat and CoE-DT complement each other.

In summary the goals of this project are:

WATER MANAGEMENT (LONG TERM) AND SAFETY MANAGEMENT

1. Determine which biotopes will develop in the Perkpolder tidal basin, and to which extent these biotopes will contribute to the agreed environment-related goals for the Scheldt estuary, as well as the conservation goals for Natura 2000 (“instandhoudingsdoelstellingen Natura 2000”)
2. Knowledge development in relation to water safety management (“waterveiligheidsbeheer”), such as the development of the inlet and stability of the foreshore.
3. Knowledge development concerning the effectivity of the seepage discharge installation in order to protect the fresh-water resources for agricultural usage.

KNOWLEGDE DEVELOPMENT (SHORT TERM)

4. The development of knowledge about the biotic and abiotic factors and their relations in the first years of transition from a fresh-water agricultural area to a salt-water tidal area. This knowledge will help to shape the design of future tidal restoration projects;

EDUCATION ENHANCEMENT

5. Training of young professionals by improving the knowledge of teachers to be supported by state-of-the-art case studies;

NETWORK IMPROVEMENT AND KNOWLEDGE DISSEMINATION

6. Promoting the circulation of knowledge within the field by combining all the knowledge within the site of *DeltaExpertise site*.

1.6 RESEARCH QUESTIONS

1.6.1 MORPHOLOGY AND HYDRODYNAMICS

1. How does the Perkpolder tidal basin compare with the other tidal basins in the vicinity?
2. What are the large-scale height changes in the Perkpolder basin, before and after the opening of the inlet?
3. Wat is the sedimentation rate at the Perkpolder basin?
4. What are the morphological changes in man-made tidal creeks?
5. How does the inlet develop over time?
6. What are the processes behind the morphological development?

1.6.2 GROUNDWATER

7. What is the effect of the new tidal area on the groundwater system in the adjacent agricultural area? Also, is the implemented mitigation measure called SeepCat compensating the effects properly?
8. What is the tidal propagation in the aquifer below the tidal area?
9. What is the effect of the tides on the salinity of soil and groundwater in the tidal area?

1.6.3 VEGETATION AND SOIL

[1] From the standpoint of Rijkswaterstaat, the knowledge development is not the main objective, but at the same time in many policy documents this ‘knowledge development’ is stressed as being very important, for example: “Deltaprogramma 2016” and “Kennis- en Innovatie Agenda Deltatechnologie 2016-2019”.

10. How do abiotic and biotic sediment properties affect seedling survival and lateral expansion?
11. How do these abiotic and biotic sediment properties (that affect vegetation establishment) change in time and space at Perkpolder?
12. What is the role of seed availability and seed dispersal for the vegetation development?
13. What is the pattern of colonization and lateral expansion by pioneer species, along the elevational gradient?

1.6.4 BENTHIC MACROFAUNA AND BIRDS

14. How does the colonization process of benthic macrofauna develop in the de-poldered area?
15. Are the benthic communities in the Perkpolder tidal basin similar to benthic communities in similar ecotopes in the Western Scheldt?
16. How will vegetation establishment affect the benthic macrofauna and vice versa (interactions)?
17. How does the development of Perkpolder tidal basin compare to the development of Rammegors in the Eastern Scheldt? What can be learned about the design of de-polders areas?
18. How is the Perkpolder tidal basin used by birds?

1.7 ACCOUNTABILITY

Chapter 1 is written by HZ (Matthijs Boersema). Chapter 2 is written by Deltares (Jebbe van der Werf) and HZ (Matthijs Boersema), and the work of Deltares focuses on the modelling, and the work by HZ focuses on the field measurements. Chapter 3 is written by Deltares (Perry de Louw). Chapter 4 is the work of NIOZ (Tjeerd Bouma) and Chapter 5 is written by Wageningen Marine Research (Tom Ysebaert).

Not unimportant for this study is the contribution of the students Xinyue Zhao (MSc thesis), Mireille Martens (BSc thesis), Marjolein van Vliet (3rd year minor), and Jens Schouwenaars (BSc thesis).

This report is a progress report, to be updated every year thus replaced by the newer version. The final version will be made available for a wider audience. This progress reports are for the internal usage of the institutions involved.

2 MORPHOLOGY AND WATER MOVEMENT

2.1 INTRODUCTION

In this chapter we will discuss the morphological changes following the opening of the Perkpolder tidal basin that took place on June 25, 2015. These changes are focusing on three areas: the tidal flat on the seaward side of the inlet (part 1 of Figure 2.15), the pond directly behind the inlet (part 2) and the tidal flat with creeks (part 3). Secondly, the changes in the cross-section of the inlet are analysed. To obtain a better understanding of the large-scale changes in height, the hypsometric curves of the Perkpolder tidal basin are made before, during, and ten months after the opening of the inlet. Finally, the Perkpolder tidal basins at the time of the opening are compared with other basins in the vicinity.

Besides the morphology, the flow velocities in the inlet are studied and utilized to calibrate a Delft 3D model. The model results offer a better understanding of the processes that drive the morphological development in Perkpolder. Subsequently, the model is used to study the effect of the inlet width, the creeks and the pond.

In this study the channels are defined below MLW (mean low water), the sand and mud flats or tidal flats are located between MLW and MHW (mean high water). The salt marshes are defined above MHW (Figure 2.1). The word 'creek' is not only used for tidal streams in the salt marsh, but also in the tidal flat.

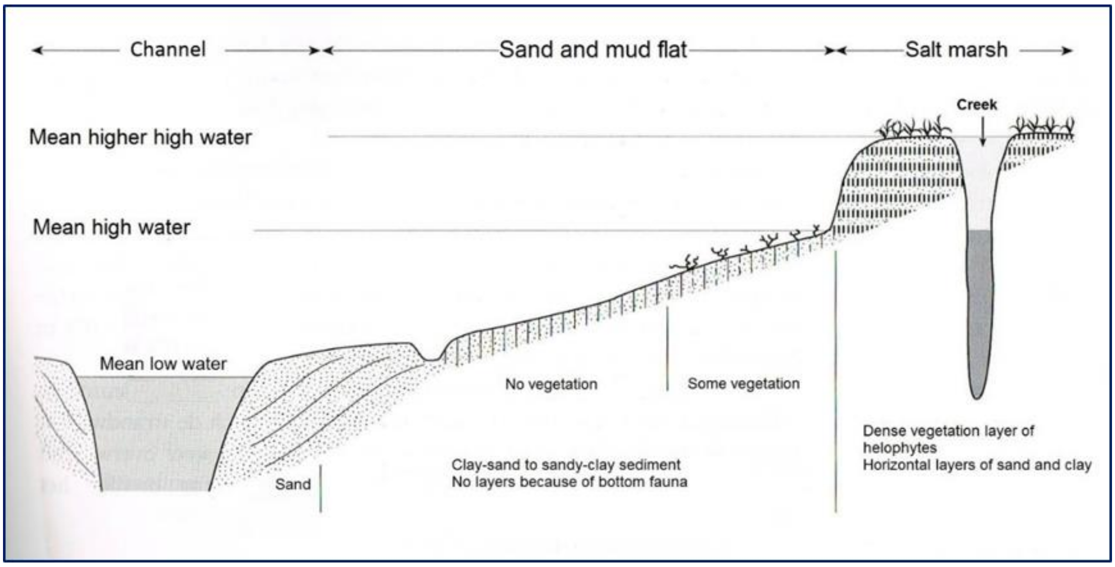

Figure 2.1 Composition of an intertidal area (Zagwijn, 1986)

2.2 DATA AND METHODS

2.2.1 HEIGHT MEASUREMENTS IN SUBTIDAL AND INTER TIDAL AREAS

The first dataset used is a LiDAR measurement of the Perkpolder area during the period when the area was still used for the agricultural purposes (20-12-2013). The second dataset is a composite of multi-beam and DGPS measurements collected in May of 2015 by the contractor, combined with LiDAR data (May of 2015) from the area outside of the Perkpolder basin. It is assumed that this dataset represents the moment at the opening (T0), although it is apparent from the data that this is not the case for the area next to the dike (see Figure 2.11). This T0 data covered the outer area, inlet and complete intertidal area (see Figure 2.6). The multi-beam measurements hereafter cover the same area, but without the area to the south of approximately y = 379 km RD. Table 2.1 presents an overview of the available bathymetry data.

The multi-beam and LiDAR data are used to study the large-scale morphological changes, the changes in the tidal inlet and are utilized as a base layer for the Delft 3D modelling.

Table 2.1 Overview of morphological measurements in Perkpolder intertidal area and surroundings.

Code	Date	Coverage	Instrument	Resolution
T-1	20-12-2013	Complete area of interest	LiDAR	2 m x 2 m
T0	25-06-2015	Complete area of interest	Multi-beam + DGPS and LiDAR	2 m x 2 m
T1	30-07-2015	Without shallow intertidal area	Multi-beam	1 m x 1 m
T2	29-10-2015	Without shallow intertidal area	Multi-beam	1 m x 1 m
T3	08-01-2016	Without shallow intertidal area	Multi-beam	1 m x 1 m
T4	19-04-2016	Without shallow intertidal area	Multi-beam	1 m x 1 m

2.2.2 SEDIMENT THICKNESS IN SHALLOW INTERTIDAL AREA

The sedimentation inside the intertidal area was measured by Martens (2016) during three field measurement campaigns in April of 2016 (Figure 2.2). The method is based on the assumption that the initial bed level (T0, see Table 2.1) inside the Perkpolder is non-erodible. The sediment thickness was determined by pushing a bamboo stick (Ø = 2 cm) into the soft sediment layer until it touched the solid surface underneath, it is assumed that this surface is the bed level as of the June 25, 2015 (T0). The sedimentation thickness was recorded at 545 locations and determined by the average of five measurements (Figure 2.2).

At six cross-sections (Figure 2.9) over the artificial tidal creeks, the sedimentation thickness is measured to obtain a more detailed picture concerning the sedimentation in the creeks. These measurements are executed on July 11, 2016. The sediment thickness is measured utilizing the same method as described above, also the surface level is measure with a DGPS.

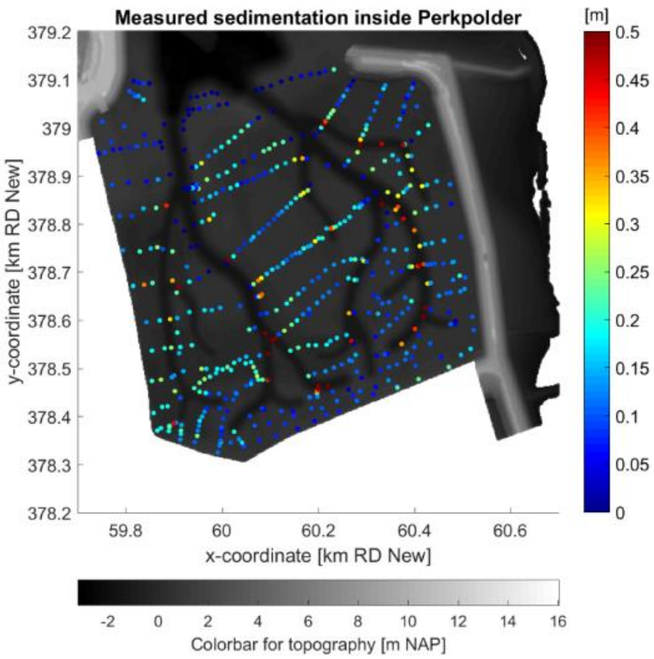

Figure 2.2 Sedimentation measurements in April of 2016, measured during three field campaigns

Table 2.2 Overview of sediment thickness measurements in Perkpolder intertidal, and creeks

Unit	Date	Coverage	Instrument	Resolution
m	04-2016 (3x)	Shallow intertidal area (Part 3)	Bamboo stick	#545/50 ha
m NAP	11-07-2016	Six cross-section over creeks	Bamboo stick, DGPS	#1/m

2.2.3 CROSS-SECTION INLET INTERTIDAL AND SUPRA TIDAL

To have a complete coverage of the tidal inlet between the two dykes, the multi-beam measurements (Table 2.2) are extended with a measurement in the higher parts of the inlet cross-section. The bed levels across the inlet were measured by HZ-student Van Vliet (2015) on 25-11-2015 using Differential Global Positioning System (DGPS; Figure 2.3). The 153 DGPS measurement points were concentrated on the northern part; the inner channel was too deep to measure and covered by the multi-beam measurements. It is assumed that morphological changes in these higher parts of the inlet, close to the two dyke heads is limited, therefore only one measurement was taken in 2015 while the second measurement will be taken by the end of 2016.

Table 2.3 Overview of height measurement of inlets cross-section (higher parts)

Unit	Date	Coverage	Instrument	Resolution
m NAP	25-11-2015	Intertidal and supratidal part of inlets cross-section	DGPS	#153/400 m

2.2.4 FLOW VELOCITIES INLET AND WATER LEVELS

Figure 2.3 shows the locations of 3D Aquadopp velocity measurements (deployed by Rijkswaterstaat) from 25 November to 1 December 2015 (10-minute data), on six locations and with 0.1 m bins over the water depth. In addition, the 10-min water level data from the Walsoorden tidal station (xRD = 60.3 km, yRD = 379.7 km) just north of Perkpolder intertidal area was used.

Table 2.4 Overview of water level and velocity measurements

Unit	Date	Coverage	Instrument	Resolution
m/s	25-11-2015 until 1-12-2015	Intertidal and supra tidal part of inlet cross-sections	Aquadopps	6 points – 10 min
m NAP	25-11-2015 until 1-12-2015	Intertidal and supra tidal part of inlet cross-sections	Aquadopps	6 points – 10 min
m NAP	Continues	Point measurements at Walsoorden	Pressure sensor	10 min

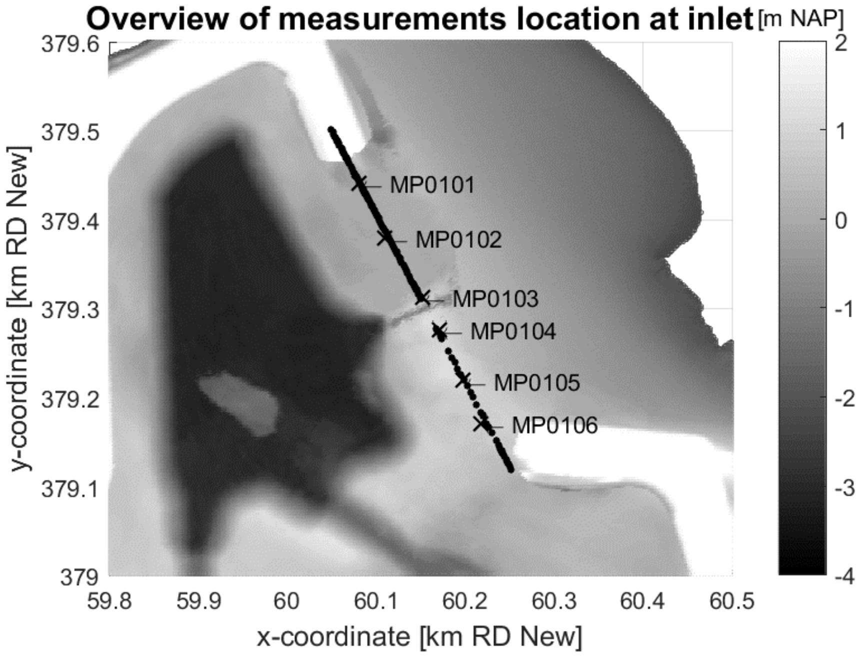

Figure 2.3 Overview of locations DGPS bed level measurements across the inlet (dots) and Aquadopp velocity measurements (crosses) with the underlying T0 bathymetry.

2.3 RESULTS

2.3.1 COMPARISON WITH OTHER BASINS

Figure 2.4. Tidal basins

Table 2.5. Tidal basins, with tidal range, and distribution of channels, flats and marches (values indicated with * are predictions other values are based on 'Waternormalen' from Rijkswaterstaat). Basins in italics are not yet open.

Tidal basin	Total area (ha)	MLW (m NAP)	MHW (m NAP)	Channel (%)	Tidal flat (%)	Salt march (%)
Perkpolder	75	-2.06	2.56	11	88	1
Saeftinghe	2800	-2.11	2.72	1	47	52
Sieperdaschor	100	-2.11	2.72	0.5	32	67.5
Hedwigepolder	*295*	*-2.22**	*2.82**	*0*	*99*	*1*
Waterdune	*250*	*-0.55**	*0.55**	*17*	*20*	*63*
Rammegors	142	-0.20*	1.40*	4.5	72	23.5

shows five tidal basins in the vicinity of Perkpolder, with some of them not yet open (Hertogin Hedwigepolder and Waterdune). The basins vary in size and tidal range (Table 2.5). The calculated percentages of channels, tidal flats, and salt marches are based on the definition that was mentioned earlier, and presented in Figure 2.1. Since this definition is only based on height levels, the bed levels of tidal creeks are added to the area of tidal flats, so tidal creeks are not recognized as separate morphological features.

Based on the latest LiDAR data of the different areas, hypsometric curves are calculated (Figure 2.5), and for Perkpolder tidal basin the T0 data is used (Table 2.1). Hypsometric curves show the distribution of basin surface area with height. The y-axis represent the height or surface elevation, the x-axis shows the fractional area below a given elevation contour, a/A (Boon & Byrne, 1981), where 'a' is the area below a given elevation, and 'A' is the total basin area.

