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RAMMEGORS TIDAL RESTORATION

FINAL REPORT

CENTRE OF EXPERTISE DELTA TECHNOLOGY
APRIL 2019

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MANAGEMENT SAMENVATTING

Inleiding

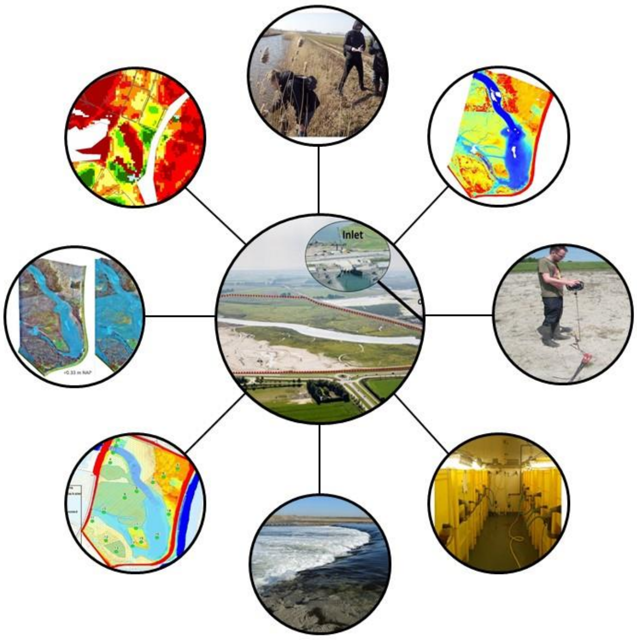
De aanleg van dijken, dammen en andere barrières ter bescherming van de bevolking en hulpbronnen in de laaggelegen zuidwestelijke delta van Nederland heeft geleid tot een transformatie van de Oosterschelde. Van een open estuarium is de Oosterschelde veranderd in een zoutwaterbekken achter een halfopen stormvloedkering. Studies hebben sindsdien een sterke afname van de getijdengebieden aangetoond, voornamelijk als gevolg van een onbalans tussen de bestaande bekkenmorfologie en het getemperde getij. Deze onbalans staat bekend als de 'zandhonger'. Rijkswaterstaat gebruikt twee manieren om de gevolgen van de zandhonger in de Oosterschelde te ondervangen: i) de bestaande slikken en schorren beschermen, en ii) nieuwe intergetijdengebieden creëren. Het Rammegors project is een voorbeeld van de tweede benadering.

Rijkswaterstaat Zee en Delta is verantwoordelijk voor de realisatie van het project getijherstel Rammegors. Andere partners in het Rammegors consortium zijn de HZ University of Applied Sciences, Koninklijk Nederlands Instituut voor onderzoek der Zee (NIOZ), Wageningen Marine Research (WMR) en Deltares. Het Rammegors consortium streeft een aantal doelen na met dit project:

1. Het vergroten van de kennis over het abiotische (grondwater) en biotische (vegetatie ontwikkeling en benthische gemeenschappen) factoren die de korte-termijn (0-4 jaar) ontwikkelingen na het herstel van het getij sturen;

2. Training van jonge professionals door het verbeteren van de kennis van docenten die worden ondersteund door state-of-the-art case studies;

3. Bevordering van kenniscirculatie in het veld door het bundelen van alle kennis binnen de Delta Expertise-site.



Visuele samenvatting van de uitvoering van de monitoring van het Rammegors gebied. De belangrijkste aspecten van de monitoring zijn de ecologische ontwikkelingen, het grondwatersysteem, en onderwijsversterking en kennisverspreiding.

Grondwater

De grondwatermonitoring in Rammegors omvat grondwater- en stijghoogtemetingen in en buiten het getijdegebied, EM-Slimflex-metingen in peilbuizen, metingen van de zoet-zout verdeling met elektromagnetische metingen vanuit een helikopter, en metingen van de onverzadigde zone. De afsluiting van Rammegors van de Oosterschelde gedurende een periode van 43 jaar heeft gezorgd voor een verzoeting van Rammegors en van een kleine gebied in de aangrenzende polders. Een zoetwaterlens met een dikte van ongeveer 10 tot 20 meter heeft zich ontwikkeld onder Rammegors, die zich honderden meters buiten Rammegors uitstrekt. De lens heeft een dikte van ongeveer 3 tot 6 m in de Prins Hendrikpolder en 7 tot 10 m in de Van Haaftenpolder. De zoetwaterlens wordt door de boeren niet gebruikt voor irrigatie. De verwachting is dat verzilting van de zoetwatervoorraad door de opening van Rammegors zal plaatsvinden in dezelfde tijdspanne als de eerdere verzoeting of zelfs sneller.

Uit de resultaten van de grondwatermonitoring is geen effect te zien van het herstel van Rammegors op de stijghoogte en het grondwaterpeil. Ook de SlimFlex-metingen in het landbouwgebied laten (nog) geen effecten op de zoetwaterlens zien. Volgens de grondwatermodelsimulaties kunnen er echter wel enkele effecten van de opening van Rammegors voor de omliggende Zuid- en Noord-polders worden verwacht. Zoute kwel en stijghoogte kunnen toenemen voor een zone 100 - 300 m van Rammegors, met de grootste effecten dichtbij Rammegors. Significante verhogingen van grondwaterstanden in de orde van 10-20 cm worden alleen verwacht voor een zone 50-100 m van Rammegors. Het model geeft echter aan dat het grootste deel van Rammegors binnen 10 jaar zal verzilten. De SlimFlex-metingen in het getijdegebied laten ook al een sterke verzilting van de bovenste 5 tot 10 meter zien. Het zoute Oosterschelde water, dat dagelijks tweemaal Rammegors instroomt, infiltreert de bodem in. Toch laat het model ook zien dat er zelfs na 50 jaar nog steeds kleine zoetwaterbellen aanwezig zijn onder gebieden die nooit (of sporadisch) onder water staan. Op basis van de monitoring en de modellering wordt verwacht dat de verzilting zal doorgaan voor zowel het getijdengebied als de omliggende polders. Het wordt daarom aanbevolen om de hydrologische monitoring voor de komende 5 tot 10 jaar voort te zetten.

Bodemdieren

Een snelle kolonisatie van de benthische macrofauna is waargenomen in Rammegors. De gemeenschappen verschillen aanzienlijk van voorjaar tot najaar 2017, maar veranderden minder na het najaar van 2017. In het voorjaar van 2017 bereikten soortendichtheden hoge waarden, vooral voor de brakke moddergarnaal *Manocorophium insidiosum* en muggenlarven *Chironomidae*. In de herfst van 2017 verdwenen deze brakke soorten bijna uit het gebied. Hun aanwezigheid in de herfst, zelfs in kleine aantallen, evenals de waarneming van de brakke kokkel *Cerastoderma glaucum* geven aan dat, bijna een jaar na het getijherstel, delen van Rammegors nog steeds onder invloed van brak water staan. In het voorjaar vond er een verdere afname plaats van deze brakke soort die de overgang naar een mariene omgeving aangeeft. De ontwikkeling van benthische macrofauna vertoont een relatie met de hoogte. Een optimum in de soortenrijkdom, dichtheid en biomassa werd gevonden rond 0,4 m NAP. Soortenrijkdom en dichtheid nemen significant af met een toename in sediment compactheid (bulkdichtheid). Compactere bodems lijken minder soorten in lagere dichtheden te bevatten. Verder vindt er een toename in soortenrijkdom, soortendichtheid en biomassa plaats met toenemende afstand van het inlaatmiddel.

Vegetatie

De vegetatiemonitoring richt zich op typerende vegetatiegemeenschappen, zaadbeperking, bodemchemie en bodemdrainage. De resultaten laten zien dat zoetwatervegetatie zich terugtrekt en wordt vervangen door slikvegetatie. Er is een aanzienlijke afsterving van zoetwatervegetatie zoals riet en gras in de overstroomde gebieden. De vegetatie wordt vervangen door zoutwatersoorten zoals *Salicornia* en *Aster*. Verder wordt geconcludeerd dat er geen zaadbeperking is. Drijvende netten en zaadvallen tonen een enorme beschikbaarheid aan vitale zaden van *Aster*, *Salicornia* en riet. Bovendien verandert de verdichting van de volgroeide bodem in de laatste drie monitoringsjaren niet als gevolg van het nieuwe overstromingsregime. Dood organisch materiaal had geen merkbare invloed op de redox- en sulfideconcentratie in het poriewater van de top 10 cm bodemsediment. Dit verklaart waarom het afsterven van zoetwatervegetatie op geen enkele manier de vestiging van kweldervegetatie heeft beïnvloed. Het mesocosm experiment laat zien dat slechte bodemdrainage een negatief effect heeft op de overleving van de kiemplant. De belangrijkste parameters voor getijdenherstelprojecten die uit het zaailing overlevingsexperiment komen zijn de hoogte van het bed en de bijbehorende inundatietijd. Voor zaadoverleving lijkt het overstromingstijdoptimum tussen 5 en 50% te liggen.

Onderwijsversterking en kennisverspreiding

Studenten zijn actief betrokken bij het Rammegors-project om de volgende generatie waterprofessionals te trainen. Meerdere excursies met studenten zijn georganiseerd, bijvoorbeeld om de EM-Slim Flex-metingen te demonstreren. Studenten namen ook deel door veldcampagnes uit te voeren en door onderzoek te doen via BSc- en MSc-scriptieprojecten (zie hoofdstuk 5 voor meer informatie over de betrokkenheid van studenten). De kennis die is verkregen als onderdeel van het project is ingebed in meerdere onderwijsmodules (bijvoorbeeld Eco-Engineering module voor tweedejaarsstudenten) aan de HZ University of Applied Sciences. Poster en mondelinge presentaties op symposia (bijvoorbeeld Scheldesymposium) en conferenties hebben gezorgd voor verspreiding van de projectbevindingen naar het werkveld. Om de kenniscirculatie in het veld verder te bevorderen worden de projectresultaten gerapporteerd op de Delta Expertise-site en verspreid via de nieuwsbrief Zuidwestelijke Delta in 2019.

Ten slotte

Verwacht wordt dat de kennisontwikkeling over het getijherstel binnen Rammegors zeer waardevol zal zijn voor lopende en toekomstige getijherstel projecten, zoals de Hedwige-Prosper polder. In het bijzonder biedt de Rammegors monitoring duidelijke tijdspaden voor grondwater- en morfodynamische aanpassing en het herstel van vegetatie en benthische gemeenschappen als reactie op de overgang van een zoet naar een zoutwateromgeving. Het consortium heeft de intentie om de monitoring in Rammegors voort te zetten met als doel de middellange termijn (4-10 jaar) effecten van getijherstel op abiotische en biotische factoren beter te begrijpen.

EXECUTIVE SUMMARY

The construction of dykes, dams and barriers to protect the human population and resources in the low-lying Southwestern delta of the Netherlands has led to a transformation of the Eastern Scheldt. Once an open estuary, the Eastern Scheldt was transformed into a saltwater basin behind a semi-open storm surge barrier. Studies have shown a strong decrease of the intertidal areas, primarily due to an imbalance between the existing basin morphology and the tempered tide. This imbalance is referred to as the 'sand deficit problem.' Rijkswaterstaat uses two approaches to overcome the sand deficit issue: i) protecting the existing marshes, and ii) creating new intertidal areas. The Rammegors project is an example of the latter approach.