Figure 2.4. Tidal basins

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Rammegors	142	-0.20*	1.40*	4.5	72	23.5

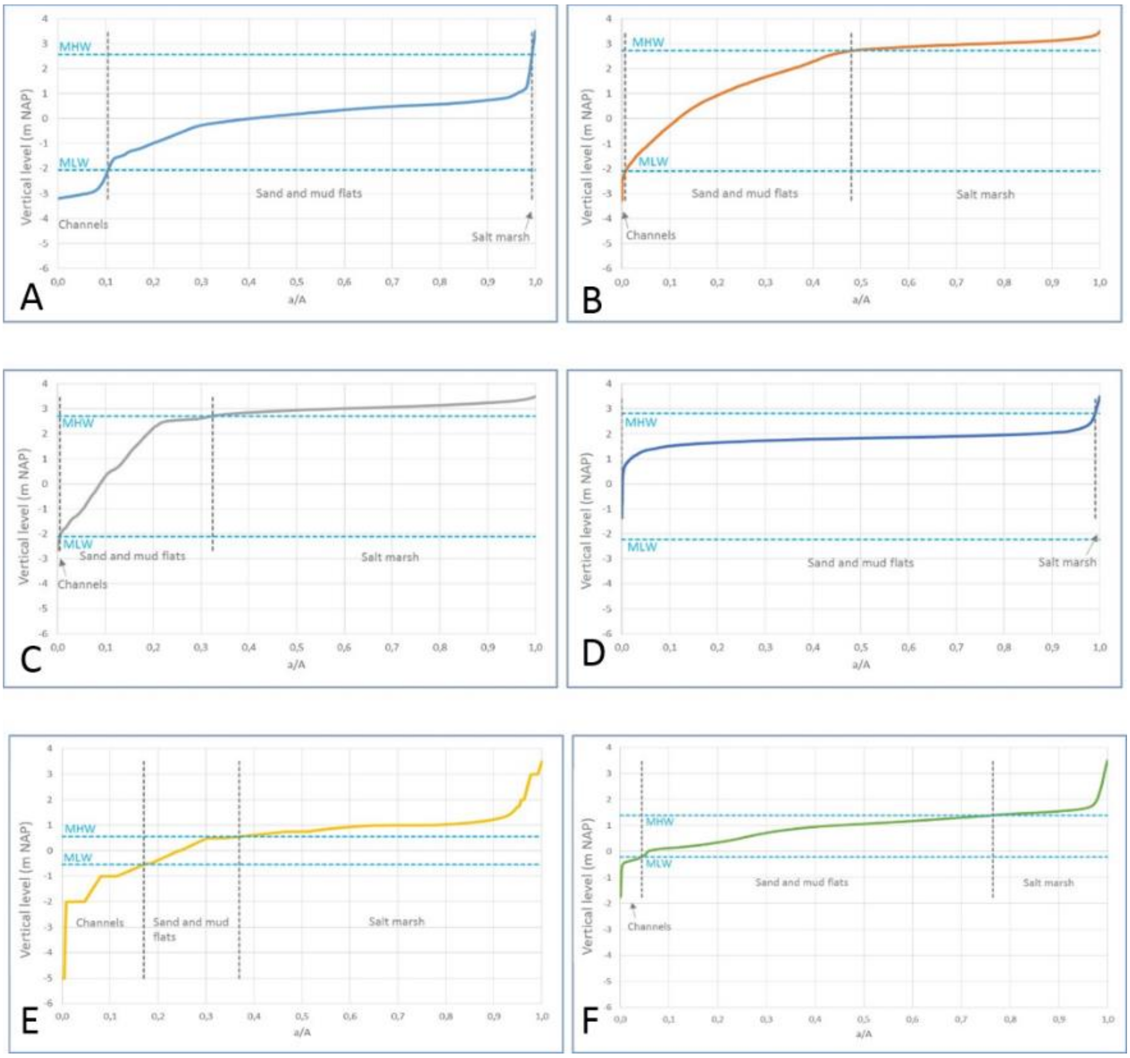


Figure 2.5. Hypsometric curves of the tidal basins: Perkpolder (A), Saeftinghe (B), Sieperdaschor (C), Hertogin Hedwigepolder (D), Waterdune (F), and Rammegors (D). On the y-axis the height, on the horizontal axis the ratio a/A, where 'a' is the area below a given elevation contour, and 'A' is the total basin area.

The hypsometric curves are used to calculate the percentage of channels, tidal flats and salt marches (Table 2.5). The high percentage of salt marches is seen in Saeftinghe (52%), Waterdune (63%) and Sieperdaschor (67.5%), which is an indication of a mature tidal basin. High coverage of tidal flats is an indication of relatively young basins, for example Perkpolder (88%) and Hedwigepolder (99%).

In Figure 2.5 the hypsometric curves of the six tidal basins are shown including the MLW and MHW water levels. The tidal range in Rammegors and Waterdune is much smaller as caused by a human-induced tempered tide. If Saeftinghe and Sieperdaschor are regarded as reference basins for Perkpolder, but at a later stage of the succession (from young to mature), it is clear from Figure 2.5 that Perkpolder tidal basin will undergo mature morphological changes if sediment import will not be a limiting factor. These changes will be much more significant than the morphological changes at the Hertogin Hedwigepolder, which is caused by the very early (1210 AD) embankment of Perkpolder and the late embankment of Hertogin Hedwigepolder at the beginning of last century (1907).

2.3.2 MORPHOLOGICAL CHANGES AFTER OPENING

Figure 2.6 shows the T0 bathymetry of the Perkpolder area, including a small inlet channel, a deep pond in the northern part and artificial creeks to promote intertidal sedimentation and drainage to favour vegetation growth.

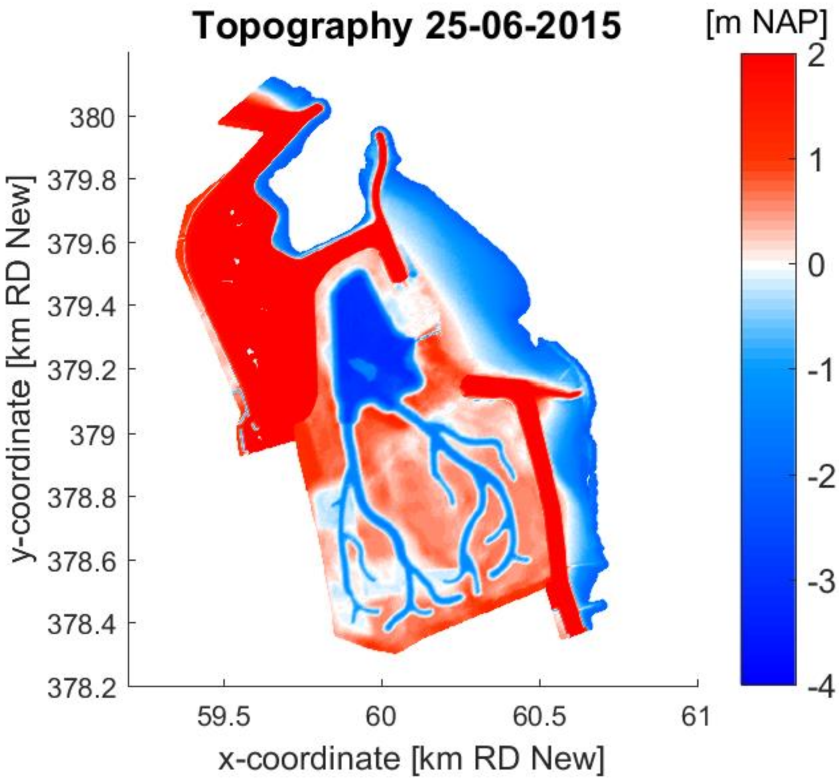
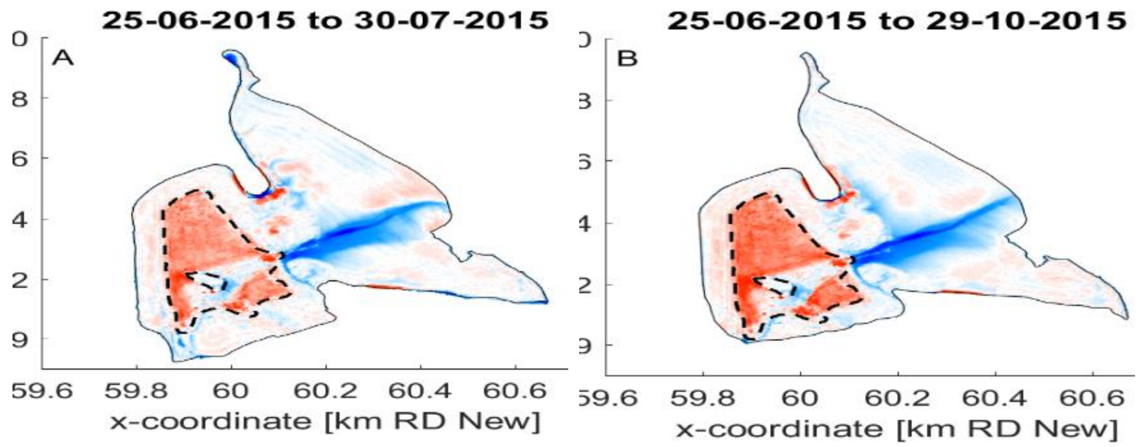


Figure 2.6 T0 bathymetry (May/June 2015).

POND AND OUTER AREA TIDAL FLAT (PART 1 AND 2)

Figure 2.7 shows the morphological development during the period of May/June 2015 (T0) to 19 April 2016 (T4), or about 10 months. This figure clearly demonstrates the sedimentation of the pond (up to 2 m) and the erosion of the inlet (up to 4 m). The morphological changes are the largest between T0 and T1 (the first 1-2 months).



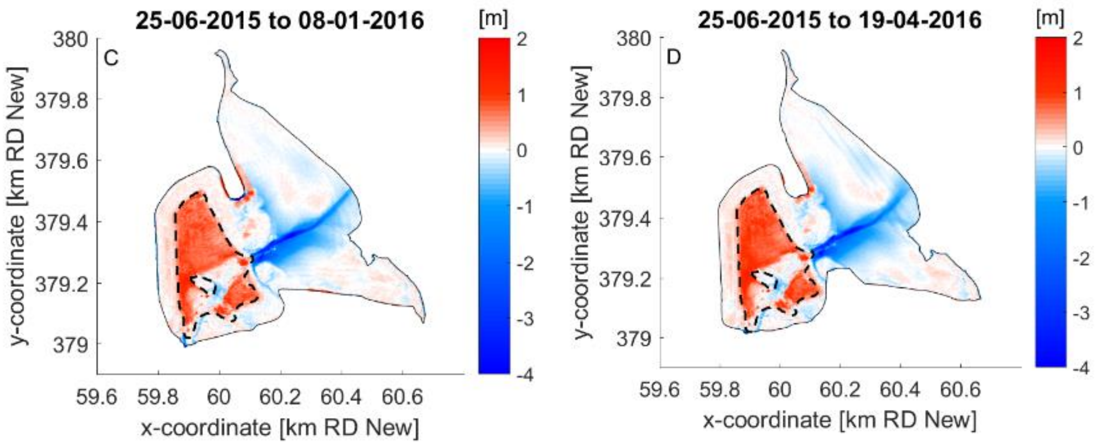


Figure 2.7 Sedimentation and erosion between T0 (May/June 2015) and T4 (19 April 2016).

TIDAL FLAT AND CREEKS (PART 3)

Figure 2.8 shows an interpolation of the sedimentation field measurements (Figure 2.2) taken in April of 2016 (Martens, 2016). The sedimentation typically varies between 0 and 50 cm, although locally the larger values were found. The largest sedimentation seems to occur along the creeks (up to 100 cm).

The mean accretion rate in the zone with artificial creeks is 15 cm in ten months (18 cm/yr). The brown areas in Figure 2.8 represent the locations where the most of the sediment is deposited. It is clear that the highest accretion rates are to be found in the tributary channels of the main two creeks. Sedimentation on the tidal flat is much more limited and ranges from 0 to 15 cm. In the northern part of the two main creeks we observe that no sedimentation occurs, but erosion does take place, which results in a wider channel.

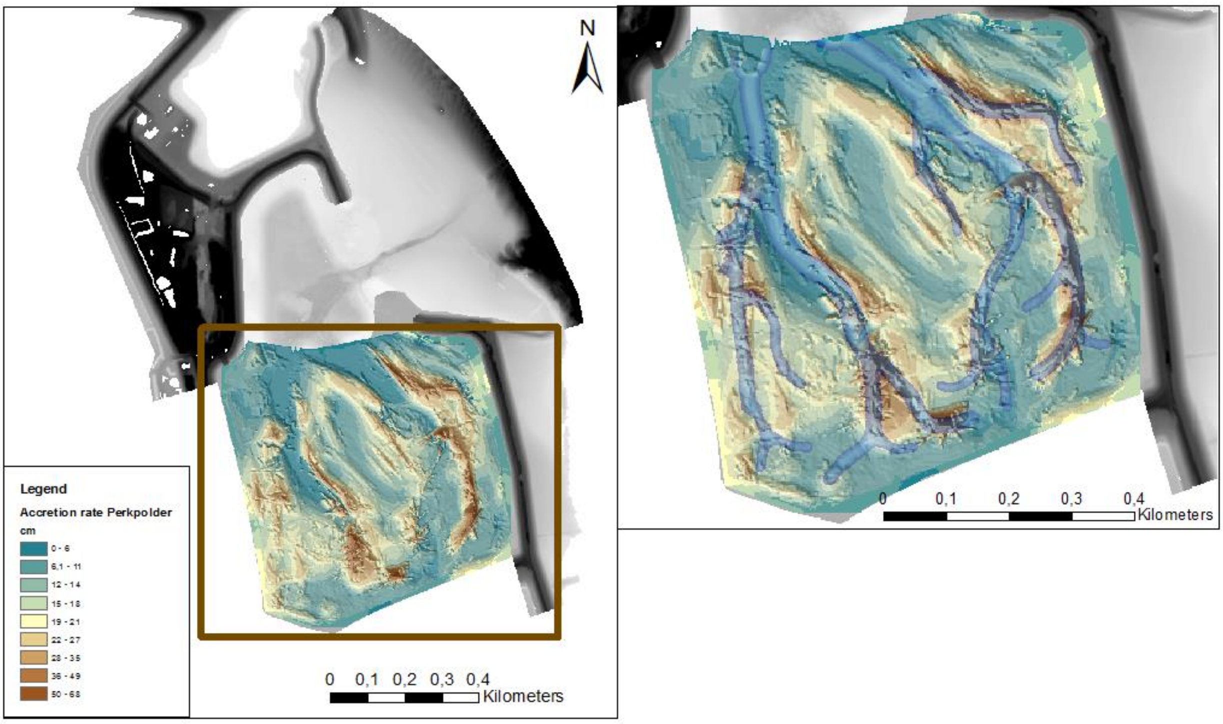
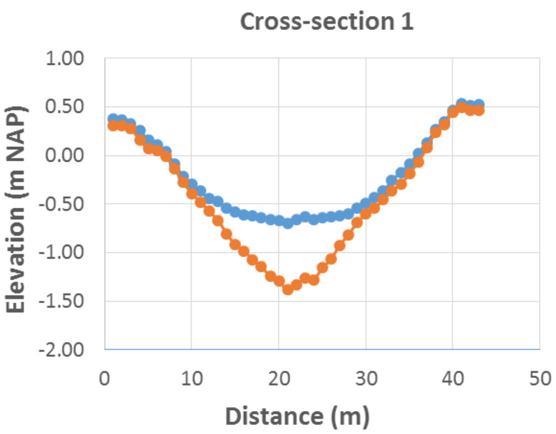
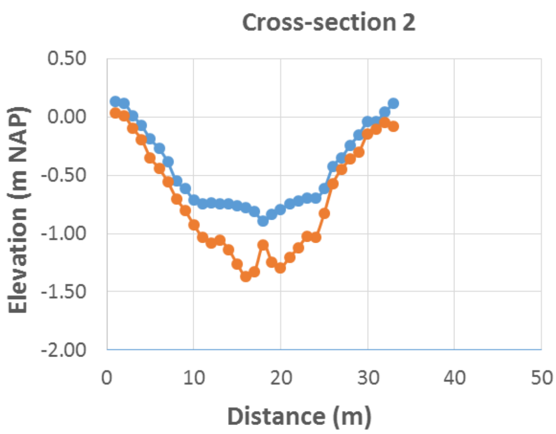


Figure 2.8. Sedimentation map of Perkpolder. On the map to the right the artificial channels are plotted on top of the accretion map

Figure 2.9. Locations of cross-sections

The sedimentation in the artificial tidal creeks is measured at six cross-sections (Figure 2.9). The results are presented at Figure 2.10. The cross-sections show a generally strong sedimentation at the lower parts of the creeks. Cross-sections closer to the pond demonstrate a more limited sedimentation.





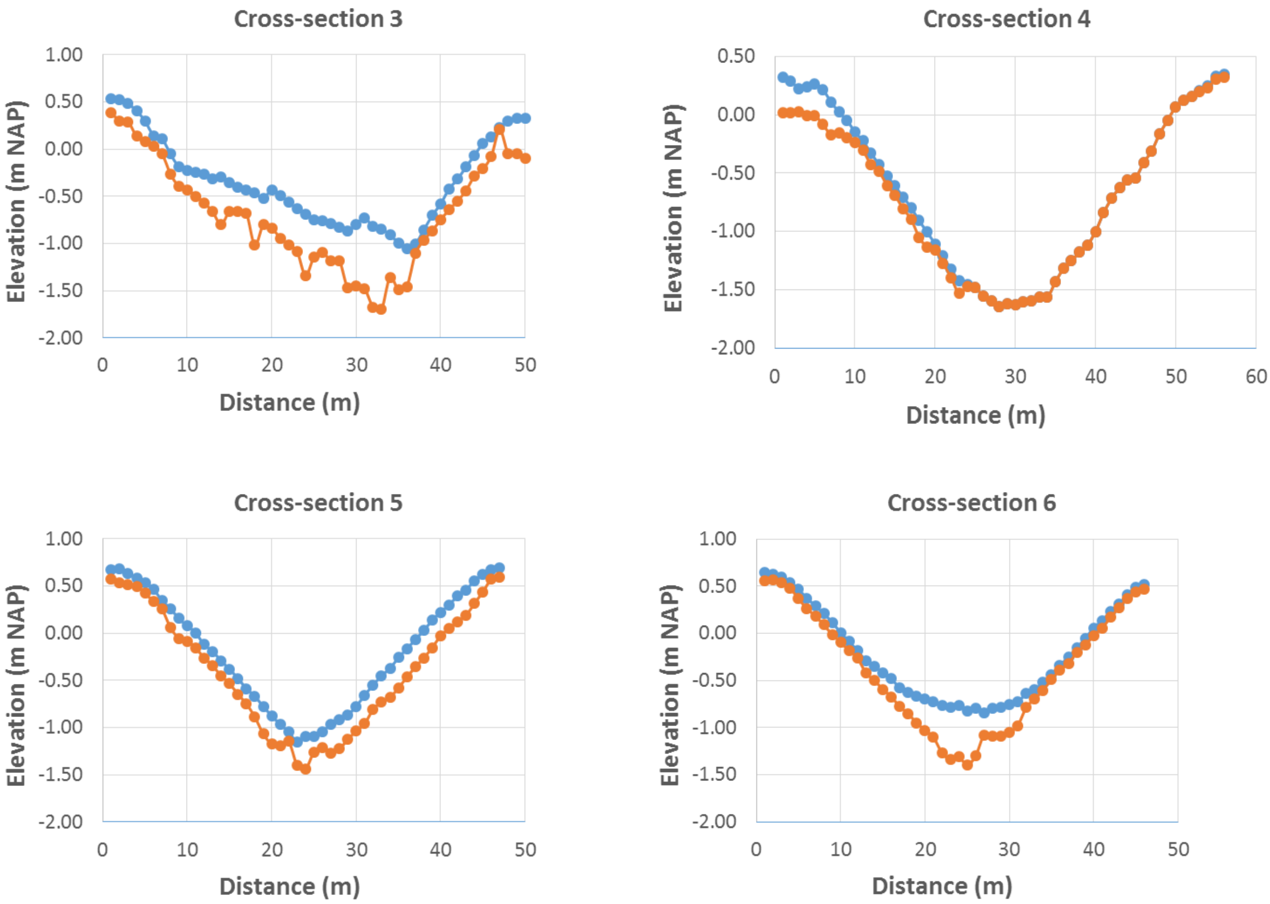


Figure 2.10. Cross-section over creeks in the tidal flat area

CROSS-SECTION TIDAL INLET

Figure 2.11 shows how the bevel levels at the inlet developed, Figure 2.12 shows the changes in the cross-sectional area of the inlet over time, below a water level of +90 cm NAP. The main inlet channel (around the Aquadopp locations of MP0103 and MP0104) has widened and deepened during the period between June (T0) and July (T1) of 2015. After that period, the changes became much smaller, although there is a continuing trend towards an increase of the inlets cross-section (Figure 2.12). In the initial phase (T0-T1) a smaller secondary channel developed at the right-hand side of the left dike. Furthermore, this figure shows that the multi-beam and DGPS measurements match well, except for the location of the dikes in the T0 measurements (see the additional discussion of this in Section 2.2).

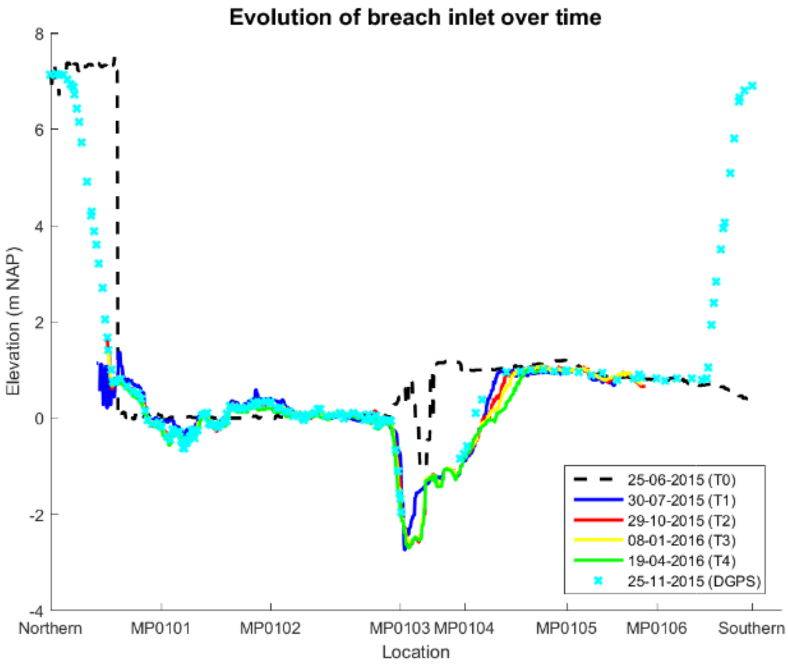


Figure 2.11 Morphological development of the inlet.

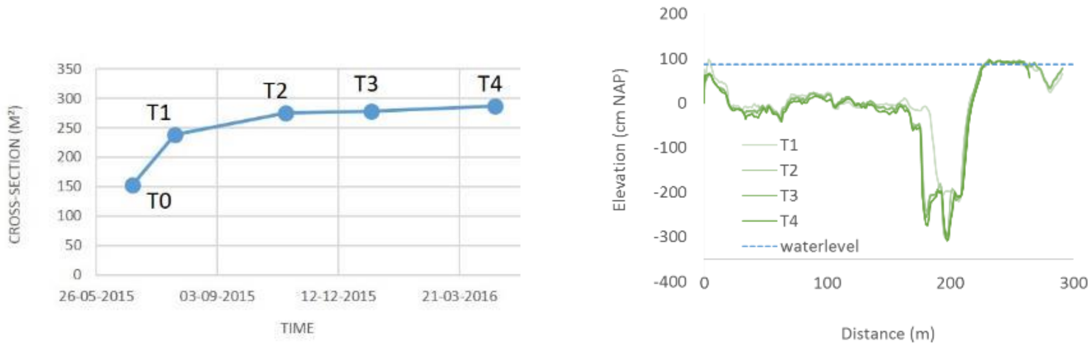


Figure 2.12. The development of the cross-section of the tidal inlet over time. Cross-sectional area is calculated at a water level of 86 cm NAP, as the picture to the right shows.

2.3.3 FLOW VELOCITIES AND DISCHARGE OF TIDAL INLET

The normal velocities and discharges at the inlet are flood-dominant, i.e. the peak flood values are larger than the peak ebb values. This is mainly related to the fact that the peak flood velocities occur at a higher water level (and water depth) than the peak ebb velocities.

At Walsoorden, Mean High Water (MHW) is +2.6 m NAP, and Mean Low Water (MLW) is -2.1 m NAP in 2015. For the T0 situation (figure), the tidal storage based on MHW and MLW is 1.6 million m^3 . This corresponds well with the tidal prism based on estimated discharges from the velocity, water level and bed level data, which results in an average volume of 1.7 million m^3 (November 2015).

By using the T0 elevation data from June of 2015, and the measured water levels at Walsoorden measurement stations, the flood and ebb discharges in and out of the Perkpolder tidal basin are calculated. The Perkpolder basin is regarded in this calculation as a storage reservoir, and the water levels in this reservoir have an instantaneous response to water levels at Walsoorden. These calculations confirm the earlier-mentioned flood-dominance. The flood-dominance is larger during the spring tide, while during neap tide the flood-dominance is not very visible.

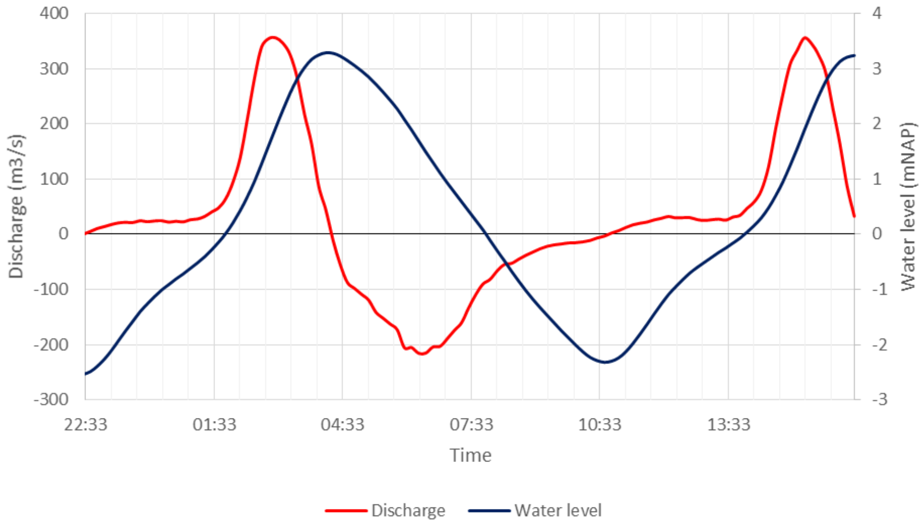


Figure 2.13. Calculated discharge at the inlet, and water levels measured at Walsoorden during spring tide.

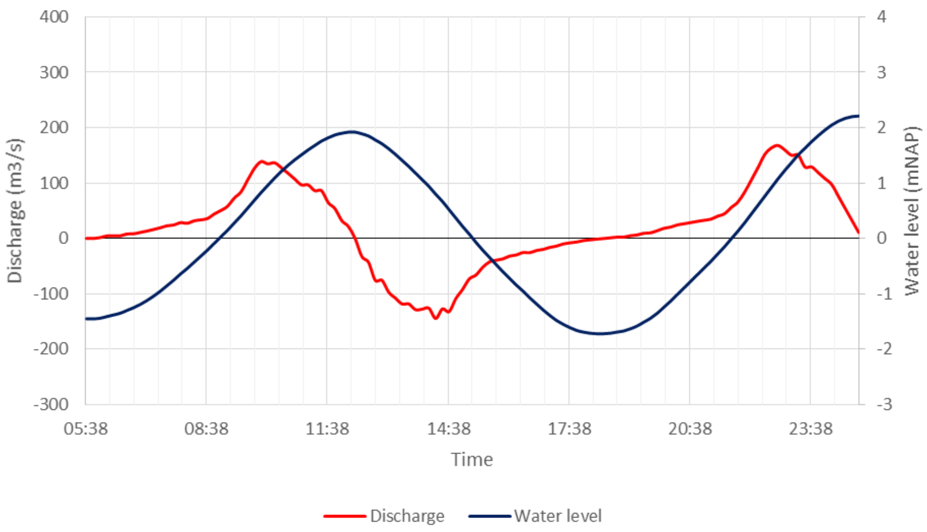


Figure 2.14. Calculated discharge at the inlet, and water levels measured at Walsoorden during neap tide.

2.3.4 SEDIMENT BALANCE

Figure 2.16 shows the volume changes in three parts of the area of interest (Figure 2.15). Herein it is assumed that the sediment volume of Part 3 follows the same trend as Part 2. Furthermore, the point sedimentation measurements of Part 3 were interpolated to get a complete spatial coverage. As a result, the sediment volumes of Part 3 are rather uncertain.

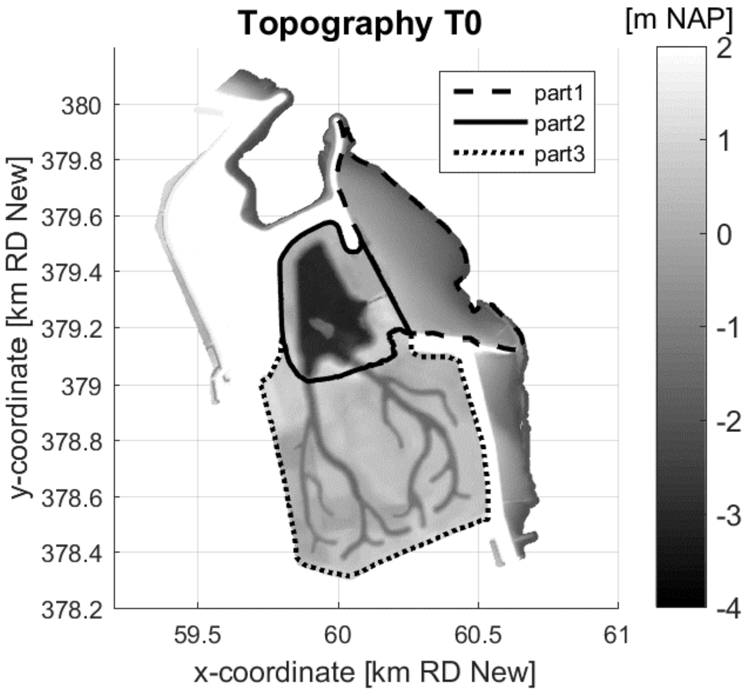


Figure 2.15 Division of the area of interest into three parts for volume analysis. Part 1: outer area, Part 2 pond area and Part 3 intertidal area.

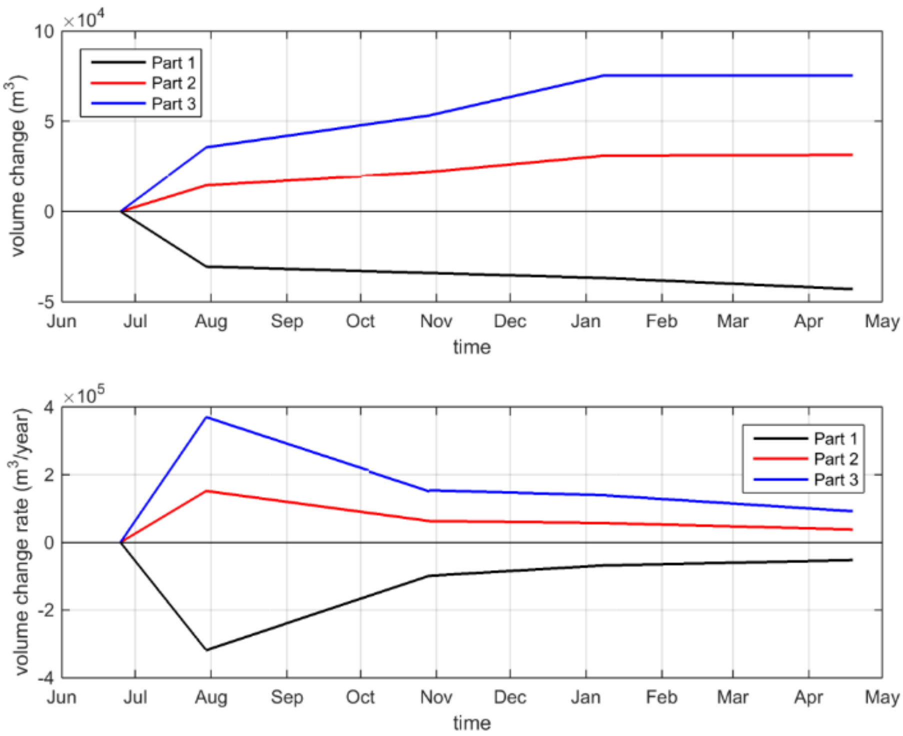


Figure 2.16 Sediment volume development over time.

The volume changes reflect the relaxation of the volume changes in time. The outer area (Part 1) loses sediment, while the inner parts (Parts 2 and 3) gain sediment. The sediment volume of the inner area, Parts 2 and 3, increases with 107 x 10^3 m^3 between June 2015 and April 2016, or 130 x 10^3 m^3/year. This sediment is due to local erosion of the inlet (sand and mud) and the net suspended sediment inflow (mostly mud). The initial sedimentation in Perkpolder is dominated by the local erosion effect; thereafter the second process is more important.

The sediment volume of the inner area increases with 57 x 10^3 m^3 between July (T1) and April 2016, i.e. 78 x 10^3 m^3/year. This corresponds to 47 x 10^3 tons/year, assuming a dry bed density of 600 kg/m^3 (in between the density of freshly deposited mud and a consolidated muddy bed). The tidal prism is approx. 1.7 million m^3. For a typical mud concentration of 50 mg/l, this corresponds to a maximum net sediment influx of 85 tons/tide or 60 x 10^3 tons/year, implying a trapping efficiency of about 80%.

2.3.5 LARGE-SCALE CHANGES IN HEIGHT

The maps below show the surface levels at various moments in time, in December 2013 (T-1), June 2015 (T0), and April 2016 (T4 + stick). The last map is a composite of T4 multi-beam data, LiDAR measurements (Table 2.1) and the bamboo stick measurements (Figure 2.2). The hypsometric curves (Figure 2.18) show the changes in the surface level. The differences between T-1 and T0 are due to excavation work of the contractor. The top layer of the surface was removed, a pond in the northern part was creating including creeks in the south. After opening most of the changes are visible in the lower part of the hypsometric curves. This is caused by the large sedimentation in the pond (see also Figure 2.7) and the sedimentation at the creek bedding around -1,0 m NAP (see also Figure 2.10).