Rijkswaterstaat Zee en Delta is responsible for the realization of the *Tidal recovery Rammegors* project. Other partners in the Centre of Expertise Delta Technology consortium are HZ University of Applied Sciences, Royal Netherlands Institute for Marine Research (NIOZ), Wageningen Marine Research (WMR) and Deltares. The Rammegors consortium is interested in pursuing a number of goals with this project:

1. Increasing the body of knowledge on the abiotic (i.e. groundwater) and biotic (i.e. vegetation establishment, benthic communities) factors controlling the short-term (0-4 years) developments after tidal recovery;
2. Training of young professionals by improving the knowledge of teachers to be supported by state-of-the-art case studies;
3. Promoting knowledge circulation within the field by combining all the knowledge within the Delta Expertise site.

The groundwater monitoring in Rammegors included EM-Slimflex measurements, FRESHEM numerical modelling and vadose zone measurements. The isolation of Rammegors from the Eastern Scheldt for a period of 43 years caused a freshening of Rammegors and small zone in the adjacent polder areas. A freshwater lens of about 10 to 20 meter thickness has developed below Rammegors, which extents for several hundreds of meters outside Rammegors. The lens has a thickness of about 3 to 6 m in the Prins Hendrikpolder and 7 to 10 m in the Haaftenpolder. The freshwater lens is not used by the farmers for irrigation. It is expected that salinization of the freshwater stock by the opening of Rammegors will take place in the same time span or even faster.

From the groundwater monitoring results, no effect of the restoration of Rammegors on the hydraulic head and phreatic groundwater level was visible. According to the groundwater model simulations, some effects of the opening of Rammegors for the surrounding Southern and Northern polders may be expected. Saline seepage and hydraulic heads may increase for a zone 100-300 m from Rammegors, with largest effects close to Rammegors. Significant increases of phreatic groundwater levels of 10-20 cm are only expected for a zone 50-100 from Rammegors. The model, however, indicates that the largest part of Rammegors will be salinized within 10 years. Yet, the model also shows that even after 50 years there will

still be small freshwater patches present below areas that are never (or sporadically) inundated. Based on the monitoring and the modeling efforts, it is expected that salinization will continue for both the tidal area and the surrounding polders. It is therefore recommended to continue the hydrological monitoring for the coming 5 to 10 years.

A fast colonization of the benthic macrofauna was observed in Rammegors. The communities significantly differed between spring and autumn 2017, but did not change after autumn 2017. In spring, densities reached high values, especially for the brackish mud shrimp *Manocorophium insidiosum* and mosquito larvae *Chironomidae*. In autumn, these brackish species almost disappeared from the area. Their presence in autumn, even in low numbers, as well as the observation of the brackish cockle *Cerastoderma glaucum* indicate that, almost a year after the tidal restoration, parts of Rammegors are still under influence of brackish water. In spring a further decline occurred among the brackish species indicating the transition to a marine environment. Benthic macrofauna development shows a relation with elevation. An optimum of species richness was found around 0.4 m NAP with lower values at both lower and higher elevations.

The vegetation monitoring focused typifying vegetation communities, seed limitation, soil chemistry and drainage. The results show that fresh water vegetation is retreating and being replaced by the intertidal vegetation. There is a substantial die-off of fresh-water vegetation such as reed and grass in the inundated areas. The vegetation is replaced by salt-water species as Salicornia and Aster. Furthermore, it is concluded that There is no seed limitation. Floating nets and seed traps show a huge availability in vital seeds of Aster, Salicornia and Reed. Furthermore, the compaction of the mature soil did not change in the last three monitoring years due to the new inundation regime. Dead organic material had no noticeable influence on the redox and sulfide concentration in the pore water of the top 10 cm in sediment. Hence, the die off of the fresh-water vegetation probability did not impact the establishment of salt-marsh vegetation in any way. The mesocosm experiment shows that poor drainage has a negative effect on seedling survival. The most important parameter for tidal recovery projects coming out of the seedling survival experiment is the bed elevation and its corresponding inundation time. For seed survival, the inundation time optimum seems to be between 50 and 95% dry time.

Students were actively involved in the Rammegors project to train the next generation of water professionals. Multiple excursions with students were organized to, for example, demonstrate the EM-Slim Flex measurements. Students also participated by conducting field campaigns as well as by doing research through multiple BSc and MSc thesis projects (see Section 5 for details on the student involvement). The knowledge obtained as part of the project is embedded in multiple teaching modules (e.g. Eco-Engineering) at the HZ University of Applied Sciences. Poster and oral presentations at symposia (e.g. Scheldesymposium) and conferences has provided dissemination of the project findings to the working field. To further promote knowledge circulation within the field, the project findings will be reported on the Delta Expertise site and synthesized in Zuidwestelijke Delta newsletter in 2019.

It is anticipated that the knowledge development on the tidal recovery within Rammegors will be highly valuable for ongoing and future tidal restoration projects, such as the Hedwige Prosper managed realignment. Specifically, the Rammegors monitoring provides clear timeframes for groundwater and morphodynamic adjustment and the recovery of vegetation and benthic communities in response to the transition from a fresh to a saltwater environment. It is important to note that the monitoring in Rammegors is continued with the aim to better understand the medium-term (4-10 years) effects of tidal recovery on abiotic and biotic factors.

1. INTRODUCTION

1.1 BACKGROUND

The building of sea dykes, dams and barriers intended to protect the human population in the low-lying Southwestern delta of the Netherlands, has led to a transformation of the Eastern Scheldt. This area, once an open estuary, changed into a saltwater basin behind a semi-open storm surge barrier. Studies in the last 25 years show a strong decrease of the intertidal areas, due to an imbalance between the existing basin morphology and the tempered tide, also known as the 'sand deficit problem.' The size of the intertidal area decreases by 50 ha per year on average.

Salt marches in the Eastern Scheldt are at risk due to wave erosion in combination with the lack of sufficient sediment in the water column to support vertical accretion. This comes as a result of sand deficit in the Eastern Scheldt. Rijkswaterstaat pursues two approaches in order to support the area with salt marches: 1) protecting the existing marches, and 2) creating new intertidal areas. The Rammegors project is an example of the latter approach.

Around 40 years ago the area of the Rammegors (142 ha) was still connected with the Eastern Scheldt (Figure 1). The area was part of a dynamic tidal system consisting of deep channels, tidal flats and salt marshes. The construction of the *Schelde-Rijndijk* and the *Krabbenkreekdam* marked the end of this tidal system and the Rammegors turned into a brackish- and freshwater natural area.

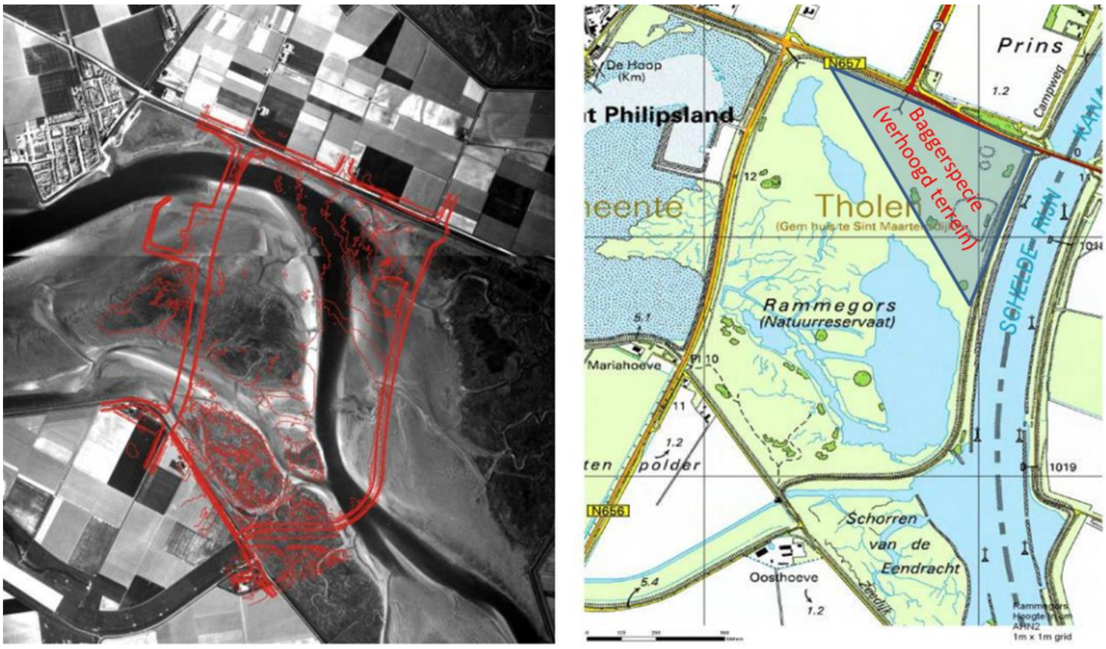


Figure 1. Aerial view of the Rammegors from 1966 (left) and the current situation (right). source: Rijkswaterstaat.

In the end of 2014 the Rammegors was again connected to the Eastern Scheldt with the construction of three culverts (width: 3.5 m; length: 60 m), through the *Krabbekreekdam,* to generate a reduced tide that allows the development of typical salt marsh vegetation (Figure 2). The culverts will be closed when the water level at the Eastern Scheldt side is around 1.65 m NAP. At the Rammegors side, a dam (was constructed to limit the water outflow of the area, and ensure a shallow water area in the Rammegors (14 ha).

1.2 TIMELINES

After the first opening on December 5th 2014, several unforeseen technical problems occurred (see also Figure 3):

- **December 19th 2014**: culverts closed due to scour of the sandy channel bottom at the Eastern Scheldt side. A stagnant water body remained in the Rammegors area, covering 50% of the area.
- **February 18th 2015**: culverts opened after construction (2th opening).
- **April 22th 2015**: culverts closed due to a breach in the dam at the Rammegors side. Culverts remained closed during most part of the year for safety reasons. In this period both stagnant water covering 100% of the Rammegors area, as well as no water (0%) was observed (pers. obs. NIOZ).
- **December 5th 2016**: culverts opened after construction works (3th opening).
- **May 1st 2017**: culverts closed for one week to replace a cylinder. Stagnant water covering 75% of the Rammegors area.
- **September 1st 2017**: culverts closed for one week to replace a sensor. Stagnant water covering 75% of the Rammegors area.

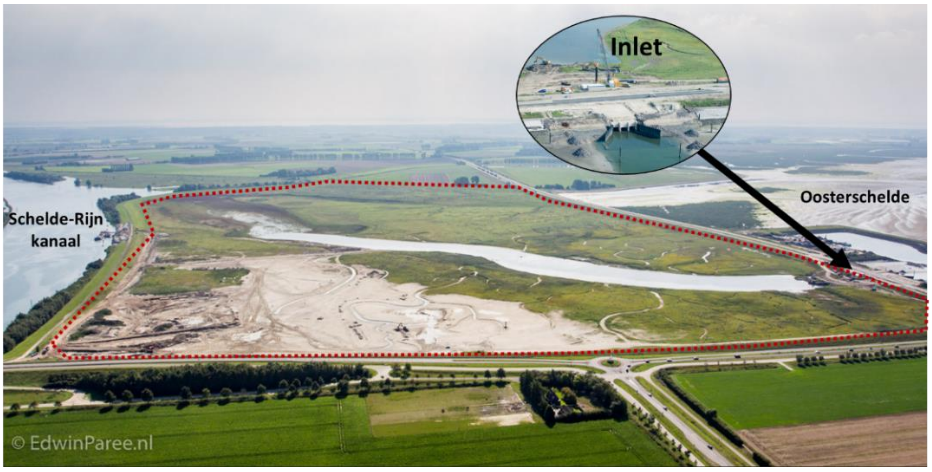


Figure 2. Aerial picture of the Rammegors area (red dotted line) during the construction of the inlet (September 2014). Photo: Edwin Paree.