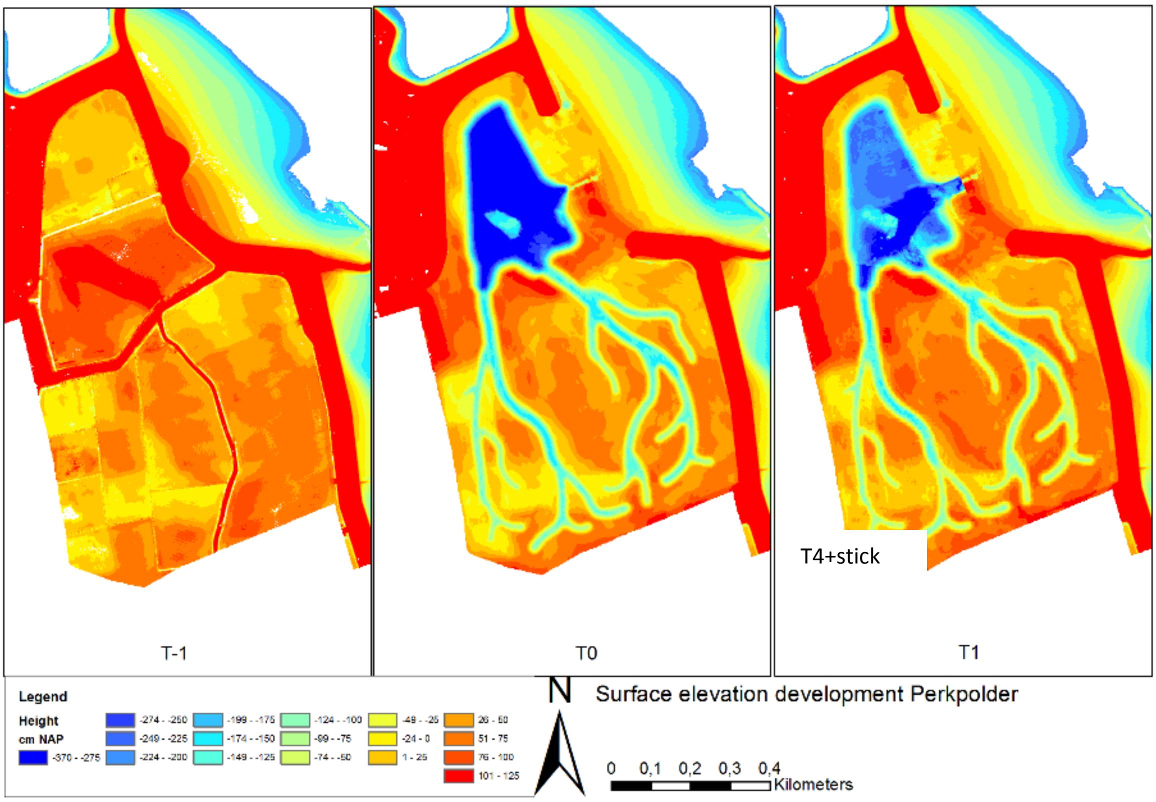


Figure 2.17. Elevation maps of the Perkpolder tidal basin, T-1 (December 2013), T0 (June 2015), and T4+stick (April 2016).

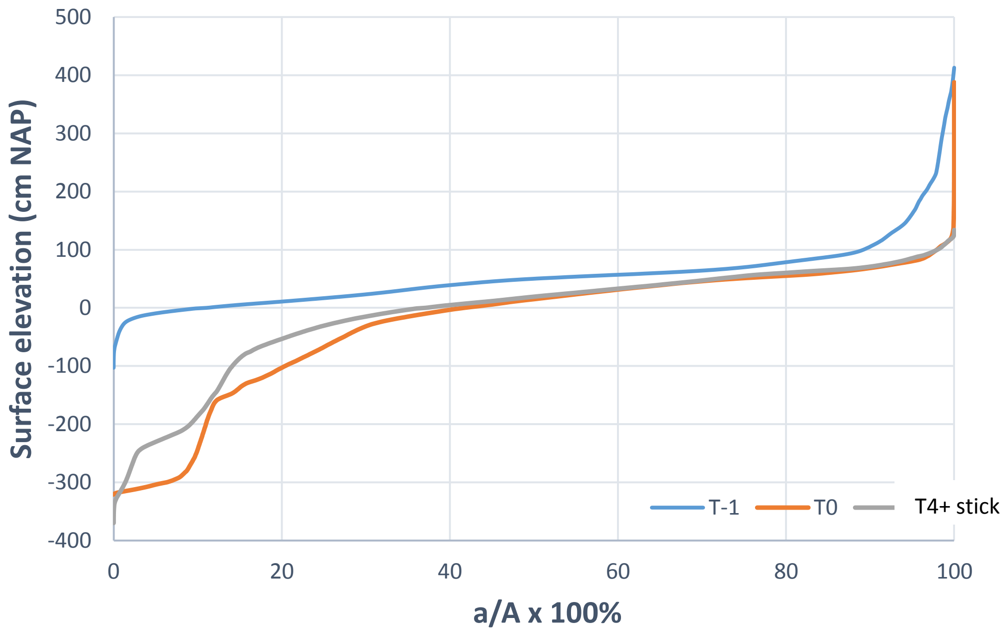


Figure 2.18. Hypsometric curves of the Perkpolder tidal basin T-1 (Dec. 2013), T0 (June 2015), and T4+stick (April 2016). On the y-axis the surface elevation, on the horizontal axis the ratio a/A, where 'a' is the area below a given elevation contour, and 'A' is the total basin area.

2.4 DELFT3D MODELLING

2.4.1 MODEL SET-UP

A depth-averaged (2DH) Delft3D model was set-up to simulate hydrodynamics, sediment dynamics and morphodynamics under tidal influence. Figure 2.19 shows the model domain; the grid resolution is ~20 m x 20 m.

Figure 2.19 Domain Perkpolder Delft3D model.

The hydrodynamic boundary conditions are obtained from the Delft3D-NeVla model (Vroom et al., 2015) and the mud concentration boundary conditions from the LTV – slib model (Van Kessel et al., 2011). The model considers 1 sand fraction with a median diameter D_{50} = 0.15 mm and a dry bed density of 1600 kg/m^3 and 1 mud fraction with a settling velocity w_s = 1 mm/s and a dry bed density of 500 kg/m^3. The model distinguishes between a relatively fast-responding muddy (fluff) layer on top of fully-mixed sediment bed layer consisting of sand and mud.

2.4.2 MODEL CALIBRATION AND VALIDATION

The model reproduces the inlet velocities reasonably well with the help of a correlation coefficient, R^2, between 0.36 and 0.77 and a bias between 0.01 and 0.06 m/s for the six measurement locations. As an example, the Figure 2.20 demonstrates the comparison between measured and computed velocities at the location MP0102.

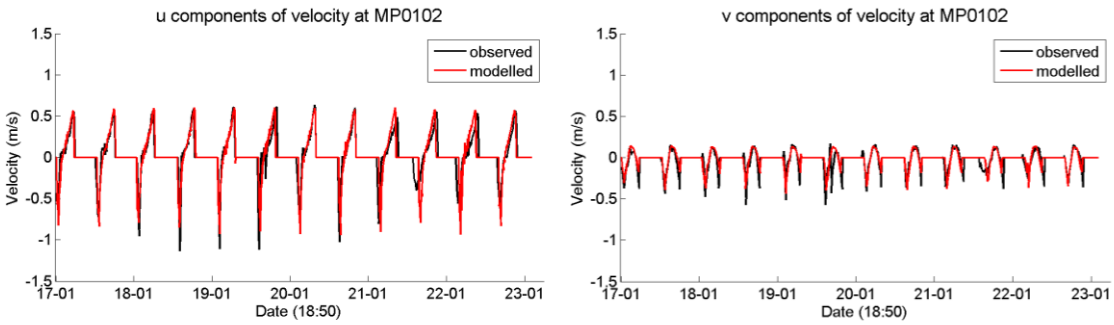


Figure 2.20 Comparison of measured and computed velocities at location MP0102. u = velocities normal to the inlet (inflow is positive), v = velocities parallel to the inlet (positive is toward the Northwest).

Following this the settings of the sediment model were changed in order to reproduce the net sediment influx. Finally, we compared the measured and computed bed level changes. The Figure 2.21 shows that the general sedimentation trends are reproduced by the model.

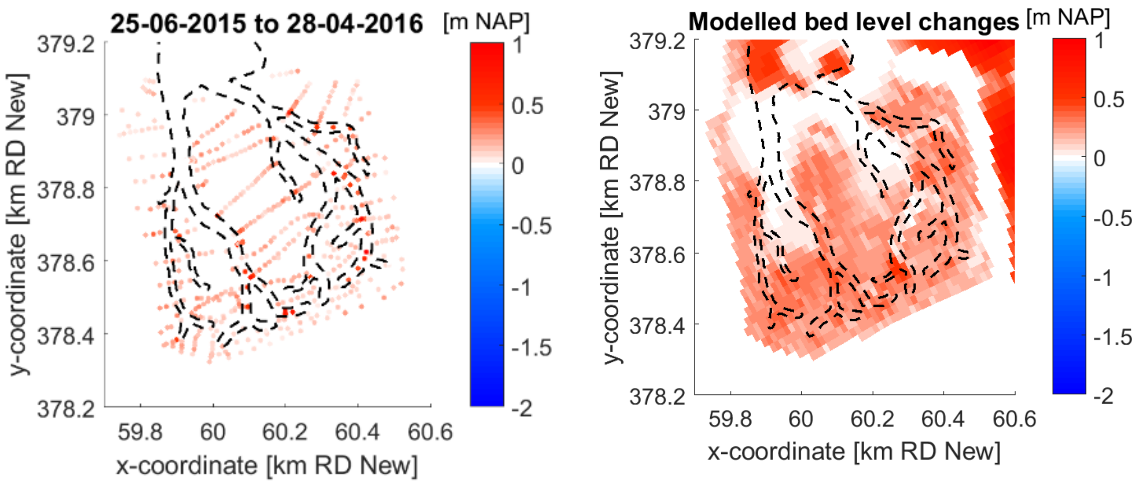


Figure 2.21 Observed (left) and computed (right) sedimentation in Perkpolder. (Unit should be [m] instead of [m NAP].)

2.4.3 MODEL APPLICATION

We used the Delft3D model in order to better understand the processes that drive the morphological development of Perkpolder. Subsequently, the model was used to study the effect of the inlet width, the creeks and the pond. Figure 2.22 shows that a 50% reduction of creeks and pond depth has a limited influence upon the Perkpolder sedimentation. No creeks and pond results in a very different pattern. It also reduces the total sedimentation, as the net sediment influx is smaller due to the smaller tidal prism. A 50% change in inlet width only seriously affects sedimentation and erosion around the inlet (Figure 2.23).

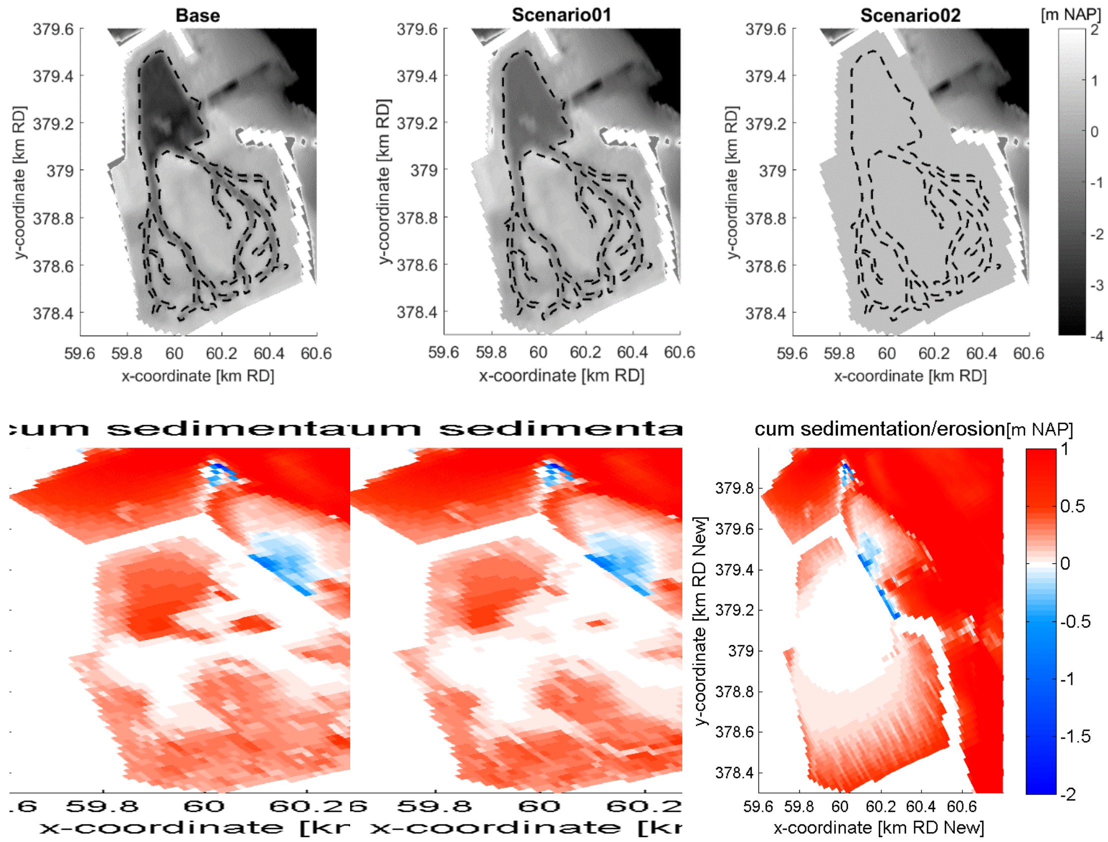
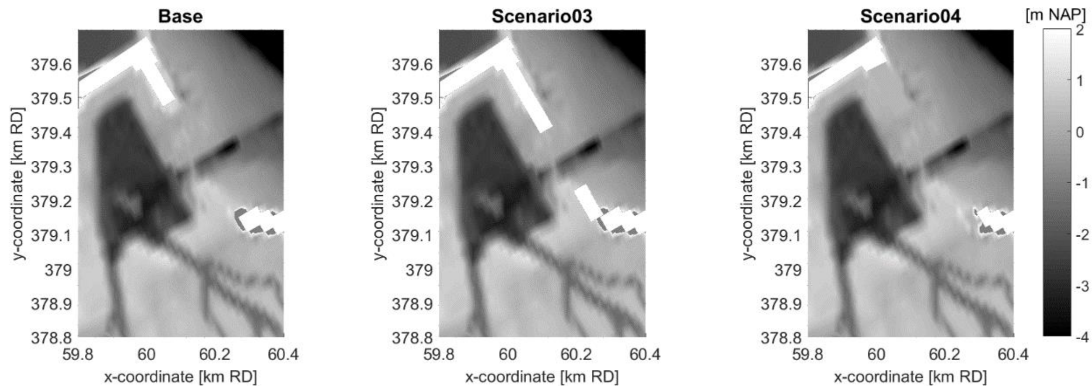


Figure 2.22. Effect of reducing depth of the pond and creeks with 50% (Scenario 1) and 100% (Scenario 2).



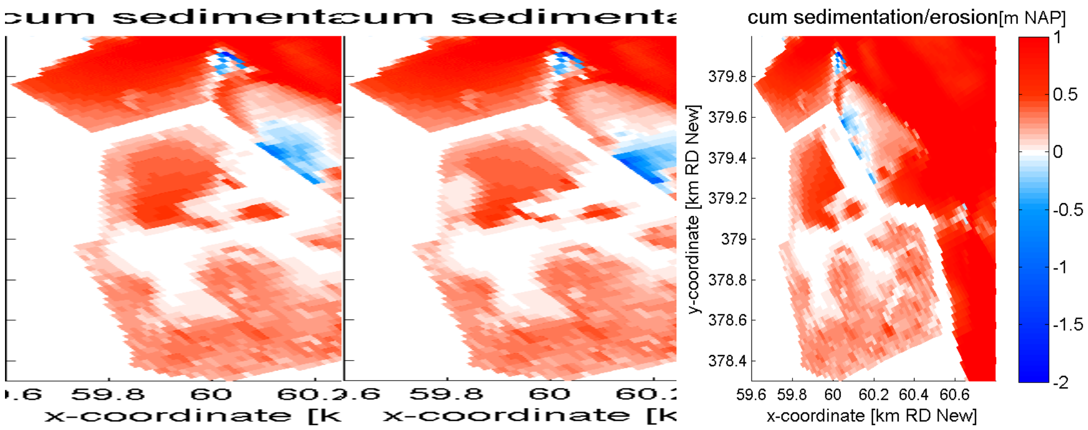


Figure 2.23 Effect of changing the inlet width. Scenario 3: 50% decrease, Scenario 4: 50% increase.

2.5 DISCUSSION

The largest morphological change in the new Perkpolder area occurs during the first 1-2 months following the opening on June 25, 2015. The inlet erodes and this sediment drops into the deep pond just inside Perkpolder area. Thereafter, the inlet is more or less in equilibrium and further sedimentation of Perkpolder is controlled be net sediment influx from outside, which is probably mainly muddy. Every tide about 1.7 million m^3 water flows in and out. With a typical mud concentration of 50 mg/l, we can estimate the net sediment influx to be 60 x 10^3 tons/year. Assuming a dry bed density of 600 kg/m^3, this implies that about 80% of the incoming sediment is trapped inside Perkpolder area between 30 July 2015 (T1) and April 2016 (T4).

A 2DH Delft3D model was set up to simulate hydrodynamics, sediment dynamics and morphodynamics due to tidal forcing. The model reproduces the measured velocities and the inlet reasonably well, and was further calibrated on the estimated net sediment influx and the morphological changes between June 2015 and April 2016. Thereafter, the model was used to better understand how the new intertidal area develops. It was shown than a 50% volume reduction of creeks and pond hardly affects the sedimentation, which is also the case for a 50% change in inlet width. The latter does influence the more local sedimentation and erosion patterns, i.e. close to the inlet.

2.6 RECOMMENDATIONS

Next steps are:

1. Further investigation of the settings and choices of the model, such as the influence of initial bed composition and the duration of the simulation period.
2. Distinction between initial sedimentation mainly related to local erosion of the inlet, and the more long-term development related to the net sediment influx from outside.
3. Further model validation using spring 2016 bed levels, as well as frequent point measurements of bed levels and bed composition
4. Exploration of the influence of waves.
5. Further scenario analysis.