Figure 3. Outflow of saltwater during ebb from the Rammegors (right side of photo) into the Eastern Scheldt through the culverts in the Krabbenkreek dam (left side of photo). Photo: Tom Ysebaert.

1.3 MONITORING AND RESEARCH IN THE RAMMEGORS

The present project focuses on the short-term (< 4 years) changes that take place in the Rammegors and surrounding polders during in the period from 2015 to 2017. In addition to these short-term monitoring activities and research, other objectives of the long-term monitoring are mentioned in this report. The long-term monitoring is guaranteed within the existing governmental programs (MWTL and SNL-program) and is not part of this CoE-project.

This project focuses on the main biotic and abiotic developments in the area, which are possible salinization through the groundwater of the surrounding polders, vegetation and soil development, and colonization by the benthic organisms. In addition, the morphological development is monitored by aerial photographs, and this part will begin in 2017 when enough data becomes available. Other developments such as the use of the area by birds, fish, mammals, insects, and social acceptance will not be investigated. However, some of these developments are covered within the existing long-term state programs of Staatsbosbeheer.

1.3.1 ***OBJECTIVES***

Rijkswaterstaat Zee en Delta is responsible for the realization of the project of *tidal recovery Rammegors* and is interested in pursuing a number of long-term goals (see below). In addition, the knowledge development will be highly valuable for future tidal restoration projects.

Other partners of the Centre of Expertise Delta Technology are mainly interested in understanding the biotic and abiotic processes related to the tidal recovery. This knowledge development will also contribute to the strengthening of the education of the HZ. The implementation of the project contributes to the training of a new generation of delta-professionals. In summary, the objectives of this project are divided into the following parts:

NATURE VALUES AND ENVIRONMENTAL IMPACT (LONG TERM)

1. Does the tidal recovery in the Rammegors contribute to an improvement of the EWFD-assessment (European Water Framework Directive)?
2. Does the tidal recovery in the Rammegors contribute to the Natura2000 objectives?
3. What are the effects of the tidal recovery in the Rammegors on the groundwater system, as related to the changes in the salt- and freshwater distribution?

KNOWLEDGE (SHORT TERM)

4. Increasing the body of knowledge related to the biotic and abiotic factors controlling the developments after tidal recovery;

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 knowledge circulation within the field, by combining all the knowledge within the DeltaExpertise site.

2. GROUNDWATER

2.1 INTRODUCTION

2.1.1 *PROBLEM DEFINITION*

The restoration of the tidal area Rammegors resulted in (1) a constant flow of salt surface water into Rammegors which may infiltrate into the subsoil, (2) an average higher water level in Rammegors and (3) a change from a constant water level to a tidal effect. These changes, may have consequences for the groundwater system in and outside Rammegors. Since the areas outside Rammegors are polders with a controlled surface water level to support agricultural activities, changes in the groundwater are important for the farmers.

2.1.2 *OBJECTIVE AND RESEARCH QUESTIONS*

The objective of the groundwater part of the research is to determine the effects of the restoration of the tidal area on the groundwater system in and outside Rammegors.

The main research questions are:

1. What is the effect of the restoration of the tidal area on the fresh-salt distribution in the subsoil of Rammegors?
2. How is the process of infiltration of salt water in Rammegors taking place, how is it evolving in time and space and which factors largely control this process?
3. What is the effect of the restoration of the tidal area on the hydraulic heads, phreatic groundwater level, seepage in the agricultural area outside Rammegors?
4. What is the effect of the restoration of the tidal area on the fresh-salt distribution of the subsoil and surface water in the agricultural area outside Rammegors?

To answer the research questions, an extensive groundwater monitoring network have been set up in and outside Rammegors and explorative model calculations have been carried out.

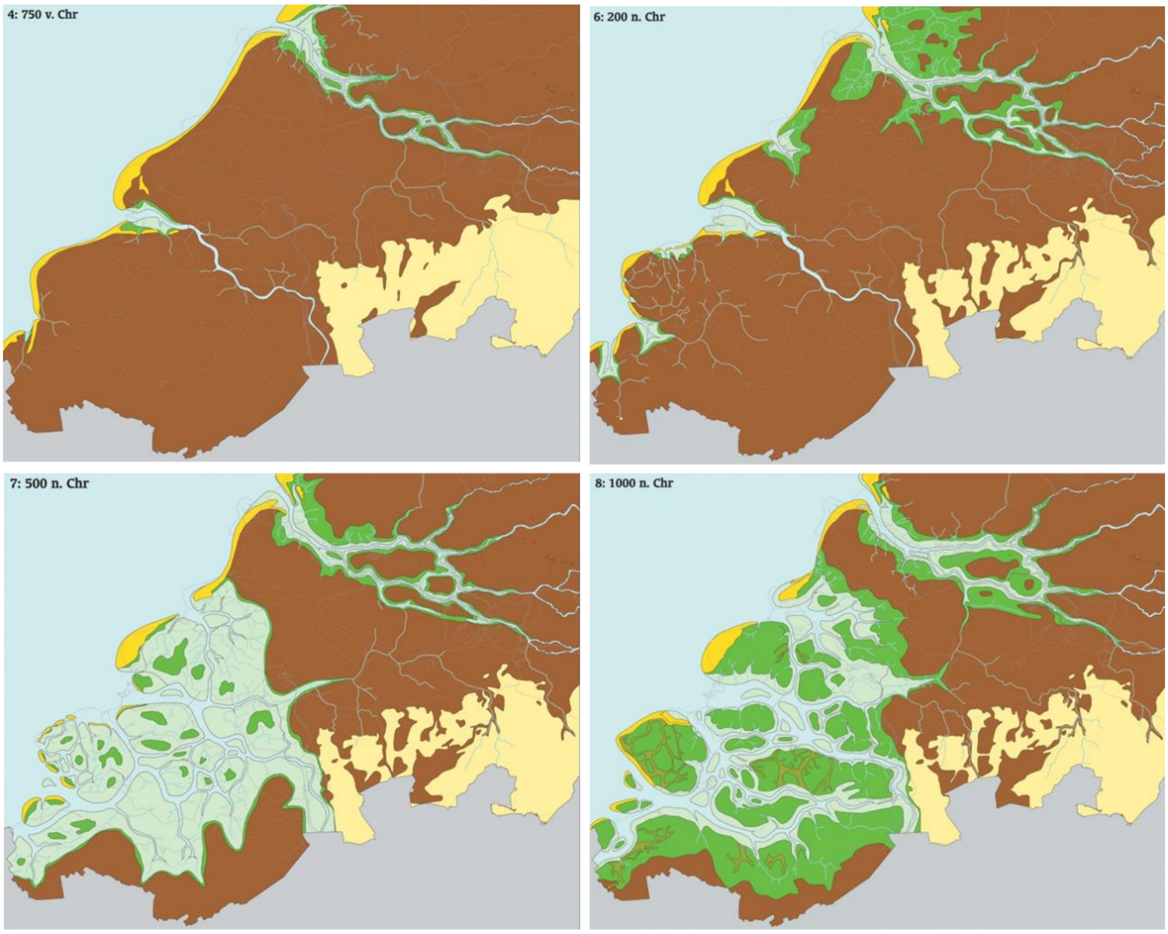
2.2 STUDY AREA

2.2.1 *INTRODUCTION*

The area of Rammegors originates from the Holocene era, about 10.000 years ago (Figure 5). The melting of the icecaps led to a sea level rise and the deposition of marine clay and sand. Due to this deposition new land arose and the sea became less influential in these areas. More humid conditions and an increase of rainfall groundwater tables caused plant growth and the formation of fresh water peat. Further sea level rise, peat excavations and storms are causes for re-intrusion of salt water into fresh water areas. The transgression and regression of salt water led to complex divide between fresh and salt groundwater within the Rammegors area.

Before 1972, Rammegors was part of a well-developed tidal system of the Krabbenkreek and the Eendracht, now Scheldt-Rhine canal. Fresh water was introduced into the area during high water moments in the Zijpe, which is the connection between the fresh Volkerak and the salt Eastern Scheldt. Salt water originated from the Eastern Scheldt (Figure 4). Rammegors has been embanked by the Krabbenkreekdam and the Oostdam, respectively on the western and eastern sides of the Rammegors. The northeastern part of the Rammegors has been used as silt depot during the construction of the Scheldt-Rhine channel. Therefore, no patterns of gullies and creeks can be found there. Due to the embankment, Rammegors has been refreshed by the rainwater, which has been collected in the past 40 years (Arcadis and Rijkwaterstaat, 2013).

Figure 4. Overview of surrounding waters near Rammegors (source: Google maps). Left figure: 1: Eastern Scheldt. 2: Zijpe. 3: Volkerak. 4: Krabbenkreek. 5: Scheldt-Rhine canal. Red dot: Stavenisse. Red square: Rammegors. Right figure: Rammegors in more detail. a: Krabbenkreekdam. b: Oostdam. Yellow dot: Inlet 'Van Haaften'.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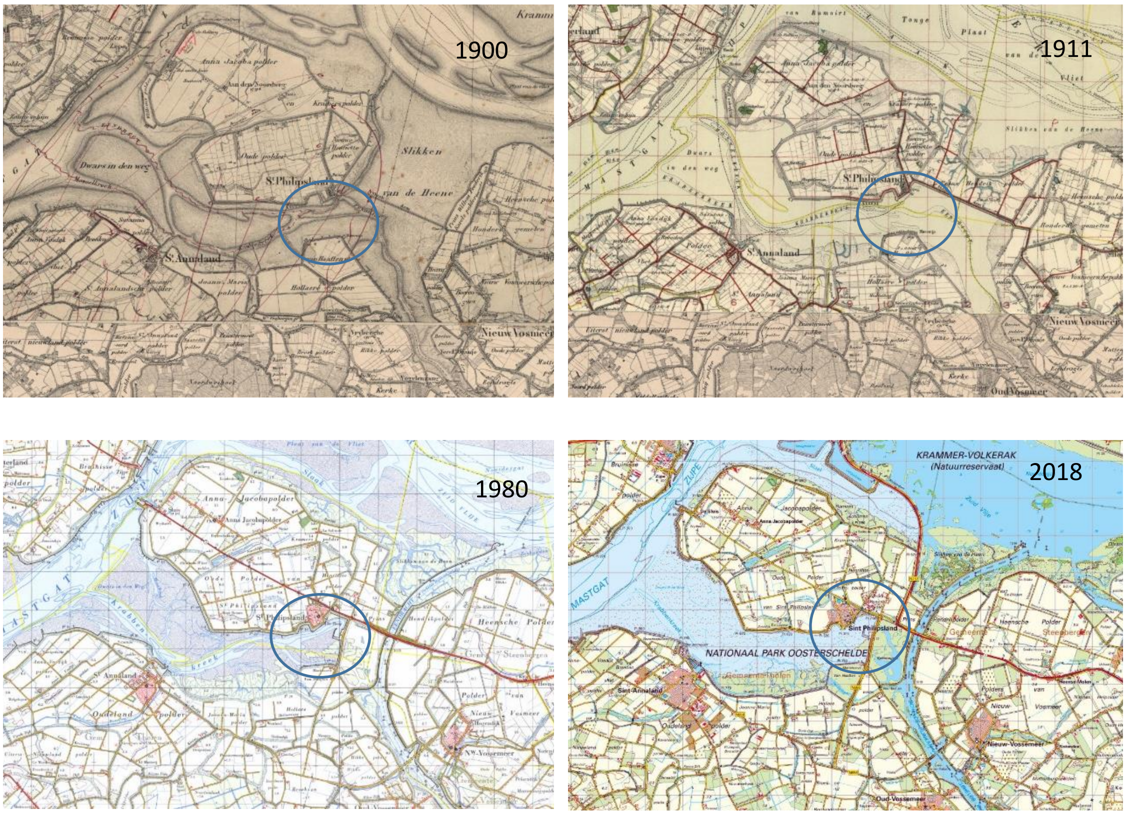


Figure 5. Transition of the Rammegors area.

2.2.2 *HYDROLOGY OF RAMMEGORS*

Figure 6 shows the most probable lithological layers configuration, inside Rammegors. The transect is an interpretation of the geometry and a few characteristics of the Dutch mainland soil of the upper 50 meter (TNO, 2013). In this transect derived from GeoTOP, the local poorly permeable layers, like clay and peat, can clearly be distinguished by the green and brown colours. Arcadis made some drillings in Rammegors, which confirm that the soil consists of sand, varying from fine to moderate coarse sand, for several meters. Locally, thin loamy, clayey- or peat layers can be found (Arcadis and Rijkwaterstaat, 2013). Figure 7 shows a clear horizontal stratification in the different geological formations (be aware of the different vertical axis). Formations of Breda, Oosterhout and Maassluis are marine deposits which consist mainly of marine sands and clays. These sediments were formed in a shallow North Sea with declining soils during early Pleistocene (Jongmans et al., 2012). The Maassluis formation is supposed to be the hydrogeological base as it has a low permeability and is used more often as hydrogeological base (P. de Louw, personal communication, 19 January 2018). Formation of Waalre and Peize and Waalre are both situated on top of the Maassluis formation. Both formations are fluviatile deposits, which were transported by the rivers Rhine (formation of Waalre) and easterly rivers (including Eridanos) (formation of Peize), during early Pleistocene (TNO, 2013). The formation of Peize and Waalre consist of both formations which are mixed with each other (Van de Meene et al., 1977; Verbraeck, 1984). The border between both formations is gradual. The formations can be differentiated at:

- Formation of Peize: white to white grey, no calcium, coarse sand, no clay layers.
- Formation of Waalre: white grey to light brown, no calcium to calcium rich, moderate coarse sand, clay layers

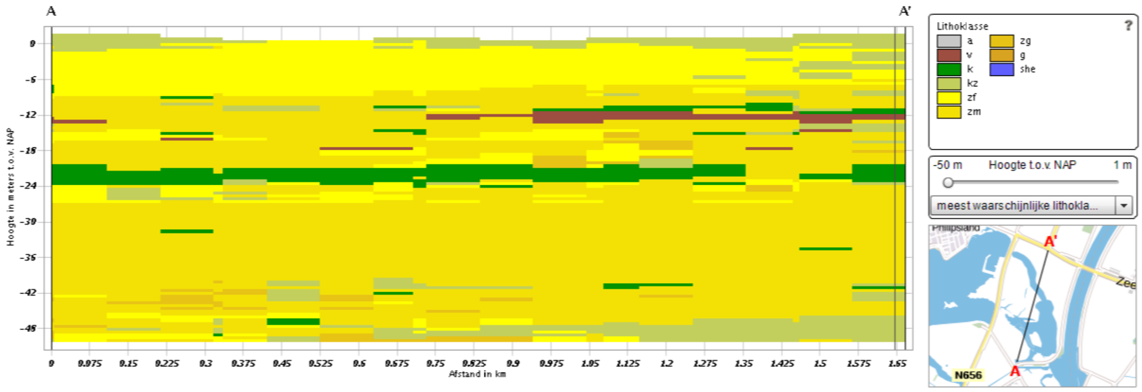


Figure 6. North-south cross section of Rammegors made by GeoTOP v1.3. Legend: a: antropogenic, v: peat, k: clay, kz: clayey/loamy sand, zf: fine sand, zm: moderate coarse sand, zg: coarse sand, g: gravel, she: shelves (source:TNO (2013)).

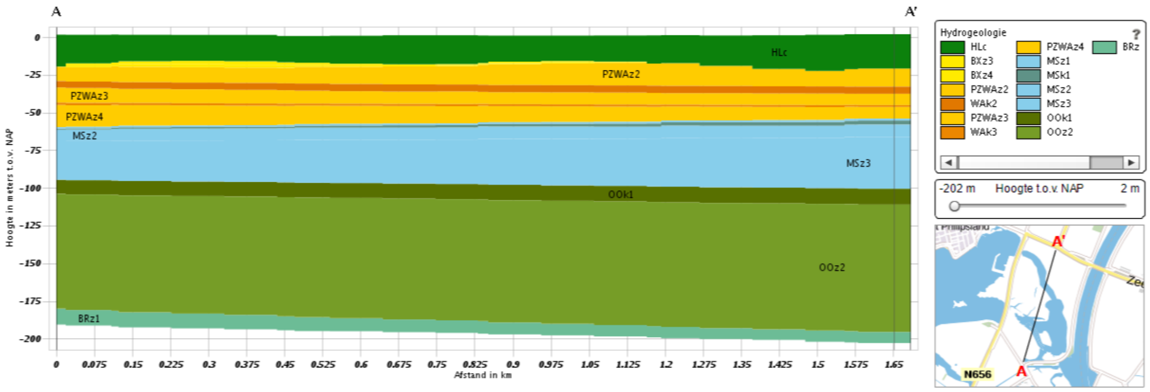


Figure 7. North-south cross section of Rammegors made by REGIS II v2.2. Legend: HLc: Holocene deposits, BX: Boxtel formation, PZW: Peize and Waalre formation, WA: Waalre formation, MS: Maassluis formation, OO: Oosterhout formation, BR: Breda formation (source:TNO (2013)).

Formation of Boxtel is situated on top of the formations of Peize and Waalre and is deposited during the late Pleistocene. The formation can be subdivided in nine different layers, which originated in different ways during cold, periglacial circumstances or in local, small processes (Schokker et al., 2005). The upper formation is the Holocene formation, which originates from the last interglacial (10.000 years before present (BP) till present) (Jongmans et al., 2012). The coastline migrated eastward due to a rising sea level. This migration is known as the Holocene transgression during which marine deposits were deposited in large parts of the Netherlands. The rivers Rhine, Meuse and Scheldt supplied a considerable amount of sediments, which formed our present delta with a natural coastal defense system, consisting of sand barriers and dunes. When the sand barriers and dunes were formed, a situation was created where marine influences were limited, which resulted in the development of peat. After the development of this peat, clay and sand were deposited in a peri-marine environment influenced by tides (Jongmans et al., 2012). These peat and clay layers are present inside Rammegors (Figure 6)

Heterogeneity plays an important role in controlling convective instabilities. More detailed information about the various depths where aquifers and aquitards can be found, as well as information on the hydraulic conductivity values of these hydrostratigraphic units are gathered from DINOloket, which provides data and information of the Dutch subsoil (TNO, 2013). The information for this investigation is gathered from two different geological models called REGIS II and GeoTOP. REGIS II is an hydrogeological model which shows the various permeable layers in the different lithostratigraphical units. The maximum depth range is 500 meter. The model provides information on the spatial variation in horizontal hydraulic conductivity. GeoTOP shows a more detailed three-dimensional image of the subsoil with a maximum depth of 50 meter below NAP and thus displays more detailed stratigraphy. In this investigation the hydraulic conductivity is, besides Dinoloket, also gathered from a research report about Rammegors made by Arcadis and Rijkswaterstaat (Arcadis and Rijkwaterstaat, 2013). In

Table 1 the main hydrostratigraphical units can be found. It is assumed that the formation of Maassluis forms the hydrogeologic base.

Table 1 Lithological layers with hydraulic conductivity values. * values gathered from Dinoloket (TNO, 2013), values gathered from Arcadis and Rijkwaterstaat (2013).

Layer	**Formation**	**Lithology**	**Height [m NAP]**	**Layerdepth [m]**	**KH [md−1]**	**KV [md−1]**
1a*	Holocene	Moderate fine, silty with local moderate till heavy sandy clay	-2	>2	0.5	0.16
1b*	Holocene	Fine sand	-10	8	3	1
1c*	Holocene	Moderate coarse sand	-12	2	7	2.33
1d*	Holocene	Compacted peat/clay	-14	2	0.01	0.0033
1e*	Holocene	Moderate coarse sand	-22	8	7	2.33
2**	Waalre	Strongly sandy till silty clay, horizontal layered	-24	2	0.26	0.025
3**	Peize/Waalre	Extremely fine till extremely coarse sand, sporadic shell holding	-41	17	16.4	8.2
4**	Waalre	Strongly sandy till silty clay, horizontal layered	-47	6	0.36	0.036
5**	Peize/Waalre	Extremely fine till extremely coarse sand, sporadic shell holding	-57	10	18	9
6**	Maassluis	Silty and sandy clay, sporadic shell holding	-64	7	0.06	0.006

2.2.3 *BATHYMETRY*

The topography and bathymetry (underwater equivalent to topography) of an area can have a major influence in the convection and thus in the salinization process of the Rammegors. For simplicity reasons, the term bathymetry will be used as term of both topography and bathymetry, in the remainder of the text. It is therefore of great importance that the bathymetry data is detailed. In this research, three different sources have been used which all differ in resolution. The most detailed map covers Rammegors itself and has a discretization size of 10x10cm (Figure 8). This photogrammetry was obtained in December 2015 with a drone in assignment of Rijkswaterstaat. The influence of vegetation (reed) on the photogrammetry is limited, because the photogrammetry is made in winter. A second map is used to fill up the gaps in the first map and for the surrounding area. This AHN map has a discretization size of 0.5x0.5 meter and was obtained by Deltares. The last map was obtained online from the actual height-dataset of the Netherlands and was used for all the gaps which were still present after combination of the two previously mentioned maps. The discretization size of this map is 250x250m (NHI, 2018).

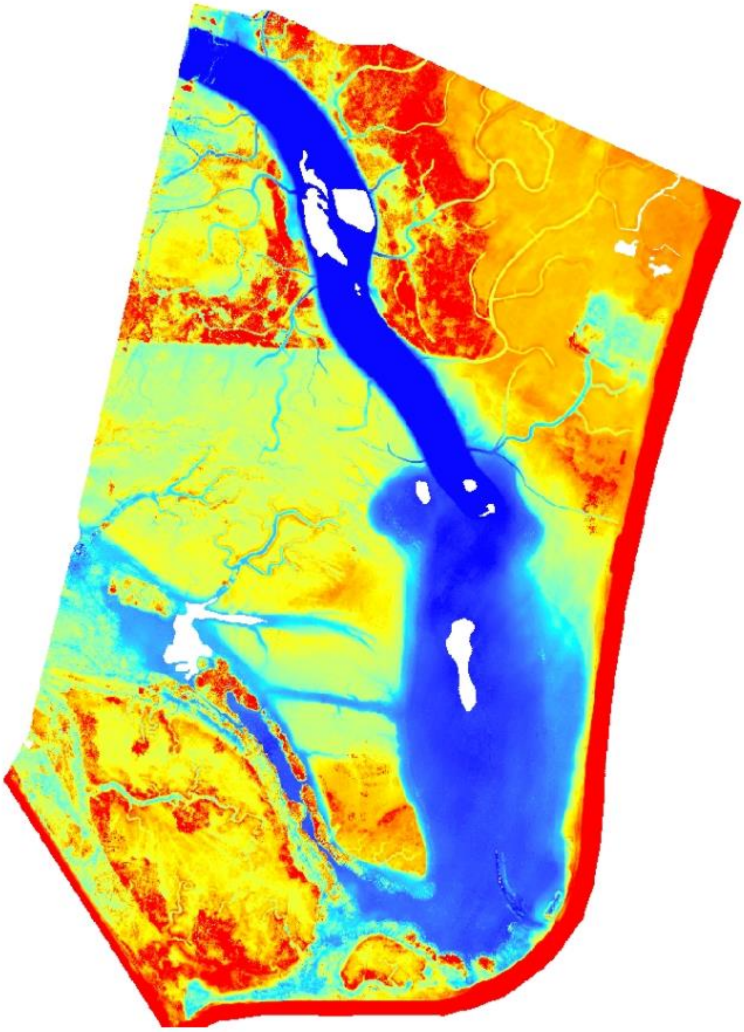


Figure 8. Bathymetry of Rammegors (source: Rijkswaterstaat).