Concerning the monitoring we recommend:

1. Suspended sediment concentration measurements close to the inlet to be able to determine the sediment influx, and to validate the Delft3D numerical model.
2. Bed-level measurements of the intertidal area, both frequent measurements at a number of points as well as well as less frequent synoptic surveys.

3. Measurements of composition and density of the intertidal area. Together with the bed level measurements this will help to better understand the morphodynamic development, and to validate the Delft3D model, which can then be used in order to further improve the system understanding.

3 GROUND WATER

3.1 INTRODUCTION

The transfer of agricultural land into tidal salt marches will affect the groundwater system (head levels, infiltration / seepage fluxes, and salinity distribution) for both the tidal area and the adjacent area. The restoration of tidal areas will cause (1) an increase of the average water level since the water level will change from polder water level (usually 1 to 3 m below sea level) to average sea level, (2) increase of hydraulic heads in the subsoil and (3) an increase of the infiltration of salt water. Effects will propagate outside the tidal area via the hydraulic heads in the aquifer(s).

Concerning the groundwater system in and outside these new tidal areas, the following 3 research questions were formulated:

1. What is the effect of the new tidal area on the groundwater system in the adjacent agricultural area and is the implemented mitigation measure SeepCat compensating the effects properly?
2. What is the tidal propagation in the aquifer below the tidal area?
3. What is the effect of the tides on the salinity of soil and groundwater in the tidal area?

3.2 METHODS

3.2.1 SEEPCAT AND GROUNDWATER EFFECTS ADJACENT AGRICULTURAL AREA

Below the adjacent agricultural area, a freshwater lens of about 10 to 15 meters provides farmers with fresh groundwater for irrigating their crops (Figure 3.1). In order to protect this freshwater lens from shrinking, a self-flowing seepage system, called SeepCat,was designed and installed to compensate the effects resulting from this local sea level rise.

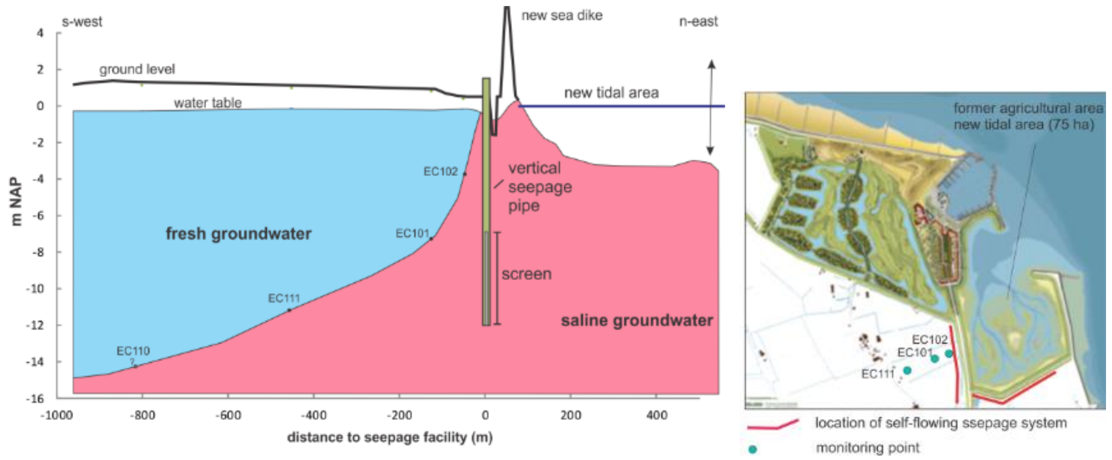


Figure 3.1. Cross-section (left) and map (right) showing the position of the seepage system and the new tidal area. The thickness of the fresh water lens (left) was determined in monitoring points EC102, EC101 and EC111 using EM-SlimFlex.

The freshwater lens below the agricultural area is one of the Badon Ghyben Herzberg type and will eventually shrink when hydraulic heads below the lens increase caused by the local sea level rise. The task of SeepCat is to release the increased pressure in the aquifer preventing the freshwater lens to decrease in size. The self-flowing seepage system consists of 61 vertical seepage wells with 5-10 m long screens, installed in the aquifer at 12 to 17 m depth. The distance between the wells is 15 to 20 m and the total length of the seepage system is 1100 m. The vertical seepage wells are connected in the subsoil with horizontal tubes which end up in control units (Figure 3.2). The hydraulic head gradient (Δh) can be regulated by raising or lowering the water level in the control unit using weirs (Figure 3.2). In this way the discharge of the seepage system can be regulated. Since the hydraulic head in the aquifer is higher than the surface water level in the control unit and ditch, seepage wells are artesian and self-flowing and no pumps are needed to extract the groundwater from the aquifer. The extracted seepage water is discharged into the surface water system and transported to a pumping station (at 1 km) where it is pumped out of the polder into the sea.

A detailed monitoring network was installed for three reasons: (1) monitoring the effects of the new tidal area on the groundwater system in the adjacent agricultural area, (2) monitoring the functioning of the seepage system, and (3) to inform the farmers. At 21 locations the hydraulic head in the aquifer is measured every hour with automatic monitoring devices ('Diver'). At 15 locations the fresh-saline interface (salinity – depth profile) is measured every half a year with the EM-SlimFlex. The discharge of the seepage system as well as the salinity is measured every hour in two control units which are connected to 3 and 7 seepage pipes.

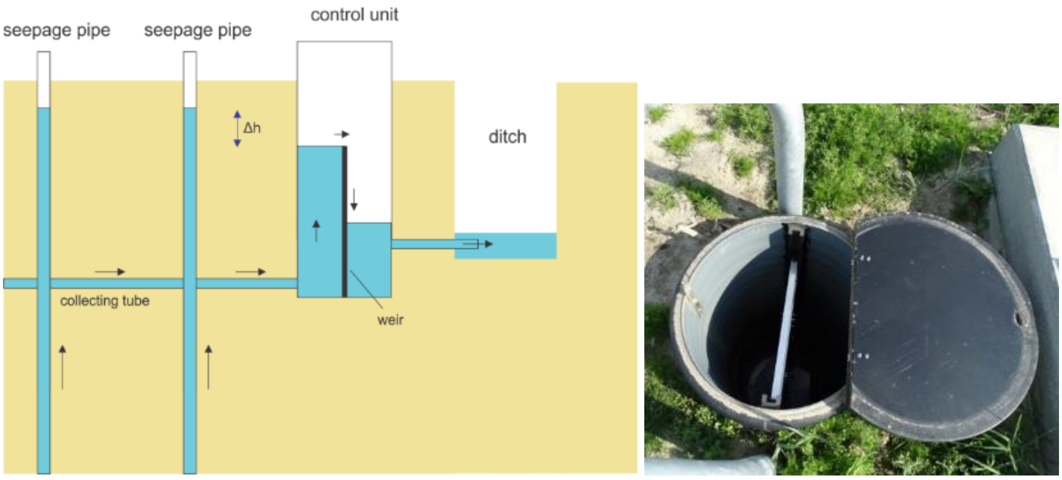


Figure 3.2. Cross section of self-flowing seepage system with seepage pipes and control unit (left) and photo of control unit with weir (right)

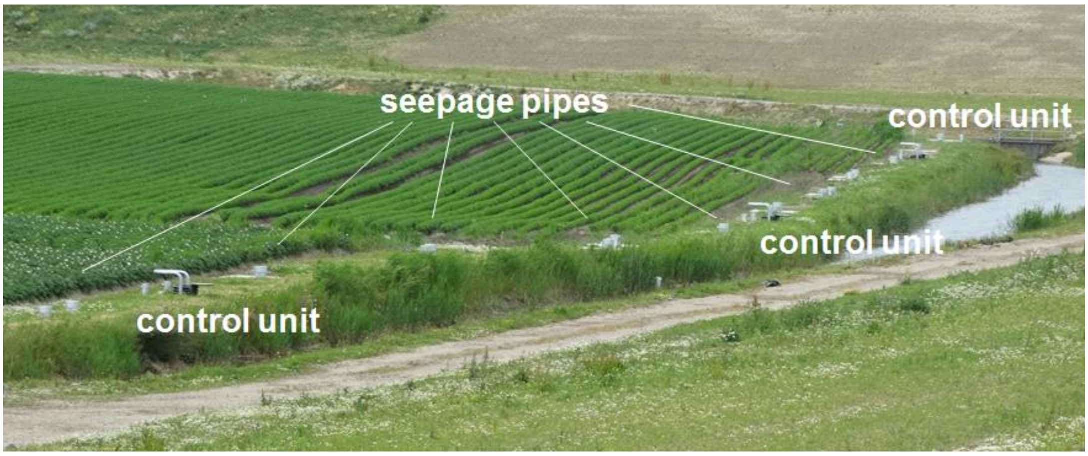


Figure 3.3. Part of the self-flowing seepage system with the position of seepage pipes and control units at the border of an agricultural field

3.2.2 TIDAL PROPAGATION IN THE AQUIFER

Effects of water level changes (like sea level rise or restoration of tidal areas) on groundwater in adjacent areas will propagate via hydraulic heads in the aquifer(s). The first step in quantifying these kinds of effects is to determine the net effect on the hydraulic head in the aquifer(s) as a result of changes at or nearby the surface. The composition of the subsoil and the morphology of the tidal area are the 2 most important factors controlling the tidal propagation in the aquifer. The tidal area morphology determines which part will be submerged and for what duration.

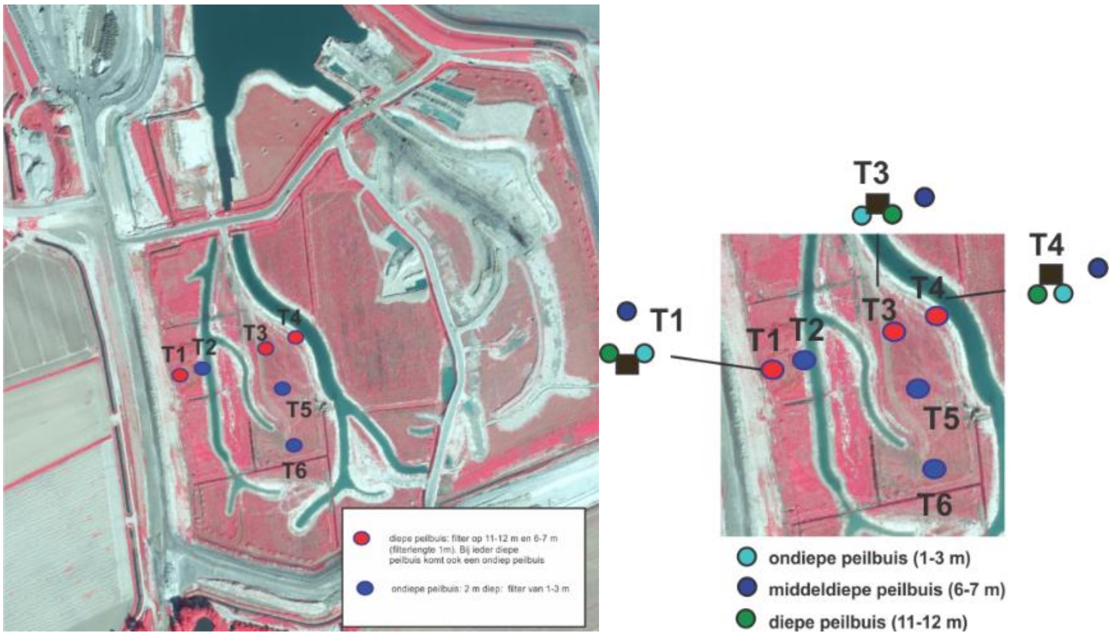


Figure 3.4. Monitoring network in tidal area with deep piezometers (red) and shallow piezometers (blue).

Table 1. Technical details of the piezometers in the tidal area.

							ground level	top piezometer	top piezometer
	x-coor	y-coor	screen depth	Diver-nr	x-coor	y-coor	m NAP	m bgl	m NAP
T1	59836	378598	1-3 m	U0484	59836	378595	0.36	2.56	2.92
	59836	378598	6-7 m	U0884	59835	378596	0.37	2.67	3.04
	59836	378598	11-12 m	T3929	59836	378595	0.36	2.53	2.89
T2	59873	378607	1-3 m	U0471	59873	378603	-0.01	2.79	2.78
T3	59997	378626	1-3 m	U1321	59998	378625	0.6	2.73	3.33
	59997	378626	6-7 m	T3936	59999	378625	0.62	2.74	3.36
	59997	378626	11-12 m	T3919	59998	378625	0.6	2.72	3.32
T4	60045	378636	1-3 m	U1329	60043	378633	0.1	2.98	3.08
	60045	378636	6-7 m	T1375	60044	378633	-0.05	3.02	2.97
	60045	378636	11-12 m	T3927	60043	378633	0.1	3.03	3.13
T5	60021	378564	1-3 m	U1332	60021	378562	0.12	2.78	2.90
T6	60036	378468	1-3 m	U1225	60038	378460	0.41	2.78	3.19

The transformation of agricultural land into tidal salt marsh land at Perkpolder makes it possible to measure the net effect and propagation into the aquifer. Therefore, a detailed monitoring network of piezometers was installed in the tidal area before the opening of the dike at 25th of June 2015. Figure 3.4 shows the position of the piezometers and table 1 summarizes the technical details of the piezometers. At three locations, the 1 m length screens of the piezometers were installed at a depth of 7 and 12 m below ground level. At 6 locations shallow piezometers were installed with screens ranging from 3m below ground level up to ground level. The piezometers were installed at different distances from the tidal creeks. All piezometers were equipped with automated pressure devices (called Divers) to measure the water pressure every 10 minutes.

Figure 3.5. Piezometers in tidal area during low tide (left) and nest of 3 piezometers installed at different depths (3, 8 and 12 m bgl)

3.3 RESULTS

3.3.1 SEEPCAT AND GROUNDWATER SYSTEM ADJACENT AGRICULTURAL AREA

Figure 3.6 shows the time series of the hydraulic head (screen depth 12 m below ground level) for a location between two vertical seepage pipes, near monitoring point EC102 (Figure 3.1). The tidal fluctuation of the hydraulic head increased from 10 cm (before 25 June) to 60 cm (after 25 June) resulting from the local sea level rise (development of the new tidal area). The increase of the daily mean hydraulic head was 16 cm. The seepage system was closed during the first month to determine direct effects of the local sea level rise where after the seepage system was thrown open. This resulted in a decrease of about 29 cm of the daily mean hydraulic head which show that the hydraulic head could be reduced more than the effects of the local sea level rise which is more than needed. Direct effects in the agricultural area due to the new tidal area and seepage system were only detected for monitoring points within 100-200 m from the tidal area.

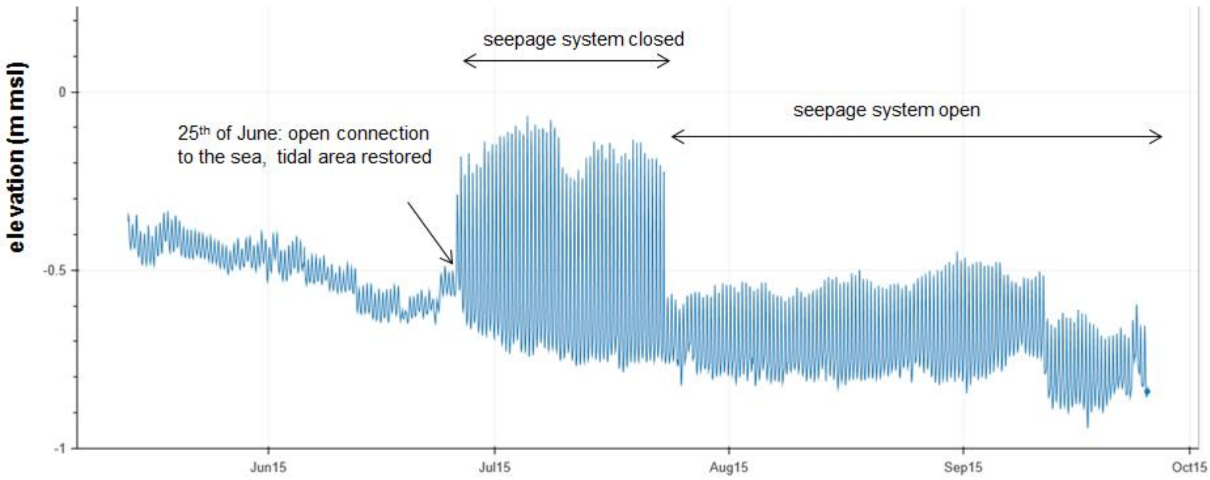


Figure 3.6. Time series of hydraulic head between two vertical seepage pipes

The measured average discharge of the seepage system was over the period October – December 2015 410 m3/day and the average salinity was 35 mS/cm. As expected, the EM-SlimFlex measurements in December 2015 didn't show any changes in fresh-saline interface due to the development of the new tidal area (Figure 3.7). Changes of salinity are induced by transport processes which are far more slowly than changes in hydraulic head caused by pressure transfer.