2.2.4 *REGIONAL GROUNDWATER FLOW*

Groundwater model Zeeland (Figure 9), made by Deltares (Oude Essink et al., 2016), shows regional groundwater flow in the Rammegors in the winter situation of 2011 in the first aquifer. There is a radial inflow of groundwater from the northern and southern boundaries and the eastern Scheldt-Rhine canal. The western boundary, the Krabbenkreek, shows a lower hydraulic head than Rammegors. The hydraulic heads in the south-east direction of the Rammegors are also lower. This could indicate that water will flow in the direction of the Krabbenkreek or in the direction of the Scheldt-Rhine channel through lower hydraulic heads in the south-east corner. Rammegors became an intertidal area in December 2016. Therefore it is likely that the regional groundwater flow near the Rammegors has locally been changed. The water levels in the Rammegors can rise till 1.36 meter during high tide. This is higher than the water levels of the surrounding polders. Taking this in consideration, you could assume that the regional groundwater flow in the new situation shows a radial outflow to the northern and southern lying polders and the Scheldt-Rhine canal on the east-side.

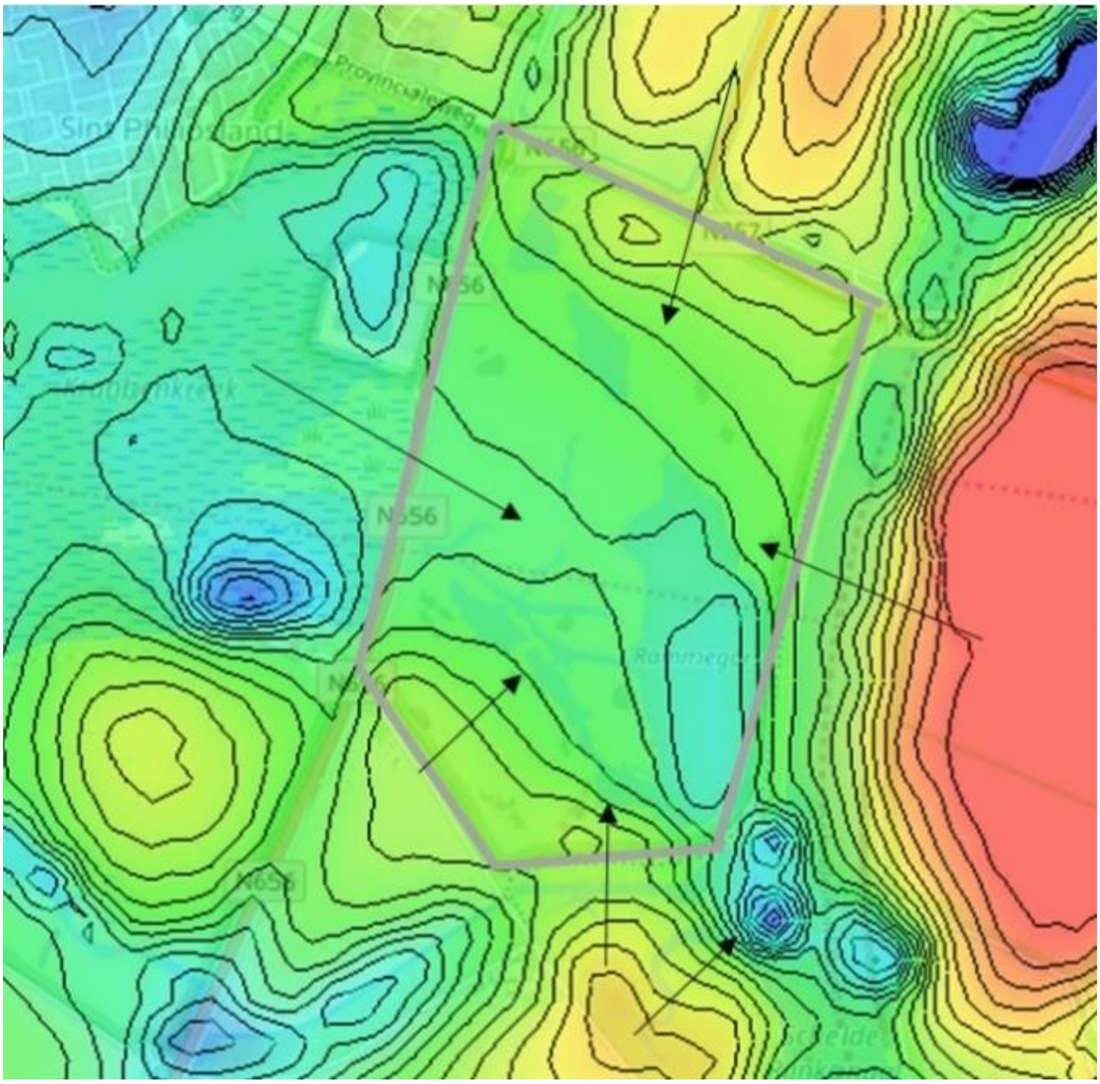


Figure 9. Isohypse map of phreatic level in Rammegors (grey polygone), winter 2011. The hydraulic heads in the dark blue areas are smaller than -0.5 m NAP and hydraulic heads in the red areas are larger than +0.5 m NAP. Black arrows indicate groundwater flow direction (source: Deltares).

2.2.5 *SURROUNDING SURFACE WATERS*

After the embankment in 1972, Rammegors has been isolated hydrologically, with no connection with the surrounding surface waters. The surrounding surface waters are:

- Krabbenkreek (tributary of Easternscheldt)
- Scheldt-Rhine channel (inlet 'Van Haaften')
- Surrounding polders (Tholen and St. Philipsland)

2.2.5.1 **KRABBENKREEK**

As a tributary of the Easternscheldt, Krabbenkreek is thus influenced by tides from the North Sea. In Figure 10 the water levels of the Eastern Scheldt are shown near Stavenisse, which is 14 km upstream of Rammegors. Water levels range from -1.5 m NAP to +1.5 m NAP, on average. The maximum inlet in Rammegors is set at +1.65 meter, due to safety measures when water levels in the Krabbenkreek are too high (Arcadis and Rijkwaterstaat, 2013).

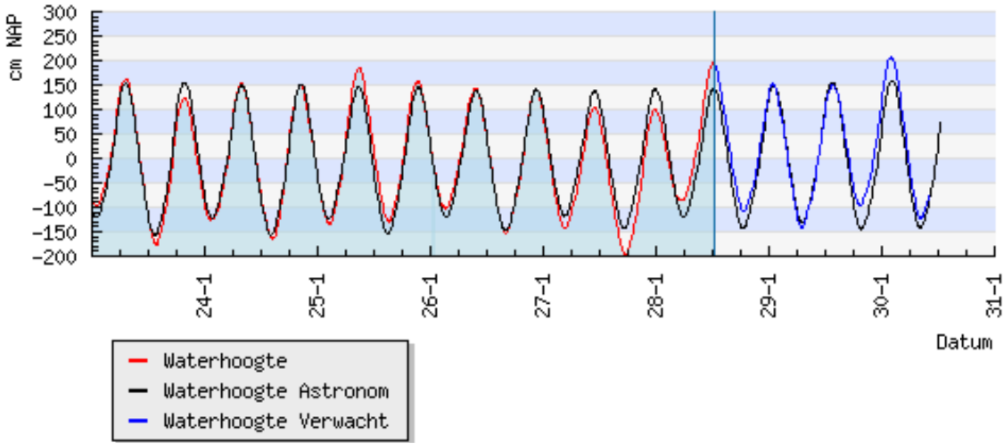


Figure 10. Water levels of Eastern Scheldt near Stavenisse. Red line: water levels. Black line: astronomical water.

2.2.5.2 SCHELDT-RHINE CHANNEL

East of Rammegors, Scheldt-Rhine canal is situated. This canal is part of the main transport route Amsterdam-Rotterdam-Flanders. The canal has been used since 1975 and is since then the connection between Krammer-Volkerak and Zoommeer (Figure 11) (Rijkswaterstaat, 2012). After the construction of the Oesterdam in 1986 and the Philipsdam in 1987, the fresh tides free Volkerak-Zoommeer was created, which is part of the Deltawerken. The water is used to maintain the water levels at designated levels in the surrounding polders in Oostflakkee, St. Philipsland, Tholen and the western part of Brabant (Rijkswaterstaat, 2012).

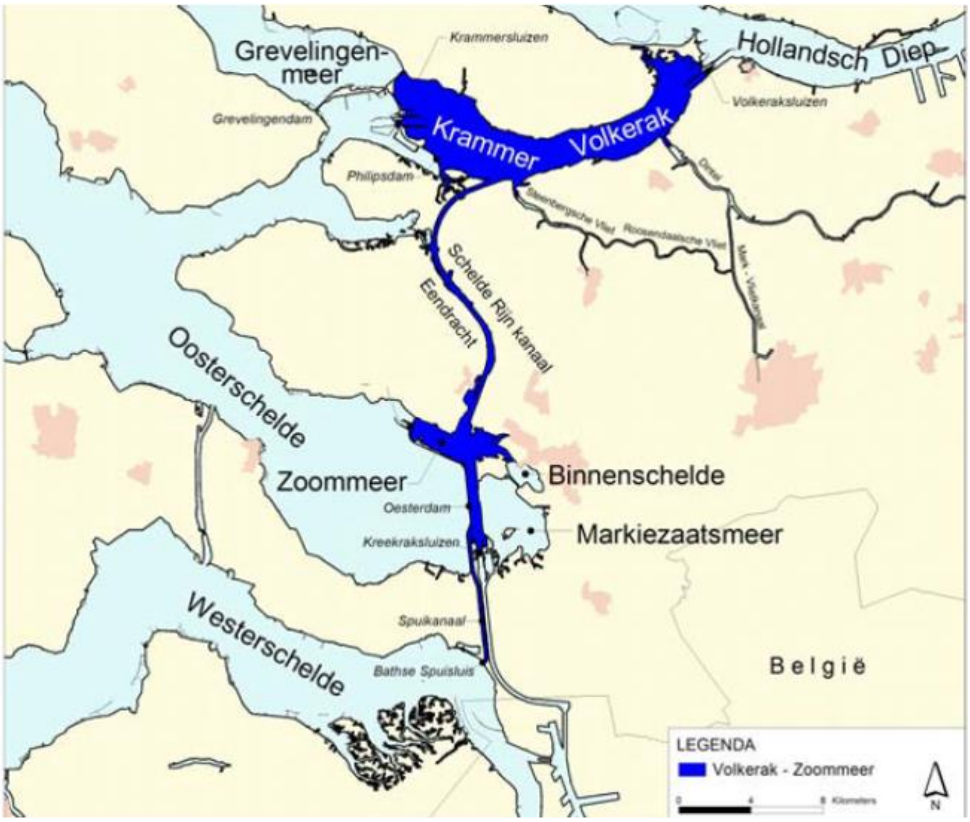


Figure 11. Overview of Volkerak-Zoommeer (source: Rijkswaterstaat (2012)).