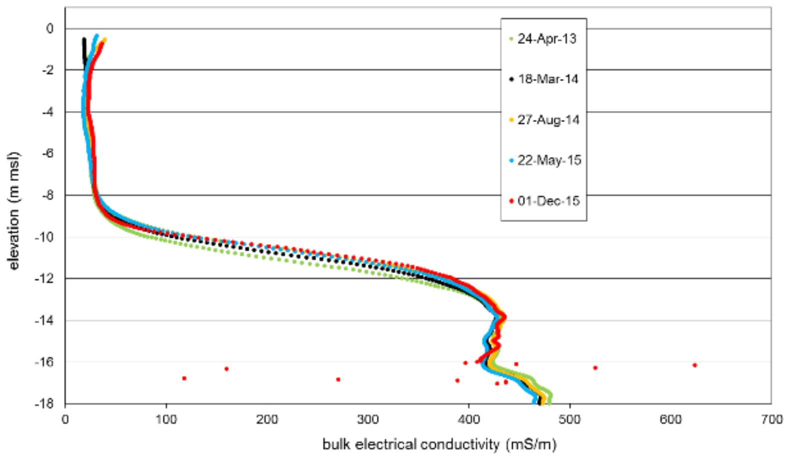
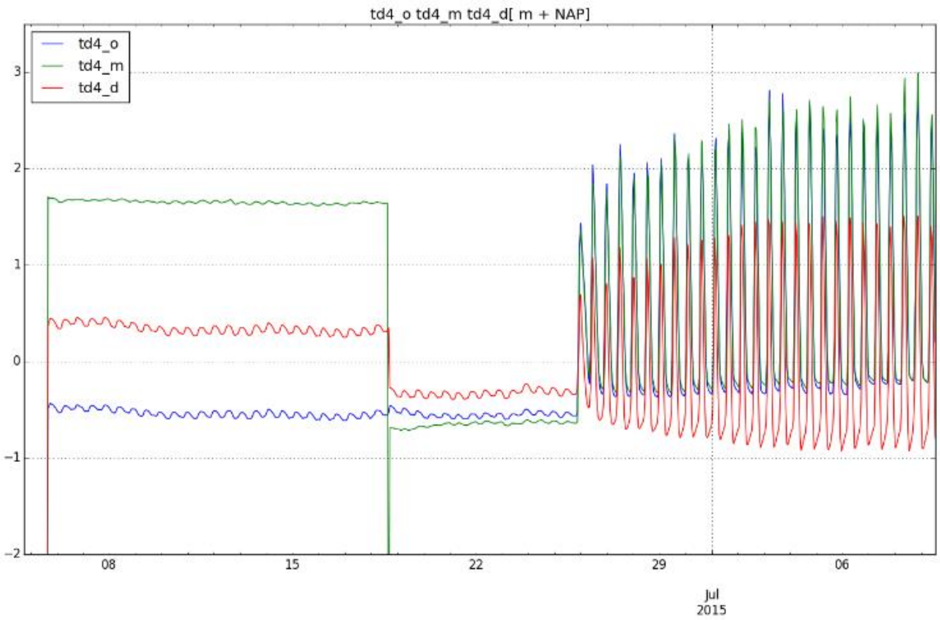


Figure 3.7. Salinity with depth measured with EM-SlimFlex

3.3.2 TIDAL PROPAGATION IN THE AQUIFER

In Figure 3.8 the measured hydraulic head of location td1 and td4 is presented for three different depths. Clearly visible is the moment of opening of the dike at 25th of June 2015 when salt water flooded the area for the first time and suddenly the hydraulic head increased as well the tidal fluctuation. Also visible is the decrease of the tidal fluctuation of the hydraulic head with depth, according to the expectations.



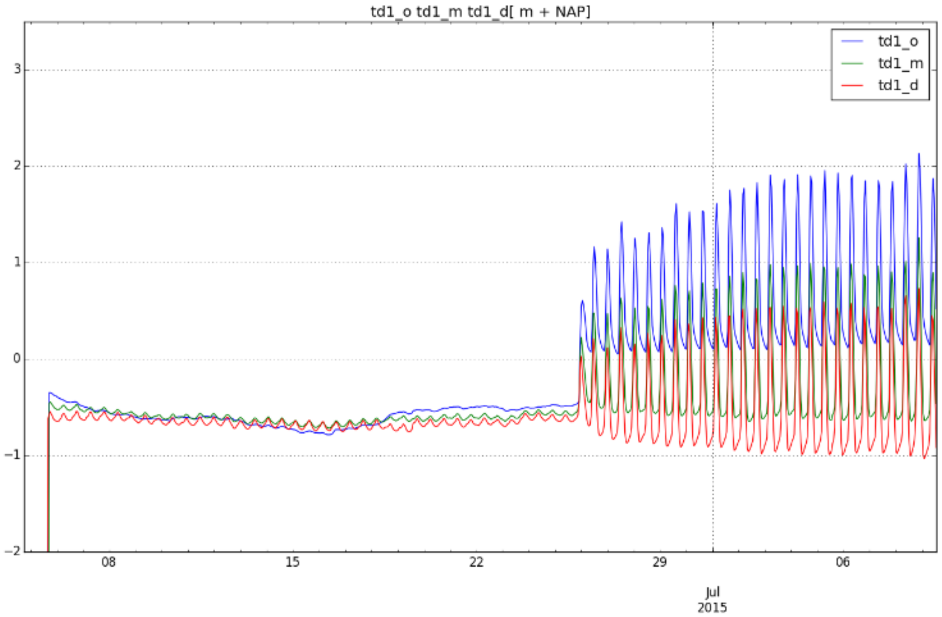
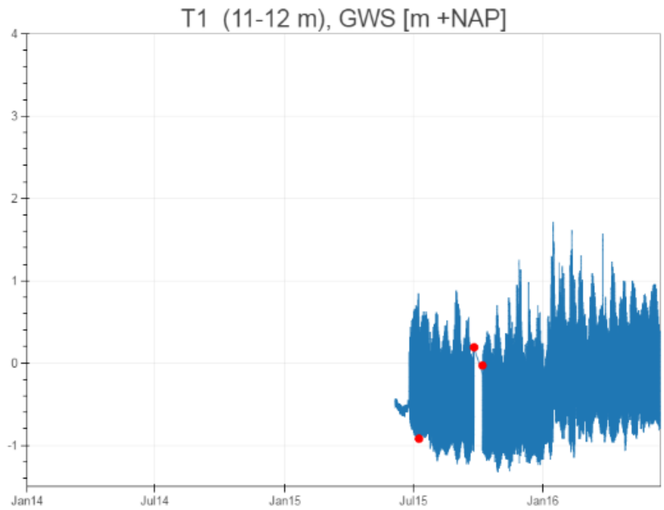


Figure 3.8. Time series of measured hydraulic heads at 3 different depths for location td1 and td4 (o= 3m, m=8m, d=12m).

Figure 3.9 shows for td1 for three different depths the time series for the entire period. The tidal fluctuations are clearly visible as well as the springtide and neap tide.

The monitoring will continue until the end of 2016 and in 2017 the monitoring data will be analyzed.



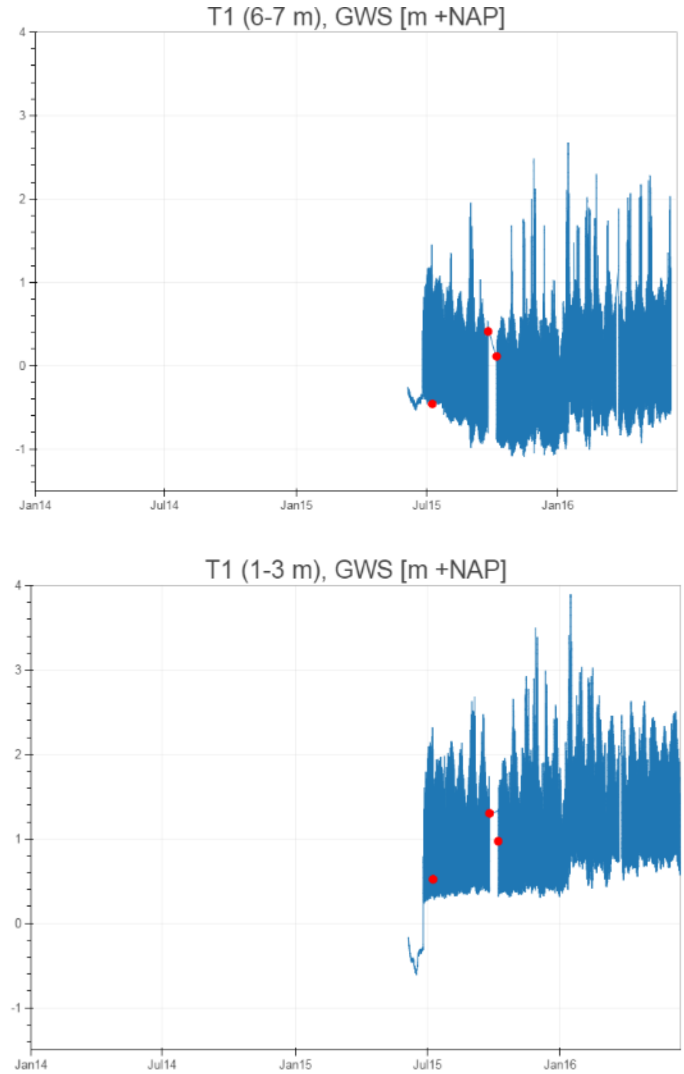


Figure 3.9. Time series of measured hydraulic heads for location td1 for the entire monitoring period.

4 VEGETATION AND SEDIMENT DEVELOPMENT

4.1 INTRODUCTION

The time it takes before vegetation will develop is a key question in many depoldering and managed realignment projects. It is often clear that in tidal area's with sufficiently high sediment concentrations in the water column, marshes will eventually develop. However, for nature goals and recreational activities in the area, it is desirable to be able to predict if this will happen on the short term (< 5 years), or if this will only be the case on the long term (> 50 year). Being able to predict the rate of development is desirable to come up with a cost effective design when a specific type of habitat is desired either from nature management perspective (e.g., in case for compensation measures or when public support depends on the type of nature that will develop). To answer this question requires obtaining an understanding of the processes that control (i.e., enable and hamper) the initial establishment and subsequent lateral expansion of pioneer species.

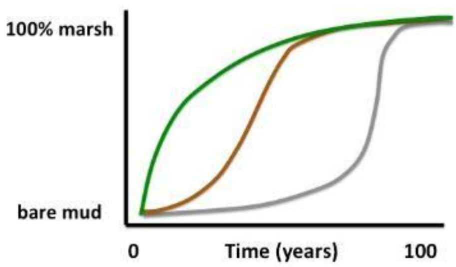


Figure 4.1. Artist impression of the development of Perkpolder (left; http://www.vnsc.eu/uploads/cache/perkpolder-hulst-1.jpg) and a schematic drawing raising the question how long it will take before this situation is realised (right).

It is well known that the initial vegetation development depends on a number of abiotic and biotic factors. For example, inundation period, and thereby the elevation, is a major factor controlling seedling survival. Recently, it was shown that short-term mixing of the sediment due to hydrodynamics (e.g. waves) is another important factor that may limit seedling survival to the higher elevations. Much less is however known about how abiotic and biotic 'sediment' properties like compaction, drainage, sediment chemistry and bioturbation may affect seedling establishment and lateral expansion. The characteristics and development of the accreting sediment may expected to be an important factor for the vegetation establishment. As schematised in Figure 4.2 differences in drainage and sediment compaction may be the driver of 2 alternative stable states, determining if seedlings will or will not establish (Figure 4.2). From the sediment development following the construction of groins by Waarde, it may be expected that "ontpoldering" areas will experience high rates of sediment accretion, but with low rates of soil compaction.

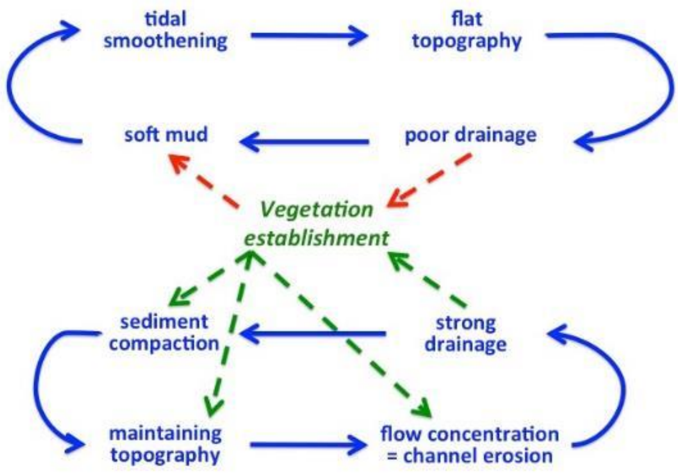


Figure 4.2. Schematisation of 2 positive feedback loops, showing how lack of drainage may cause bare tidal flats to remain bare, and drained tidal flats to rapidly develop vegetation.

4.2 RESEARCH QUESTIONS

In this study, we aim to develop generic rules on the factors that control the sediment development and the vegetation development (i.e., including both establishment and lateral expansion), by answering the following questions:

1. How do abiotic and biotic sediment properties affect seedling survival and lateral expansion?
    a. What is the effect of surface elevation, bulk-density of the sediment, and drainage?
    b. What is the effect of the soil chemistry? [2]
    c. What is the influence of bioturbation? [3]
2. How do these abiotic and biotic sediment properties (that affect vegetation establishment) change over time, and space in Perkpolder?
    a. How do these factors developed through time?
    b. Are there special patterns in the relation with distance to channel and dyke?
3. What is the role of seed availability and seed dispersal for the vegetation development? [4]
    a. Is the inflow of seeds sufficient to start the colonization process?
    b. Is there enough seed retention and sedimentation to make colonization possible in all part of Perkpolder tidal basin?
4. What is the pattern of colonisation and lateral expansion by pioneer species, along the elevational gradient?
    a. Is it possible to use the Windows of Opportunity theory to predict with parts of the area will be covered with vegetation?
    b. What is the relative importance of seed dispersal versus clonal dispersal for the colonization of the area?

4.3 RESULTS

4.3.1 PROGRESS – RESEARCH QUESTION 1

How do abiotic and biotic sediment properties affect seedling survival and lateral expansion?

[2] This research is part 'matching' from the BESAFE- project
[3] As indicated in the original quote, we focus our research on question 1a, as more is already known about 1b and 1c. Questions 1b & 1c is additional work that will only be done if there are sufficient students available to carry out the work.
[4] As indicated in the original quote, this is additional work that will only be done if there are sufficient students available to carry out the work

A mesocosm study has been carried out to quantify the effect of sediment-type (Perkpolder sediment vs. sediment collected at 2 locations in Rammegors) and drainage on seedling survival. The results show that poor drainage reduce the seedling survival at Perkpolder. The detailed results are available in a student report from Annick van der Laan (University Utrecht), which forms the base for a paper that is currently in preparation.

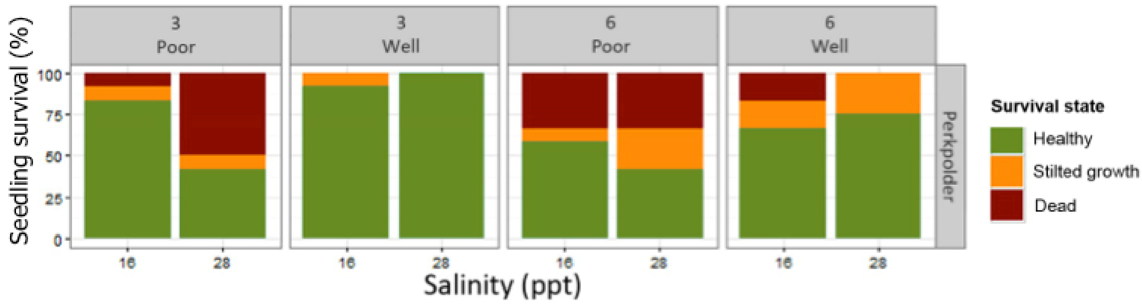


Figure 4.3. Spartina seedling survival in response to salinity (15 PPT versus 28 PPT) and drainage (poor vs. well drained) and inundation period (3 hours per tide vs. 6 hours per tide).

We have constructed mega-marsh organs for carrying out controlled field experiments (Figure 4.2 and Figure 4.3). The initiation of constructing this set-up was slightly delayed by signing of the contract. For that reason, the 1st seedlings could only be planted in august, which is a bit late in the season. Nevertheless the late start, the experiment does provide us with good insights in the seedling survival of different species along the elevational gradient and in response to soil drainage.

Figure 4.4. Drainage system in mega-marsh organ

The survival in the 1st week shows us that:

- taller plants have a better chance to survive (see 3 size classes for *Spartina*; Figure 4.4)
- less salt tolerant species (e.g., *Phragmites*) survive poorer than more salt tolerant species (e.g., *Spartina*; Figure 4.4)
- survival tends to increase with increasing elevation (e.g. *Puccinellia*; Figure 4.4) and with drainage (e.g., *Spartina*; & *Puccinellia*; Figure 4.4)

These results are however highly preliminary, and have not yet been statistically tested, and only represent the survival after 1 week. So no firm conclusions should be drawn, other than that the mega-marsh organ experiment is up and running.

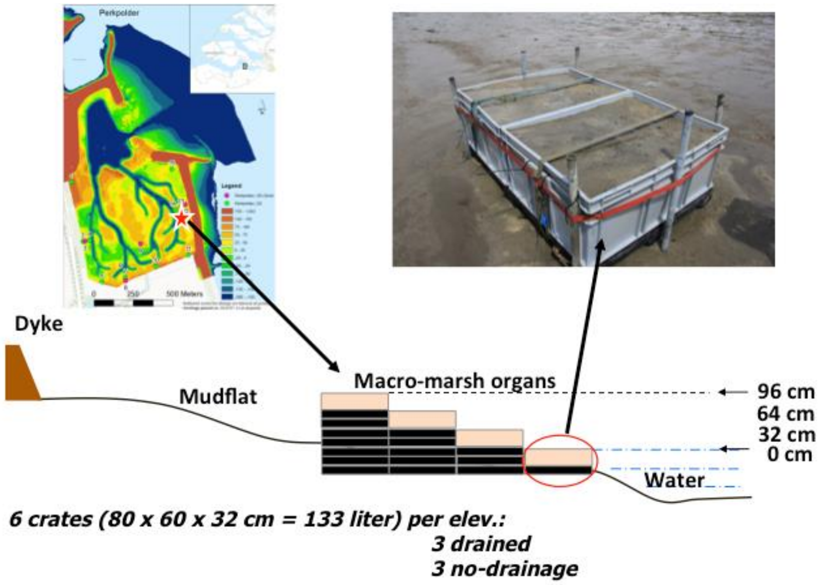


Figure 4.5. Schematic representation of the mega-marsh organ set-up, located in Perkpolder.