Inlet ’Van Haaften’ is situated south of Rammegors (Figure 13). In summer, fresh water from the Scheldt-Rhine channel is used to maintain the water levels of island Tholen. The average water level is -0.01 m NAP near the inlet and -0.43 m NAP near the outlet of the inlet (Arcadis and Rijkwaterstaat, 2013).

2.2.5.3 **SURROUNDING POLDERS**

Rammegors is surrounded by polders at the south and north side. North of Rammegors, the ’Prins Hendrikpolder’ is kept with an average water level of -0.25 m NAP in summer and -0.40 m NAP in winter. South of Rammegors,the ’Van Haaften polder’ has an average water level of -0.40 m NAP in summer and -0.60 m NAP in winter (Arcadis and Rijkwaterstaat, 2013). The water levels are maintained by the water from Scheldt-Rhine channel.

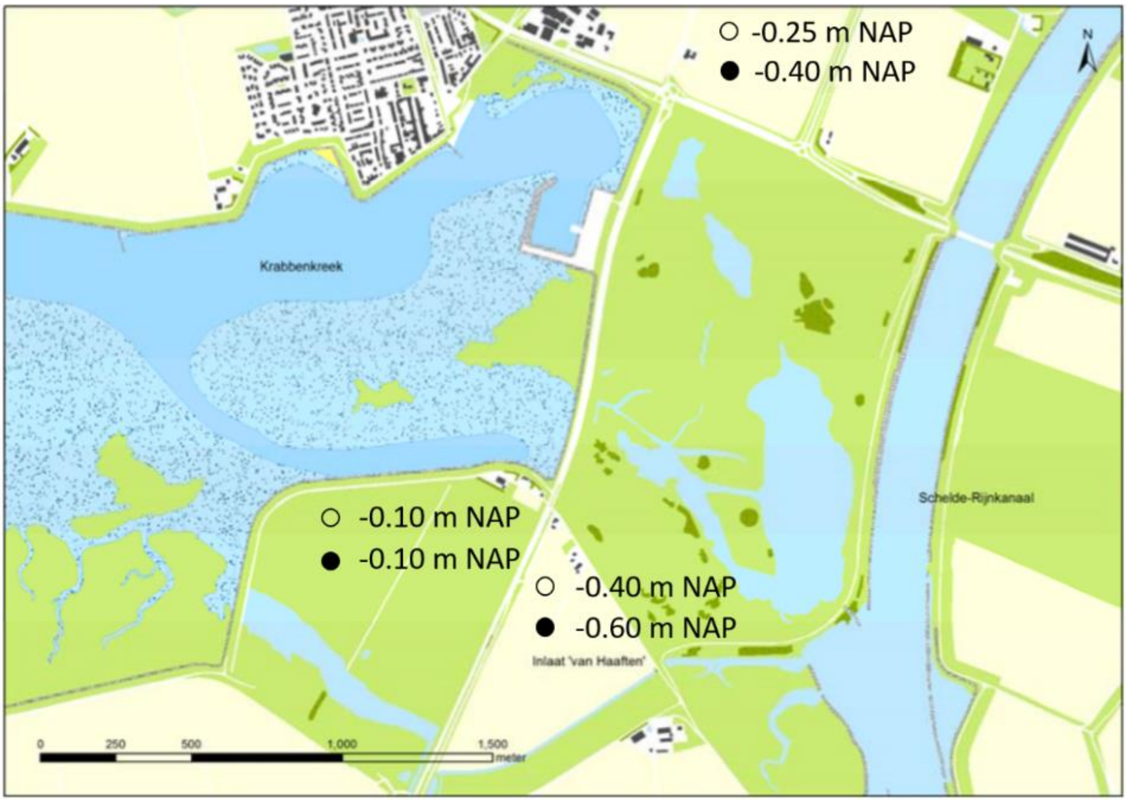


Figure 12. Overview map of nature area the Rammegors. Open circle is average water level in summer, closed Water management in study area.

The Rammegors area is excessively drained by drains, channels and open water systems like the Krabbenkreek and the Scheldt-Rhine canal. In Table 2 the different drainage systems are mentioned with their specific water levels, bottom elevations and drainage resistances. Figure 13 shows the polder stages in the area from waterboard Scheldestromen.

*Table 2. Drainage system in Rammegors. * values gathered from report 'Onderzoek naar zoute kwel bij het natuurgebied Rammegors', made by Arcadis and Rijkwaterstaat (2013), ** values based upon values from report 'Onderzoek naar zoute kwel bij het natuurgebied Rammegors', made by Arcadis and Rijkwaterstaat (2013), *** values gathered from Rijkswaterstaat website Rijkwaterstaat (2018).*

Waterway	Position	Waterlevel [m NAP]	Bottom elevation [m NAP]	Resistance [d]
Drain	Agriculture areas	Non applicable	Surface level -1	2
Ditches	Sint Philipsland	Figue 2.#	Water level - 0.1	5**
Ditches	Tholen	Figue 2.#	Water level - 0.1	5**
Krabbenkreek	-	0.0*	Bathymetry	5**
Scheldt-Rhine canal	-	-0.12***	-6***	10*
Rammegors	Main gully	0.4*	Bathymetry	5**

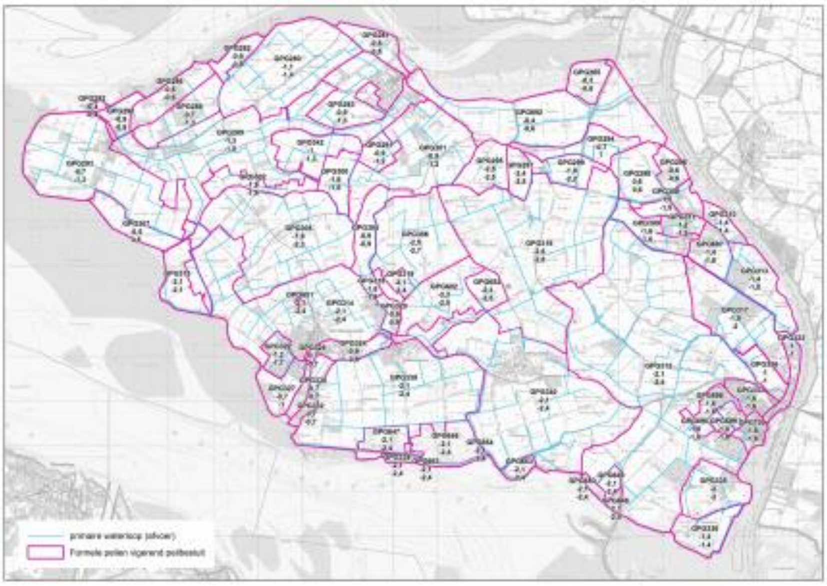


Figure 13. The maintained surface water levels of the different polder areas around Rammegors.

2.2.6 *TIDAL CONDITIONS*

Since 7 December 2016, the Rammegors is influenced by tides due to an inlet in the Krabbenkreekdam. This inlet was already opened twice. First, at 5 December 2014 and closed again at 19 December 2014, as there was too much erosion. A second time, from 18 February 2015 till 22 April 2015. The dam broke and was therefore closed. During high tide, a larger area is inundated and a larger water column is present in the gully. The average low and high tide in the Rammegors are 0.33 and 1.36 meter (De Louw et al., 2016). The left and middle images in Figure 14 show the average low and high tide situation in Rammegors, respectively. The rightest image shows the situation during extreme conditions when the safety measurements have taken place.

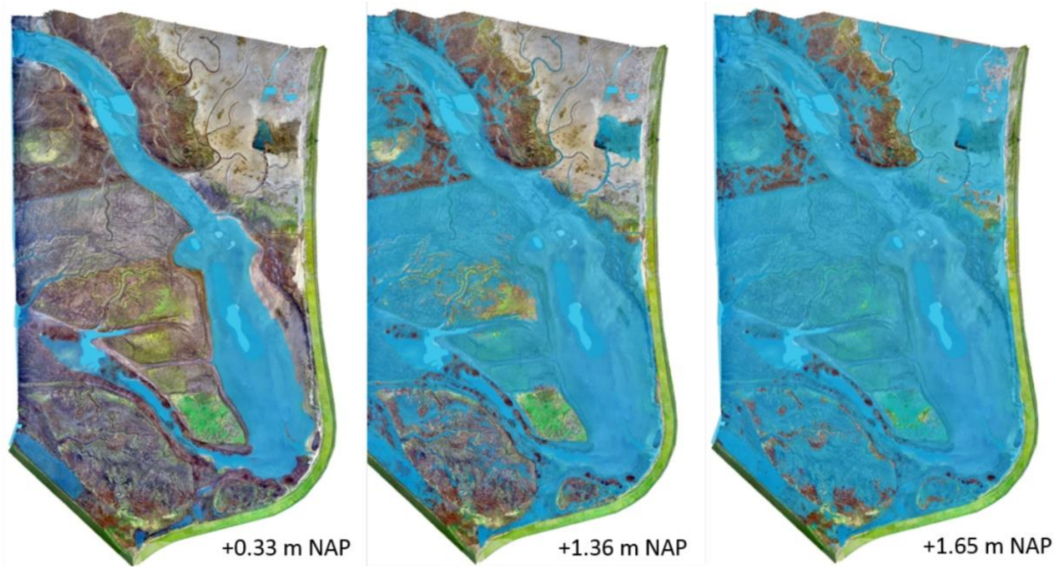


Figure 14. Tidal configurations in Rammegors. Left figure is during low tide with a water level of +0.33 m NAP. Middle figure is during high tide with a water level of +1.36 m NAP. Right figure is during spring tide with +1.65 m NAP (source: Rijkswaterstaat).

2.3 MONITORING PROGRAM

In 2011, Arcadis started a monitoring program for the two polders bordering Rammegors, the Haaftenpolder and the Prins Hendrikpolder. The monitoring program consisted of monitoring (1) the phreatic groundwater level, (2) the salinity of the phreatic groundwater, (3) the salinity of the surface water and (4) crop damage performed by AGROWA. Figure 3.1 show the locations of the piezometers. The monitoring results are described in various reports and the monitoring results from the period 2011-2015 are summarized in Arcadis (2016). In March 2016, the monitoring program was extended with four deeper piezometers for measuring the hydraulic head and the fresh-salt interface (indicated by red circles, Figure 15).

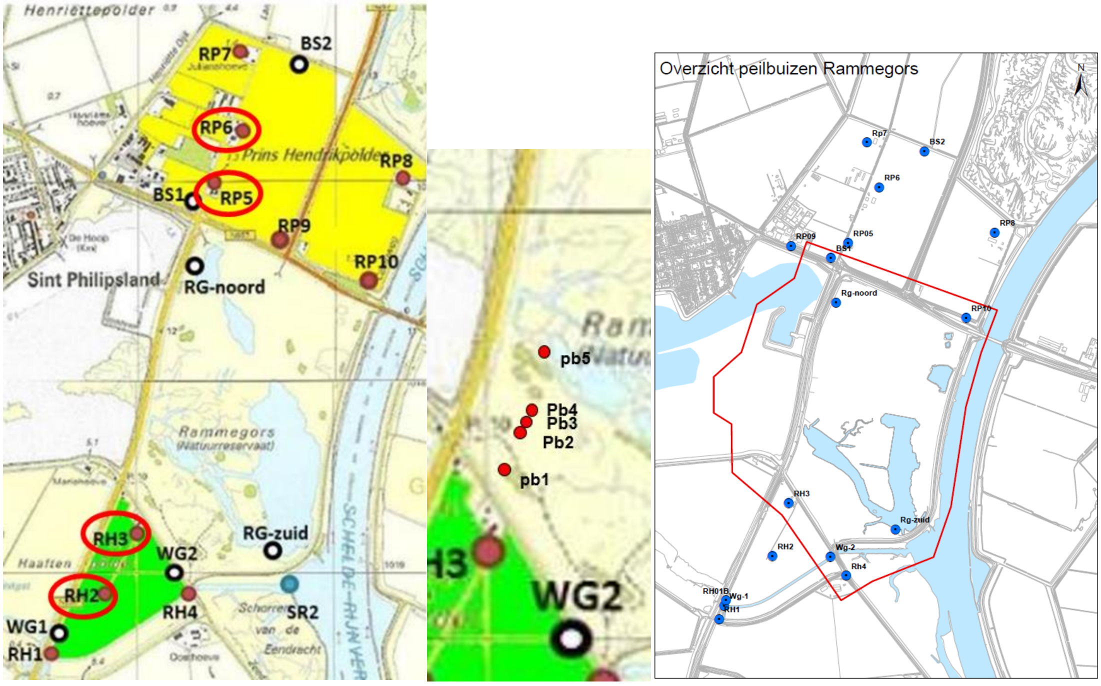


Figure 15. The locations of piezometers in the Haaftenpolder (code RH) and the Prins Hendrikpolder (code RP) and in the tidal area (pb1-pb5).

2.3.1 *PHREATIC GROUNDWATER LEVEL*

The phreatic groundwater level importantly controls the hydrological conditions for agriculture, nature and urban area. It determines crop damage during wet or dry conditions. Although the phreatic groundwater level is easy to measure, effects of changes like the restoration of the tidal area are difficult to extract from the measured time series. This is due to the strong response on precipitation, evaporation and drainage by ditches and tile drains. In general, this response is much larger than effects of interventions. At several locations in the agricultural area (see Figure 15), phreatic groundwater levels have been measured since 2011 (see Table 3).

In April 2018, extra phreatic piezometers were installed in the tidal area, among which at the locations of the five deep piezometers.

Table 3. Available groundwater timeseries.

	Name	Land surface [m NAP]	Filter relative to land surface [m]	Start timeseries	End timeseries
Haaftenpolder	RH01A	0.24	2.5	16-12-2011	18-7-2013
	RH01B	0.24	2.5	18-7-2013	14-12-2018
	RH02A	1.12	2.5	15-11-2011	14-12-2018
	RH02B	1.12	2.5	16-12-2011	27-7-2018
	RH02_deep	1.13	8.0 & 23.0	4-4-2016	14-12-2018
	RH03_shallow	1.44	2.5	31-1-2013	20-7-2017
	RH03_deep	1.49	8.0 & 23.0	4-4-2016	12-1-2017
	RH04A	0.10	2.5	16-12-2011	14-12-2018
Prins Hendrikpolder	RP05_shallow	1.14	2.1	15-11-2011	16-4-2016
	RP05_deep	1.14	8.0 & 23.0	4-4-2016	14-12-2018
	RP06_shallow	1.50	2.1	15-11-2011	14-12-2018
	RP06_deep	1.50	8.0 & 23.0	4-4-2016	12-1-2017
	RP07	1.44	2.1	15-11-2011	30-11-2015
	RP082.1	1.10	2.1	15-11-2011	27-11-2017
	RP09		3.25	18-7-2013	20-12-2016
	RP10		3.25	18-7-2013	27-11-2017
Tidal area Rammegors	PB1	1.54	14	4-5-2017	19-3-2018
	PB2_shallow	1.3	2	4-5-2017	19-3-2018
	PB2_deep	1.31	14	4-5-2017	4-10-2017
	PB4	0.82	14	4-5-2017	19-3-2018
	PB5	0.6	14	4-5-2017	19-3-2018

RG11	2.84	?	2-2-2017	14-12-2018
RG12		?	2-2-2017	14-12-2018

2.3.2 *HYDRAULIC HEAD*

The hydraulic head is the water pressure at a certain depth. Water level changes in Rammegors will propagate through the aquifer. It is therefore important to measure the hydraulic head in this aquifer. When no effects are visible in the measured in the hydraulic head, then no effects on phreatic groundwater levels and seepage fluxes can be expected. The hydraulic heads are measured with a frequency of one hour using a Diver.

At four locations in the agricultural area (RH2, RH3, RP5, RP6, see figure below for location) an extra deep piezometer was installed at a depth of 25 meter, with also a screen at 9 meter below surface. These piezometers were installed to measure the hydraulic head and to monitor the fresh-salt interface with SlimFlex in the piezometer. For each location, differences between the hydraulic head in the different screens and the phreatic water level will also indicate whether a vertical upward or downward flux is present. For each drilling a detailed bore hole description was made which can be found in the drilling report (Inpijn Blokpoel, 02P007278-RG-01). One borehole description is given as example in the Appendices.

In April 2017 five extra piezometers were installed in the tidal area to follow the propagation of the tidal fluctuations of the surface water levels in Rammegors in the deeper aquifer (Figure 16). The screens of these piezometers were situated at 14 meters depth. These piezometers were also used to monitor the fresh-salt interface with the SlimFlex-EM. The locations of the piezometer are given in Figure 15.

Figure 16. Installation of piezometers in tidal area using the flushing method.

2.3.3 *SALINITY OF THE SURFACE WATER: EC-MEASUREMENTS AND TEC-PROBE*

The salinity (EC) of the surface water was measured by RWS to monitor the salinity of the surface water coming from the Scheldt-Rijn canal, which is used for agriculture in the polder area.

On 14th of March 2016, a field survey of the salinity of the surface water was carried out by direct measuring of the EC of the surface water with an EC-device. The field survey was carried out by students of the HZ University of Applied Sciences (Figure 17).

Also, a TEC-probe was used to measure EC-depth profiles below a ditch bottom. In this way, saline seepage (upward flow of saline groundwater) can be detected without the influence of surface water flow through the ditch. A TEC (Temperature - Electrical Conductivity) probe is an instrument to measure the temperature and the electrical conductivity of the subsurface in a one-dimensional (1D) profile. The TEC probe is pushed manually into the subsurface. The measurement interval is often 0.1 m. Usually, measurements are only carried out below the water table and in soft soils (clayey and peaty soils).

Figure 17. EC-measurements by HZ-students in the ditch (left) and TEC-probe measurements at agricultural field (right).

2.3.4 *FRESH-SALT INTERFACE: ECPT*

With an electrical cone penetration test (ECPT), a probe with a conical tip is pushed into an unconsolidated subsurface with a heavy track and the cone resistance, sleeve friction, water pressure, and electrical conductivity are measured simultaneously (Figure 18). The measurement interval is usually in the order of 1-2 cm. The electrical conductivity can be used to infer the salinity profile with depth. ECPT-measurements were carried once in June 2012 at four locations outside Rammegors.

Figure 18. ECPT-vehicle to carry out Electrical Cone Penetration Tests (left). Locations of the ECPT-measurements with depth of the fresh-salt interface (right).

2.3.5 *FRESH-SALT INTERFACE: EM-SLIMFLEX*

The EM-SlimFlex is a borehole logging tool developed by Deltares and the German company Anatres. In the tool a primary electromagnetic (EM) field is generated by an alternating current in a 'transmitting' coil, which induces a secondary EM field in the subsurface. Both the primary and secondary fields are measured in a receiver coil. From the difference in phase and amplitude of the two EM fields the electrical conductivity of the subsurface can be determined. The EM-SlimFlex can be used in piezometers from 1.5 inch (3.8 cm) in diameter to determine the transition zone between fresh and saline groundwater, comparable to ECPT-measurements. The EM-SlimFlex is very suitable to repeat measurements in the same piezometer to monitor changes of the fresh-salt interface in time.

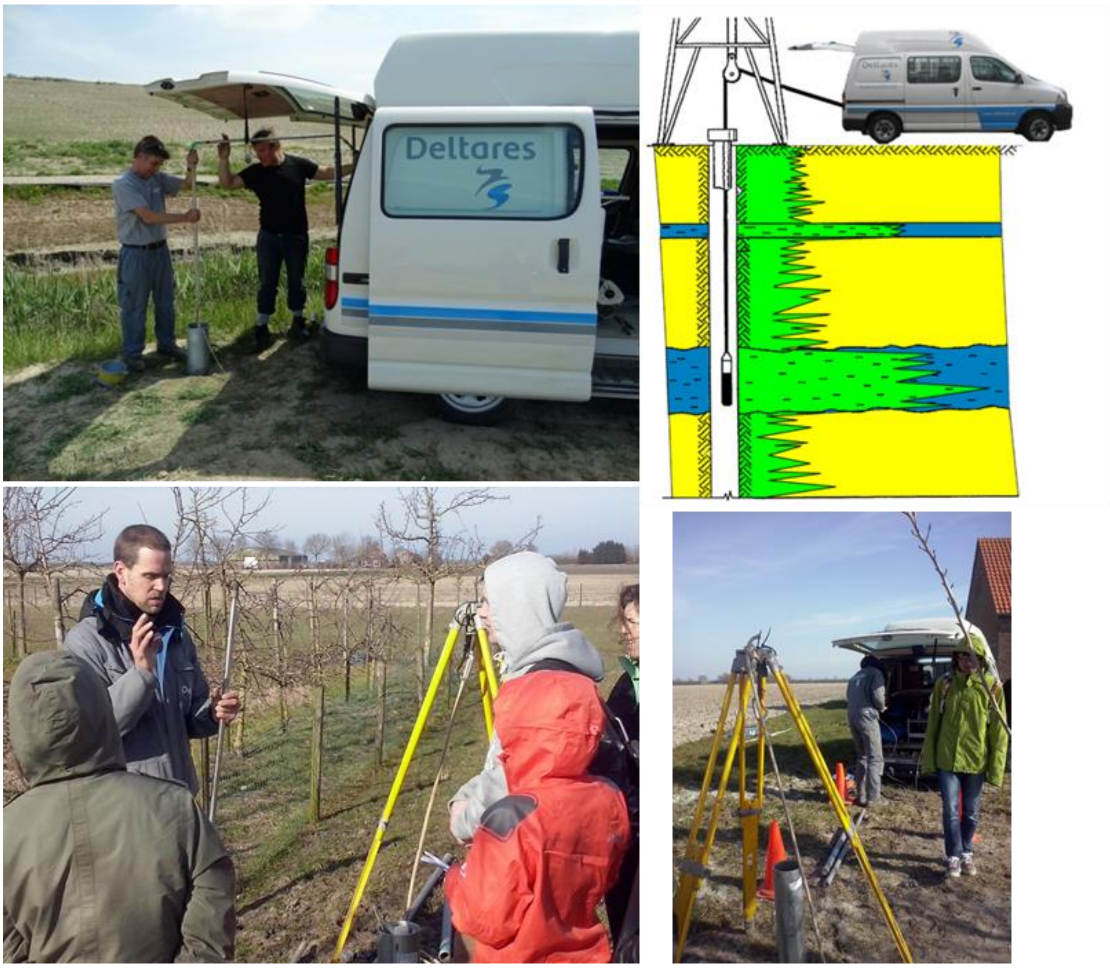


Figure 19. SlimFlex-EM measurements in a piezometer to measure the salinity distribution in the subsoil (above).Explanation of the EM-SlimFlex-method to HZ-students in Rammegors.

EM-SlimFlex measurements were conducted in the 9 deep piezometers to determine the fresh-salt interface (Figure 19). The measurements were repeated three times (March 2016, May 2017, June 2018) for the four deep piezometers in the agricultural area and two times (May 2017, June 2018) in the tidal area.