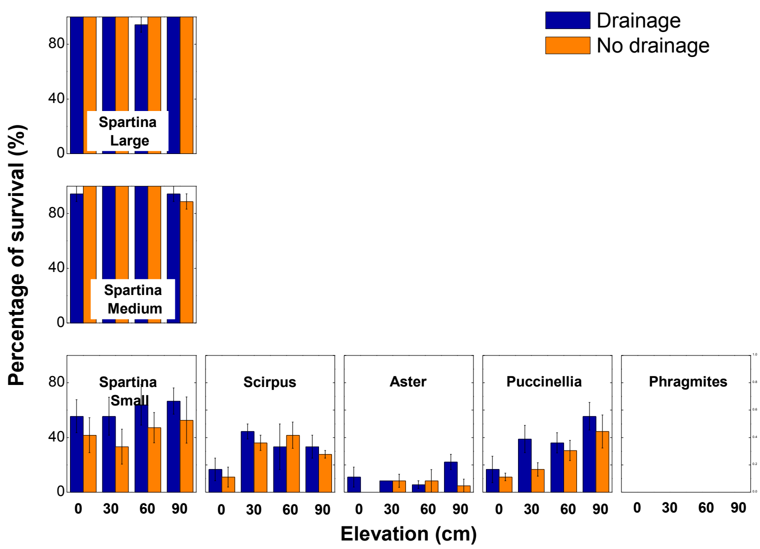


Figure 4.6. Seedling survival as observed 1 week after planting in the mega-marsh organs (preliminary observation).

4.3.2 PROGRESS – RESEARCH QUESTION 2

How do these abiotic and biotic sediment properties (that affect vegetation establishment) change over time, and how does this depend on location within Perkpolder?

There has been regular monitoring of the abiotic sediment properties at 15 locations in Perkpolder (Figure 4.7), with the timing of sampling as indicated in Table 2. The biotic properties in terms of benthic community has been sampled by Tom Ysebaert, IMARES. For the abiotic paramteres we measured elevation using a dGPS, the depth of the accumulated soft mud layer on top of the compacted soil, soil compaction using the pentrologger, and soil redox. We took sediment samples samples for grain size (top 3 cm & top 20 cm) and bulk density. Changes in sediment height have also been monitored using SED-sensors, which monitor the sediment height continuously with a 2 mm resolution (Hu et al. 2015). A student of the HZ has been measuring groundwater levels.

Some preliminary results on the abiotic sediment properties at 15 locations in Perkpolder are shown in Figure 4.8, but require further analyses before drawing conclusions.

Table 2: overview of field measurements. The samples indicated in red are still to be analysed.

Date	dGPS	SD	Diver	Grain size Top 3 cm	Grain size Core 20cm	Bulk density	Depth Mud	Penetrologger	Redox	Drone	Camera's	Seedling survival
2015/07/09	Orientation		Placed									
2015/07/21	X	Placed		X		X		X				Placement
2015/08/18				X		X						X
2015/10/27	X	Removed	Removed	X		X						X
2015/11/05	X	Replaced	Replaced	X	X	X	X	X		X		
2016/02/12	X			X	X	X	X	X	X			
2016/03/14	X			X	X	X	X	X	X			
2016/04/11	X			X	X	X	X	X	X			
2016/04/22											Placed	
2016/07/07		Removed	Removed								Check	
2016/07/11		Replaced	Replaced									

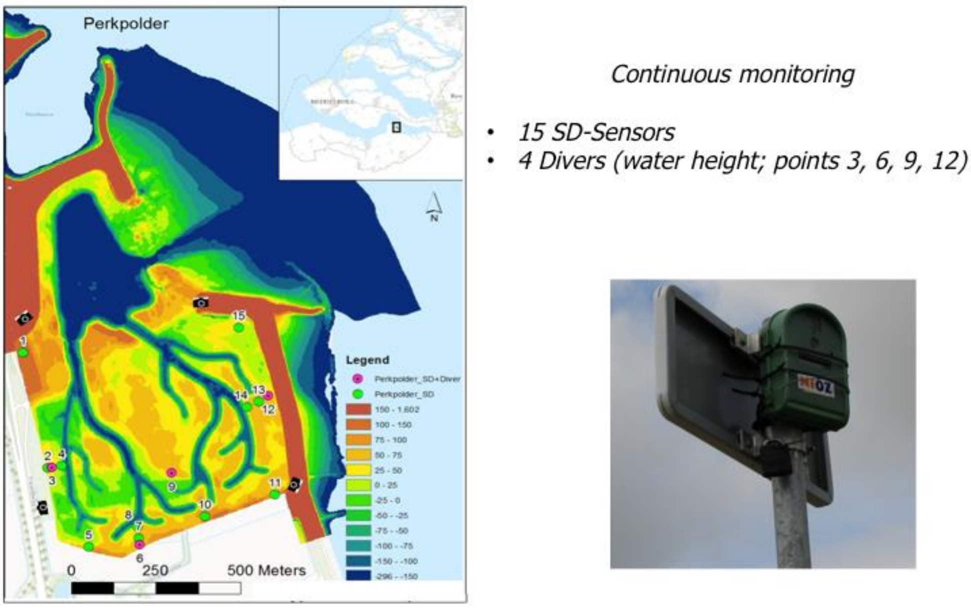


Figure 4.7. Schematic overview of the 15 locations where SED-sensors were placed and where soil properties are regularly measured (see Table 2 for timing). At locations 3, 6, 9 & 12 we also measure tidal amplitude. We measured the survival of planted Spartina and Scirpus seedlings at location 1 to 15.

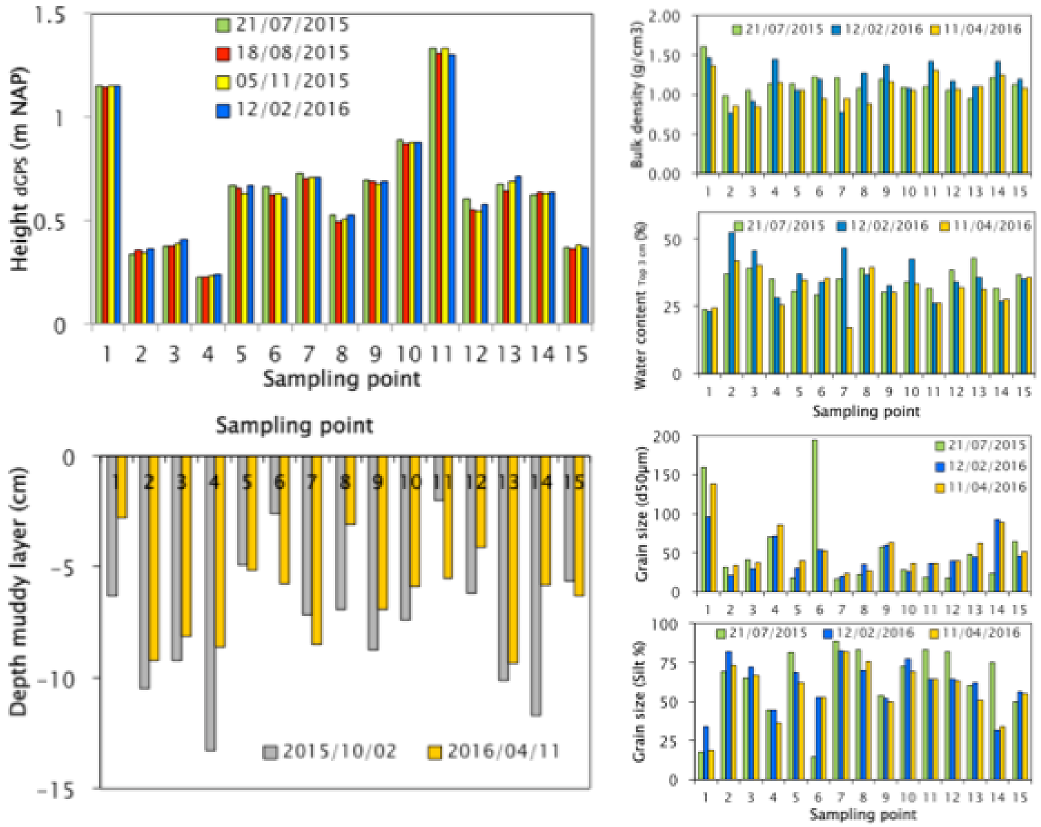


Figure 4.8. Preliminary observations on abiotic sediment properties as observed at the 15 monitoring locations (see Table 2 for timing).

4.3.3 PROGRESS – RESEARCH QUESTION 3

What is the role of seed availability and seed dispersal for the vegetation development?

As indicated in the project-offer, we would only work on this additional topic if we would attract sufficient students available to carry out the work. As this was not the case, this additional topic was not studied in the fall and winter of 2015-2016. We expect this work will be initiated in fall 2016, but the details are still to be discussed with the student.

4.3.4 PROGRESS – RESEARCH QUESTION 4

What is the pattern of colonisation and lateral expansion by pioneer species, along the elevational gradient?

We carried out a first pioneer-species survival experiment, by planting relative large *Spartina* and *Scirpus* seedlings (11 weeks old) in juli 2015 at the 15 locations where we monitor the abiotic sediment properties in Perkpolder (Figure 4.7). That is, at each of these 15 locations, we established 2 plots of $1m^2$ each: in one of the plots we planted 5 *Spartina* seedlings; in the other plot 5 *Scirpus* seedlings. We subsequently monitored their survival over time (Figure 4.9). The survival curves show that *Scirpus* seedlings died much faster than the *Spartina* seedlings (Figure 4.10). We were not able to explain spatial variability in *Spartina* seedling mortaility (data not shown).

Figure 4.9. impression of seedling survival experiment 2015-2016 in Perkpolder.

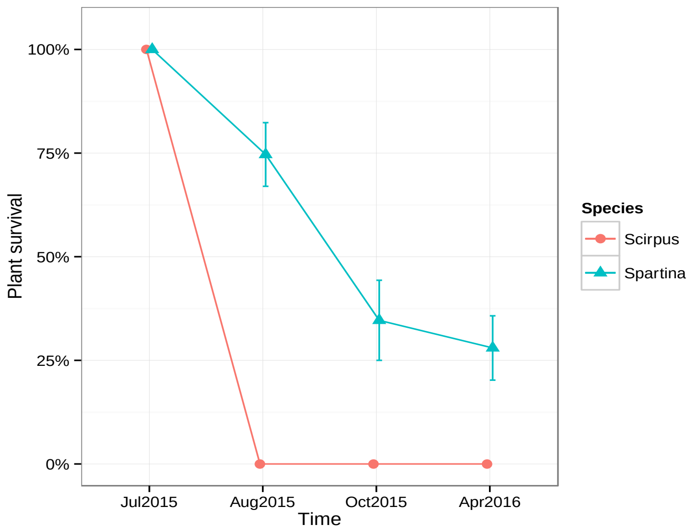


Figure 4.10. Preliminary results of seedling survival experiment 2015-2016 in Perkpolder.

At this moment, we initiated an experiment at NIOZ to study lateral expansion rates in response to sediment types.

Parameters	Species	Sediment types	Cliff heights
Numbers	3	3	5
Details	*Phragmites australis* *Scirpus maritima* *Spartina anglica*	Sand Sandy mud Mud	0, 2, 4, 8, 16 (cm)

Figure 4.11. Schematic overview of the study on lateral expansion rates

In the coming period, we intent to monitor the natural seedling establishment in Perkpolder, by marking them with a dGPS. Casual observations indicate natural seedling establishment to be low.

5 BENTHOS AND BIRD DEVELOPMENT

5.1 INTRODUCTION

Management realignment projects (or de-poldering projects) often aim at developing intertidal habitats in the newly created area. The development into non-vegetated intertidal habitat (i.e. mudflats) and eventually into vegetated intertidal habitat (i.e. salt marshes) depends on many factors related to the characteristics of the former polder and the conditions of the adjacent estuarine environment. Also biotic interactions (e.g. bioturbation) can play a role in which state the area will occur, vegetated or non-vegetated. Important environmental factors include:

- Emersion or inundation time
- Sedimentation rate
- Sediment composition
- Drainage
- Hydrodynamic conditions

Due to the relatively low-lying conditions of Perkpolder and its position in the transition zone between brackish and marine waters in the Western Scheldt, we expect that at first the area will develop into a non-vegetated intertidal zone, with low hydrodynamics and a relatively high sedimentation rate. If non-vegetated intertidal areas develop, the next question is how biodiversity will develop in these areas. Mudflats in estuaries like the Scheldt estuary are rich in benthic life. Primary producers like diatoms can form thick algal mats in these areas, which is in turn an important food source for secondary producers like benthic macroinvertebrates. Benthic macroinvertebrates in the Scheldt estuary mainly involves polychaetes, molluscs and crustaceans. In turn, these macroinvertebrates are the key food source for many fish and bird species.

5.2 RESEARCH QUESTIONS

1. How does the colonization process of benthic macrofauna develop in the de-poldered area?
    a. Does the remaining vegetation affects the colonization process?
    b. What is the influence of the elevation gradient on the colonization process?
    c. Is the colonization process depended on or related to the vertical sediment accretion rate?
    d. If in the area zones arise with standing water (no channels), what is the impact on the colonization process?
2. Are benthic communities in Perkpolder similar to benthic communities in similar ecotopes in the Western Scheldt?
3. How will vegetation establishment affect the benthic macrofauna and vice versa (interactions)?
4. How does the development of Perkpolder compare to the development of Rammegors in the Eastern Scheldt? What can be learned about the design of de-polders areas?
5. How is the Perkpolder area used by birds?
    a. Has the area a foraging function for water birds?
    b. Will the area be used by birds as a high water roost?
    c. In the future, will the area be used as a breeding area for waterfowl or marsh birds?

In this progress the early recolonization of benthic macroinvertebrates in Perkpolder is presented and related to the first development of the non-vegetated intertidal habitat. Data are presented from a sampling done in October/November 2015, five months after breaching the dike and restoring the connection with the Scheldt estuary. Also first bird counts are presented.

5.3 METHODS

5.3.1 BENTHIC SAMPLING

A total of sixteen sampling stations were chosen within the Perkpolder project area (Figure 5.1). These stations coincide with the stations that are being used by NIOZ to study the vegetation development, sediment dynamics (with SED-sensors) and soil properties. The stations are chosen as to cover the elevation gradient present but at the same time are also easy accessible.

Station	X	Y	Z
1	59 755 319	378 978 468	1,15
2	59 867 852	378 609 811	0,23
3	59 840 481	378 605 425	0,39
4	59 828 438	378 602 159	0,34
5	59 943 034	378 343 802	0,63
6	60 091 633	378 410 244	0,51
7	60 097 474	378 373 264	0,71
8	60 097 619	378 350 809	0,63
9	60 290 480	378 442 625	0,88
10	60 194 123	378 585 523	0,68
11	60 496 732	378 513 871	1,33
12	60 477 252	378 837 347	0,54
13	60 451 561	378 813 715	0,69
14	60 418 823	378 798 190	0,63
15	60 390 060	379 060 976	0,38
16	60 174 000	378 780 000	0,90

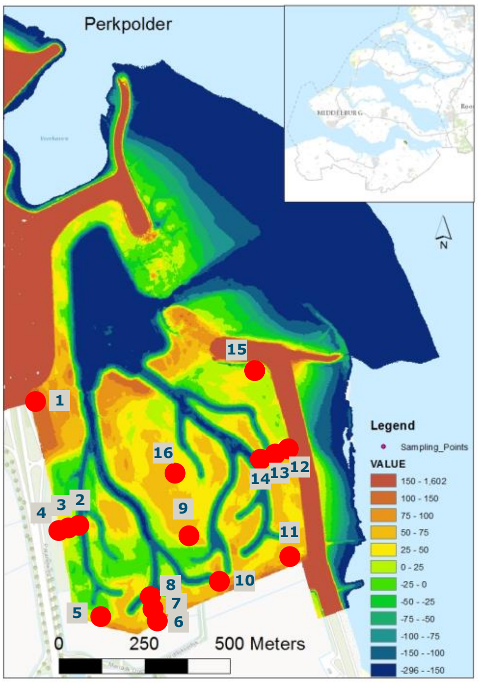


Figure 5.1. The sixteen benthic sampling points in Perkpolder. X, Y, Z coordinates of the benthic sampling stations (Z in m NAP, situation November 2015) are presented in the right table.

At each station the following parameters were collected/measured at each location (Figure 5.2):

- Benthic macrofauna: 3 cores (pooled), 10 cm ø, 10-20 cm deep, sieved over 1 mm mesh;
- Sediment composition: 1 sediment syringe, 3 cm diameter, 3 cm deep;
- Chlorophyll a content: 3 sediment syringes (pooled), 1 cm diameter, 1 cm deep;
- Coordinates (X,Y) en elevation (Z) with dGPS.

The benthic macrofauna samples were fixed with a buffered formaldehyde solution. Sediment samples were wet weighted, freeze dried, and dry weighted before being analysed for grain size with a Malvern (NIOZ). In the lab the benthic macrofauna samples were sorted out and all specimens were identified, counted and (optionally) weighted.

Figure 5.2. Benthic macrofauna sampling in the Perkpolder area, October 2015. Notice the muddy environment and the freshly deposited sediments. Some remaining of the former vegetation are still present in some parts of the area (photo top right). The photo bottom left shows benthic activity on the mud surface, with a crawling mud shrimp Corophium volutator, the most dominant species in the area. Photos: Tom Ysebaert.

5.3.2 BIRD COUNTS

To get an idea of the usage of the area by birds during low tide, observations are being made in which the area is subdivided into six subareas (Figure 5.3). During one low water three counts are being done and all species presented are counted. A distinction is being made between foraging and non-foraging birds.

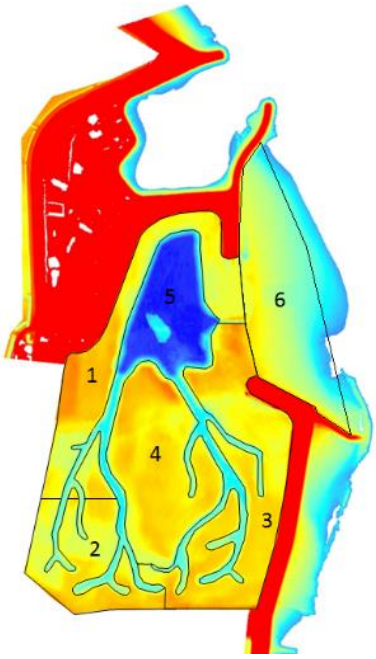


Figure 5.3. The six areas that are being counted for water birds during low tide.

5.4 RESULTS

5.4.1 ENVIRONMENTAL CONDITIONS

The elevation of the sampling stations ranged between +0,23 and +1,33 m NAP, corresponding to an emersion time of 50 – 75 %. The average median grain size was 56 ± 12 µm, ranging between 21 and 182 µm. The silt fraction was in general high, on average 59 ± 5,5 % (Figure 5.4). In terms of ecotope classification, we can consider the Perkpolder intertidal area as middle litoral ecotope (25-75% emersion), low dynamic. With respect to salinity the Perkpolder area is situated at the transition zone between brackish and salt water.

The measured sedimentation rate at the 16 stations in November 2015 varied between 2,0 and 13,3 cm.

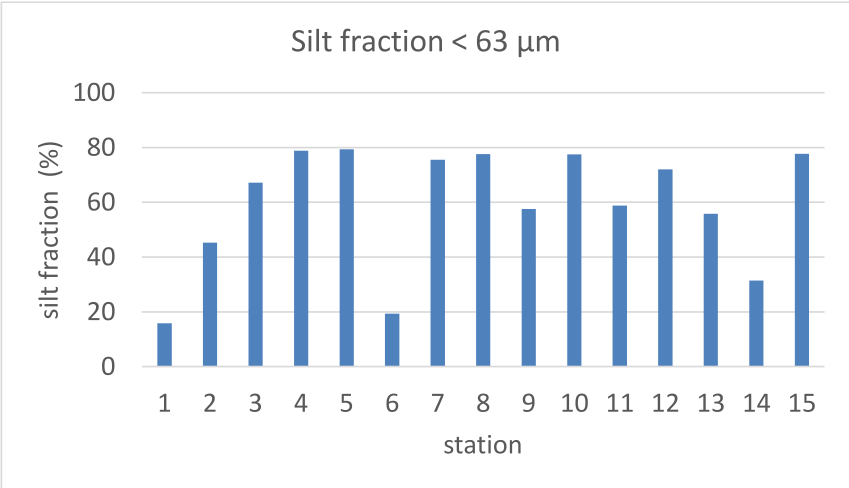


Figure 5.4. Silt fraction measured at each sampling station (situation November 2015).

5.4.2 BENTHIC MACROFAUNA

In total, 20 taxa were determined in the 16 samples, 10 taxa belonging to the Annelida, 5 to Arthropoda and, 4 to Mollusca, and 1 to Nemertea. On average, 10,1 ± 0,8 taxa per station were observed. The most common species was the mud shrimp *Corophium volutator*, observed in all 16 stations (Table 6). Other common species included the polychaetes *Polydora cornuta* and *Pygospio elegans*, the bivalve *Macoma balthica* and Nemertea and Oligochaeta. The total average density was 14990 ± 2890 ind.m^{-2}, with *Corophium volutator* (13083 ± 2113 ind.m^{-2}) by far the most dominant species in terms of density (Table 6).

Table 6. Observed species/taxon in Perkpolder with their occurrence (% of the 16 samples observed) and the average density of each species/taxon observed.

Species/taxon	Occurrence %	Density ± SE (ind.m-2)
Corophium volutator	100	13083 ± 2113
Polydora cornuta	94	584 ± 134
NEMERTEA	88	85 ± 15
OLIGOCHAETA	88	586 ± 259
Macoma balthica	81	130 ± 31
Pygospio elegans	81	127 ± 41
Eteone longa	56	45 ± 12
Aphelochaeta sp.	50	34 ± 12
Alitta succinea	50	80 ± 33
Crangon crangon	44	29 ± 11

Hypereteone foliosa	44	37 ± 12
Streblospio shrubsolii	44	34 ± 13
Heteromastus filiformis	38	29 ± 13
Peringia ulvae	38	16 ± 5
Chironomus salinarius	31	19 ± 8
Cyathura carinata	31	40 ± 18
NUDIBRANCHIA	19	8 ± 4
INSECTA	13	13 ± 11
Hediste diversicolor	13	5 ± 4
Scrobicularia plana	6	5 ± 5

A relation was observed between the amount of sedimentation and the total density of the benthic macrofauna, with higher densities observed at higher sedimentation rates (Figure 5.5).

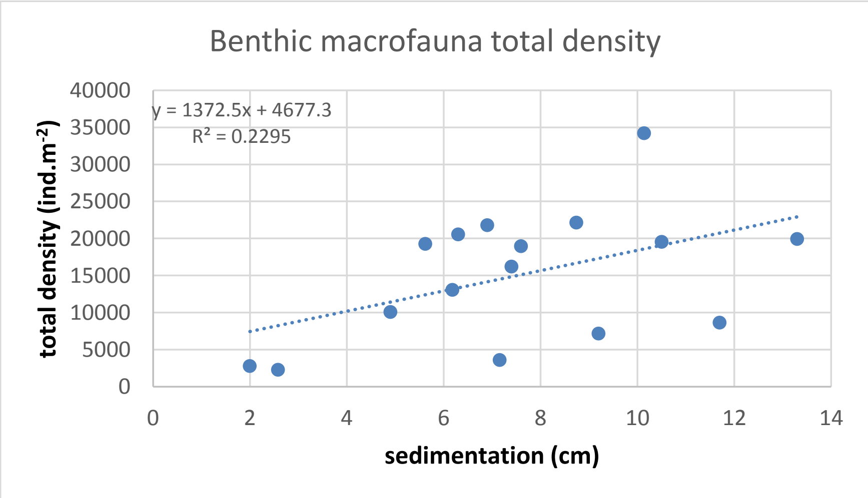


Figure 5.5. Relation between the sedimentation and the total density of the benthic macrofauna observed at each station.

5.4.3 BIRD COUNTS

Birds were counted in March 2016. The following species were observed:

- Common shellduck
- Mallard
- Wigeon
- Eurasian curlew
- Oystercatcher
- Redshank
- Little Egret
- Black-headed gull
- European herring gull
- Great crested grebe
- Grear cormorant

Waders and the common Shellduck typically forage on the tidal flat. Ducks like Mallard and Wigeon mainly occur in the creeks or resting along the creek banks. Figure 5.6 shows the distribution for two species, the common Shellduck and the Eurasian Curlew.

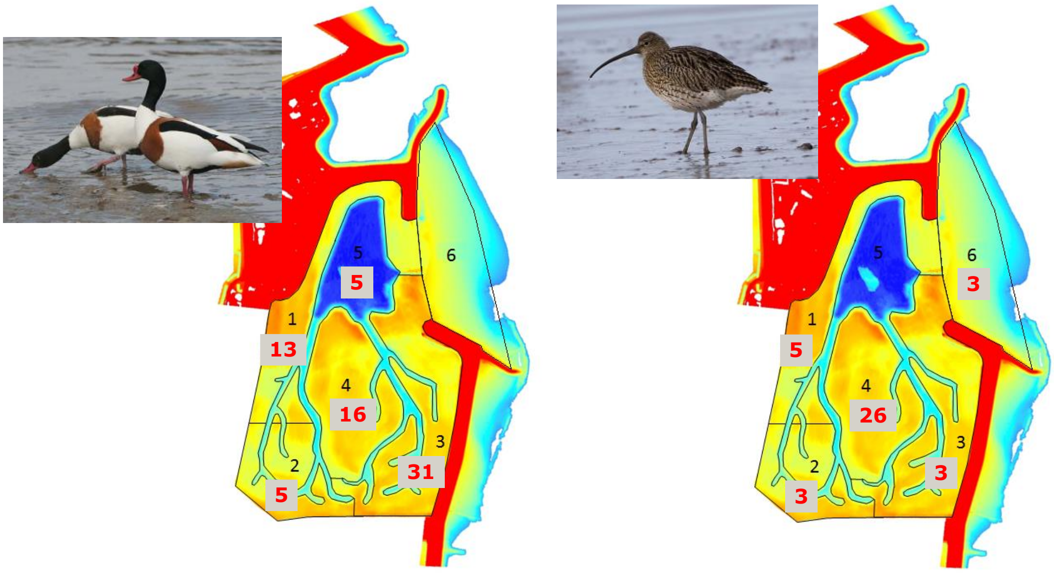


Figure 5.6. Distribution and numbers observed at low tide for Common shellduck (left) and Eurasian curlew (right) in Perkpolder (March 2016).

5.5 CONCLUSIONS

A fast recovery of the benthic macrofauna was observed in Perkpolder. Already five to six months after breaching the dike, 20 benthic taxa were observed in the area, based on a sampling of 16 stations. Also the densities reach high values, especially for the mud shrimp *Corophium volutator*, a common species for this part of the Western Scheldt This fast recovery is most likely due to the fast sedimentation of fine sediments into the Perkpolder area, forming a fresh new layer of estuarine sediment in which the benthic macrofauna can settle.

As with the colonization of the benthic macrofauna into the Perkpolder area, also estuarine birds returned. Waders like Eurasian curlew and Oystercatcher, and the Common shellduck are foraging during low tide in the intertidal zone, while the creeks are used by ducks such as Mallard and Wigeon. Little egrets look for small fish and crustaceans in the creeks.

Continuous monitoring the coming years will show how the area develop further.

6 EDUCATION

6.1 RESEARCH PROJECTS AND FINAL THESIS

In the table below the students are listed who were involved in the research at Perkpolder. The students who worked on their final thesis got the opportunity to do fieldwork and present their work at a project meeting (first progress meeting June 23, 2016, at Rijkswaterstaat, Middelburg).

study year sem. nr.	title report	names	nr. of students	study year	type of assignment	Host organisation (students institution)	Supervisors
2015-2016 semester 1	The tidal basin of Perkpolder - Monitoring the development of the inlet and an investigation of the basin characteristics	Marjolein van Vliet	1	3	Minor research	HZ (HZ)	Matthijs Boersema
2015-2016 semester 2	Height developement in tidal areas, predicting the surface level accreation for a de-embanked basin, Perkpolder Scheldt Estuary	Mireille Martens	1	4	BSc. Thesis	HZ (HZ)	Matthijs Boersema
2015-2016 semester 2	Groundwater in the new intertidal area Perkpolder	Jens Schouwenaars	1	4	BSc. Thesis	HZ (HZ)	Carla Pesch, Tjeerd Bouma and Perry de Louw
2015-2016 semester 2	Numerical modelling of morphological developement in a managed realignment project. A case study of the Perkpolder project, Western Scheldt, The Netherlands	Xinyue Zhao	1	5	MSc. Thesis	Deltares (University Twente)	Jebbe van der Werf
2016-2017 semester 1	Morphological development of Perkpolder tidal basin, (in progress)	Rien Krielen, Yves Bonné, Lars van Duren, Owen de Vlieger, Ivory Mast, Ymke Tmmerman, Loes de Jong, Eva den Boer, Marie Wahl, Mathijs Dubbeldam, Mikayla Muizer, Beatriz Benaduce Oritz	12	2	Research assignment (NLD: Lectoren opdracht)	HZ (HZ)	Edwin Paree en Matthijs Boersema
2016-2017 semester 1	Salt marsh development in tidal restoration projects (in progress)	Lasse Gillisen	1	3	Minor research	NIOZ (HZ)	Carla Pesch, Tjeerd Bouma

Mireille Martens (BSc. student HZ) busy with field measurements (April 2016)

6.2 EXCURSIONS FOR STUDENTS

On March 16, 2016 the HZ organized a recruitment event for new students. In total 40 potentials students had a program during the day. The first part of the day consist of presentations from partners (Yvo Provoost, Anton van Berchum from Rijkswaterstaat, and Matthijs Boersema from HZ). The second part of the day, the students went into the field looking at the development in the Perkpolder tidal basin, and exploring the salt water discharge facility (Perry de Louw, Deltares).

7 EXPOSURE

7.1 CONFERENCES

Parts of this project were presented during the NCK days 2016 and at the ECSA Local Meeting 2016 (Estuarine Restoration: from theory to practice and back”) in Antwerp. See the poster presentation below. An abstract of the research was printed in a ‘book of abstract’.

DELTA ACADEMY

Deltares Enabling Delta Life

NIOZ

Morphological changes at Perkpolder tidal basin

A comparison of basin hypsometry and potential sediment import

M.E. van Vliet[1], M.P. Boersema[1*], J.J. van der Werf[2], T.J. Bouma[1,3] & J. Stronkhorst[1,2]

Introduction

Since 2003 the ferry between Kruiningen-Perkpolder is out of service. This was a starting point for regional development initiatives at Perkpolder (figure 1), combining housing, recreation and the development of a salt water natural area. For the development of this area, Rijkswaterstaat made an opening in the original dyke of 400 m (June 2015), and constructed a dyke around this new tidal basin with a surface of 75 ha (figure 2).

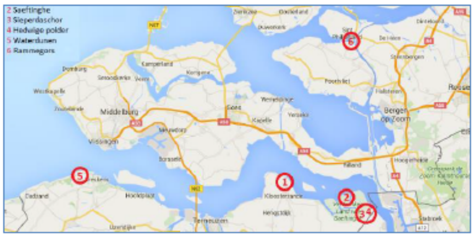


Figure 1 Locations of studied tidal restoration basins (1, 4, 5 & 6) and reference areas (2 & 3)

Fgure 2 Map of Perkpolder [Buro Lubbers]

In this study the morphological stage of the Perkpolder basin is investigated and compared with other basins which are selected for tidal restoration by the government. Furthermore the Perkpolder basin is compared with two sediment filled or mature basins (Land van Saeftinghe and Sieperdaschor), to get a better understanding of the potential sediment import into the basin.

The cross-sectional area of the inlet (dyke opening) is monitored as well with multi-beam, this will provide information about the adaptation time of the cross-section.

Figure 3 Tidal basin at Perkpolder [Edwin Paree], november 2015

This study is part of a three year monitoring and research program focusing on the morphological changes, vegetation development, groundwater influences, development of benthic species, and related bird usage of this man-made basin. The program is executed by HZ, Deltares, IMARES, NIOZ, and Rijkswaterstaat, partners of the Centre of Expertise Delta Technology.

Results

The figures below show the basin hypsometry of six basins, ***a*** is the area below a given contour line and ***A*** is the total basin area.

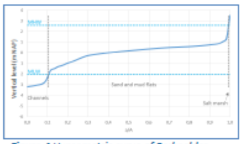


Figure 4 Hypsometric curve of Perkpolder

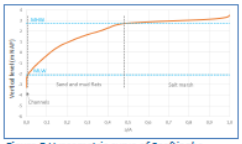


Figure 5 Hypsometric curve of Saeftinghe

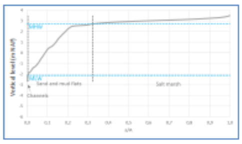


Figure 6 Hypsometric curve of Sieperdaschor

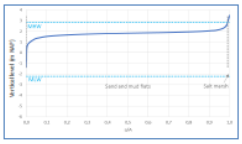


Figure 7 Hypsomeric curve of Hedwigepolder

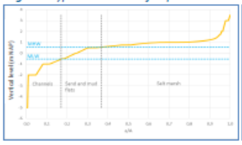


Figure 8 Hypsometric curve of Waterdunen

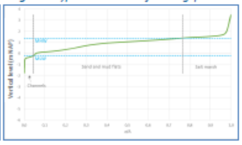
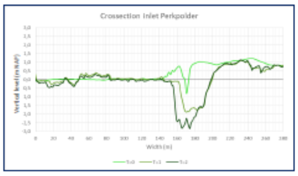


Figure 9 Hypsometric curve of Rammegors

Figure 10 Cross-sections of the inlet, at T0 (30/07/2015), T1 (29/10/2015) and T3 (08/01/2016)



Conclusion

Perkpolder is a relative low lying basin, this is due to the early (13th century) embankment of the polder. The tidal basin is at this point in time suitable for development of mudflats (figure 3). To reach the final stage of a sediment filled basin, the average basin elevation should rise approximately 2.8 m (with Saeftinghe as a reference), and import around 1.8 x10^6 m^3 of sediment. If sediment availability is not a limiting factor, the hypsometric curve of Perkpolder will show the most significant changes through time, also because the artificial imposed tempered tide in Waterdunen (figure 9) and Rammegors (figure 10) result in less sediment storage capacity. The tidal inlet show a strong changes in cross-sectional area, more data is needed to see if the equilibrium profile is reached.

This project gives a unique opportunity to monitor the development of a man-made basin and will provide Rijkswaterstaat knowledge in relation to future tidal restoration projects.

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7.2 NEWSLETTERS

An article in the newsletter of de VNSC was focusing on this research project.

Scheldetopics oktober 2016

Perkpolder: nieuw buitendijks natuurgebied vol leven

In de zomer van 2015 werd een bres gemaakt in de zeedijk van Perkpolder en is de omliggende dijk versterkt. Sindsdien stroomt de Westerschelde tweemaal per dag het voormalige poldergebied binnen. Zo ontstaat er een gloednieuw buitendijks natuurgebied...

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