2.3.6 *TIME ELAPSED ELECTRICAL RESISTIVITY TOMOGRAPHY (ERT)*

Electrical resistivity tomography (ERT) can be used to obtain a 2D-image of the resistivity (reciprocal of electrical conductivity) of the subsoil, which give an indication of the fresh-salt distribution in the shallow subsoil. The electrical resistivity is measured between a large combination of electrodes at different distances, sampled and measured automatically by a computer. By using many electrode combinations, a cross-section (in x and z direction) of the resistivity is obtained. Inversion software is used to construct a model of the electrical resistivity, based on the apparent resistivity dataset. The vertical resolution and depth of investigation depend on the electrode distance that is used.

Deltares developed a ERT-system to measure the resistivity-profiles continuously in time and space tested in Rammegors (Figure 20). The infiltration process of salt water infiltration in Rammegors could be detected with the high temporal resolution measurements. Two cables were installed: (1) a 30 m long cable installed horizontally at 30 cm depth, (2) a 15 m long cable, installed vertically in a borehole until a depth a 14 m.

Figure 20. Installation of solar platform and ERT-cable in tidal area Rammegors.

2.3.7 *FRESH-SALT DISTRIBUTION IN SUBSOIL: FRESHEM*

Electromagnetic measurements from a helicopter were carried out for the Rammegors area in March 2015 as part of the project 'FRESHEM Zeeland': **FRE**sh **S**alt groundwater distribution by **H**elicopter **E**lectro**M**agnetic survey in the Provincie of **Zeeland.** The goal of the FRESHEM Zeeland project is the development of an approach to produce a three-dimensional Cl-distribution of the groundwater by using airborne electromagnetic measurements, in combination with a-priori data, advanced modeling techniques and knowledge of the groundwater system and geology. The result is a three-dimensional distribution of the Cl- concentration of the groundwater for the survey areas in the Province of Zeeland. Cl- concentration is used as an indication for the salinity of the groundwater.

Airborne electromagnetics (AEM) comprises those methods that allow a fast investigation of the Earth's subsurface from the air ranging from a depth of some meters up to several hundreds of meters. BGR (Budesanstalt fur Geowissenschaften und Rohstoffen) uses a helicopter for carrying the EM transmitters and receivers that are housed by a tube, the bird. This bird is towed by a 45 m long cable about 30-40 m above the ground (Figure 21). The transmitting dipole signals (primary fields) are generated as continuous sinus oscillations at six discrete frequencies ranging from 386 Hz to 133 kHz. At each frequency, two components of the secondary magnetic field induced in the subsurface are recorded that are converted into resistivity's (viz. the reciprocal value of the electric conductivity) using simple models.

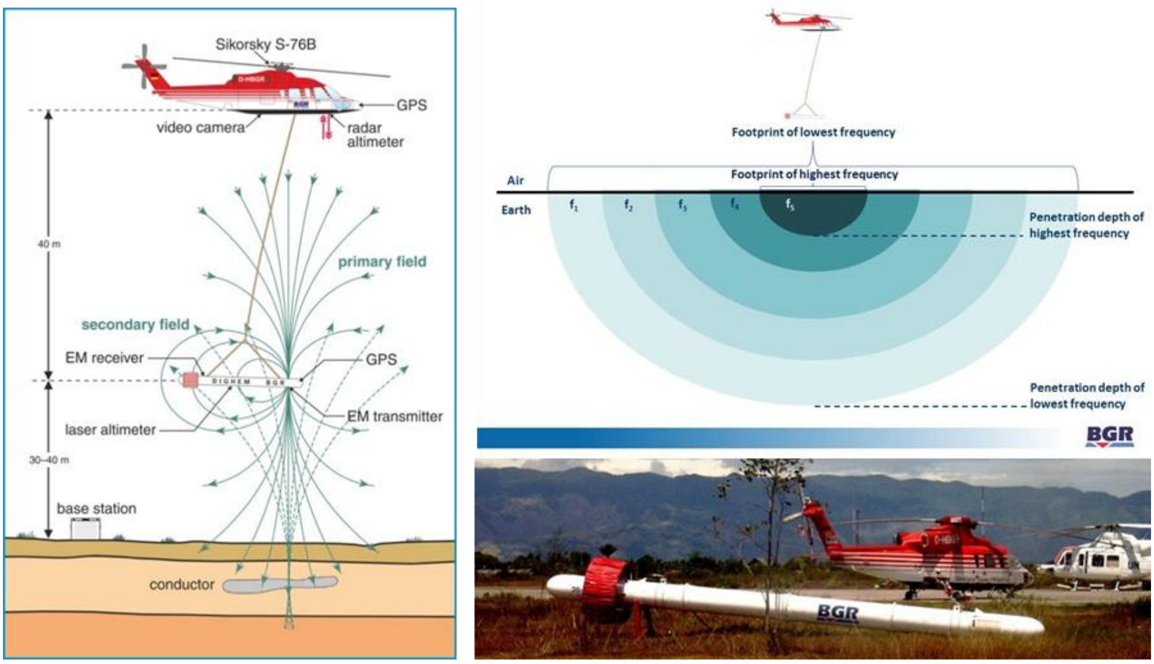


Figure 21. The HEM-system of BGR with sketch of the BGR airborne geophysical system (left), frequencies and footprint of the HEM system (upper right), BGR helicopter with bird in Banda Aceh (Indonesia) at the local airport (bottom right).

In March 2015, the HEM-survey was carried out above Rammegors. The spacing between de flight lines was ~100 m and every 4 meter a measurement was taken. Figure 22 shows the flight lines of the survey. The footprint in the shallow subsurface is -50 meters and at greater depth -200 meter. Hence, the 'point' measurement taken every 4 meters is a measurement of a circle with a diameter of 50-200 meters, approximately. The inaccuracy in depth is approximately 10% of the depth. The use of a-priori measurements implemented in the inverse modelling procedure is used to decrease this inaccuracy. The electrical cone penetration test and Slimflex-measurements in Rammegors were used for the inverse modeling process.

Figure 22. The flight lines (March 2015) with much narrow spacing above the Rammegors area (left). Helicopter with bird coming back to Airport Zeeland from survey above Rammegors. Helicopter with bird at Airport Zeeland ready to take off to map the salinity distribution at and around Rammegors.

2.3.8 *SHALLOW FRESH-SALT DISTRIBUTION IN SUBSOIL: DUAL-EM*

With DUAL-EM, the shallow fresh-salt distribution was measured for four lines in the tidal area on 20th of June 2017. One of the line is crossing the 5 piezometers in the tidal area where also EM-SlimFlex measurements have been carried out. The technique is comparable with the airborne EM-measurements, but this equipment can be handled manually and therefore only gives information about the soil-resistivity of the shallow soil. Dual-EM is frequency domain with 1 frequency and 6 different coils and may have an investigation depth between 2 to 6 meters. With Dual-EM the salinization process in Rammegors can be mapped in much more detail for this shallow part than the information obtained with airborne-EM.

2.4 MONITORING RESULTS

2.4.1 *GROUNDWATER LEVELS AND HYDRAULIC HEADS*

Groundwater heads are available from 2011 for the polders north and south of Rammegors. In the Prins Hendrikpolder the groundwater table is located approximatelly 0.5 to 1.0 meter below the land surface on the southern side (the side of Rammegors) and about 1.0 to 1.75 meter below the surface in the center of the polder (Figure 23). In summer the groundwater level is about half a meter lower than in winter. Measurements in both a shallow and deep filter at measuring point RP06 show that the head in the deep filter is higher than in the shallow filter, and thus that seepage is taking place.

In the Haaftenpolder, south of Rammegors, the groundwater table is located about 1.5 meter below the surface in summer and rises to close to the surface in winter (Figure 23). Fluctuation in the groundwater table resulting from precipitation events is larger than in the Prins Hendrikpolder. Measurements in a deep and a shallow filter at RH02 show that no or only slight seepage takes place; the groundwater heads in both filters are comparable.

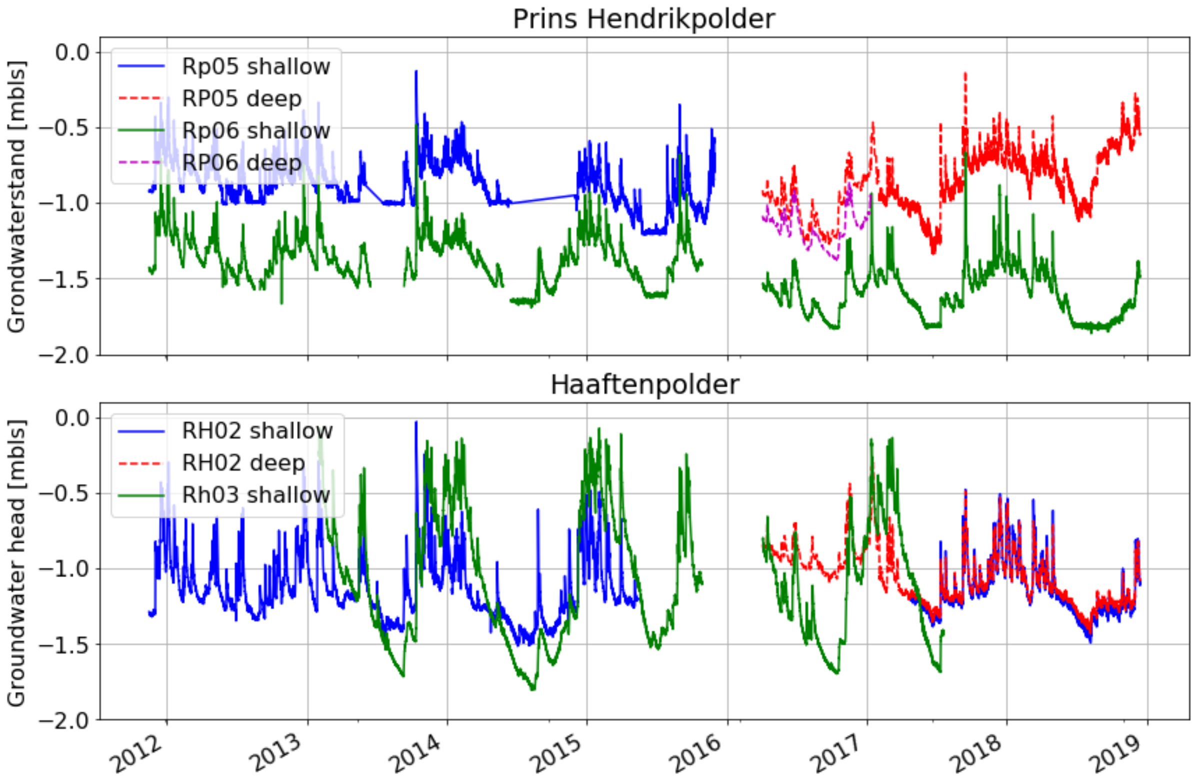


Figure 23. Long-term time series of the groundwater in the Prins Hendrikpolder on the northern side of Rammegors and in the Haaftenpolder on the southern side of Rammegors. Groundwater heads in meter below land surface.

The connection between the Eastern Scheldt/Krabbenkreek and Rammegors was opened on December 5th 2016. Since then the Rammegors area is experiencing tides. Figure 24 and Table 4 show the period around the opening of the inlet and shows that there is no reaction of the groundwater heads on the opening of the inlet. The groundwater tables at measurement points RH01 and RH04 in the Haaftenpolder show a daily fluctuation as a result of evapotranspiration during the day. The other filters do not show this variation because they were only measured daily until January 2017.

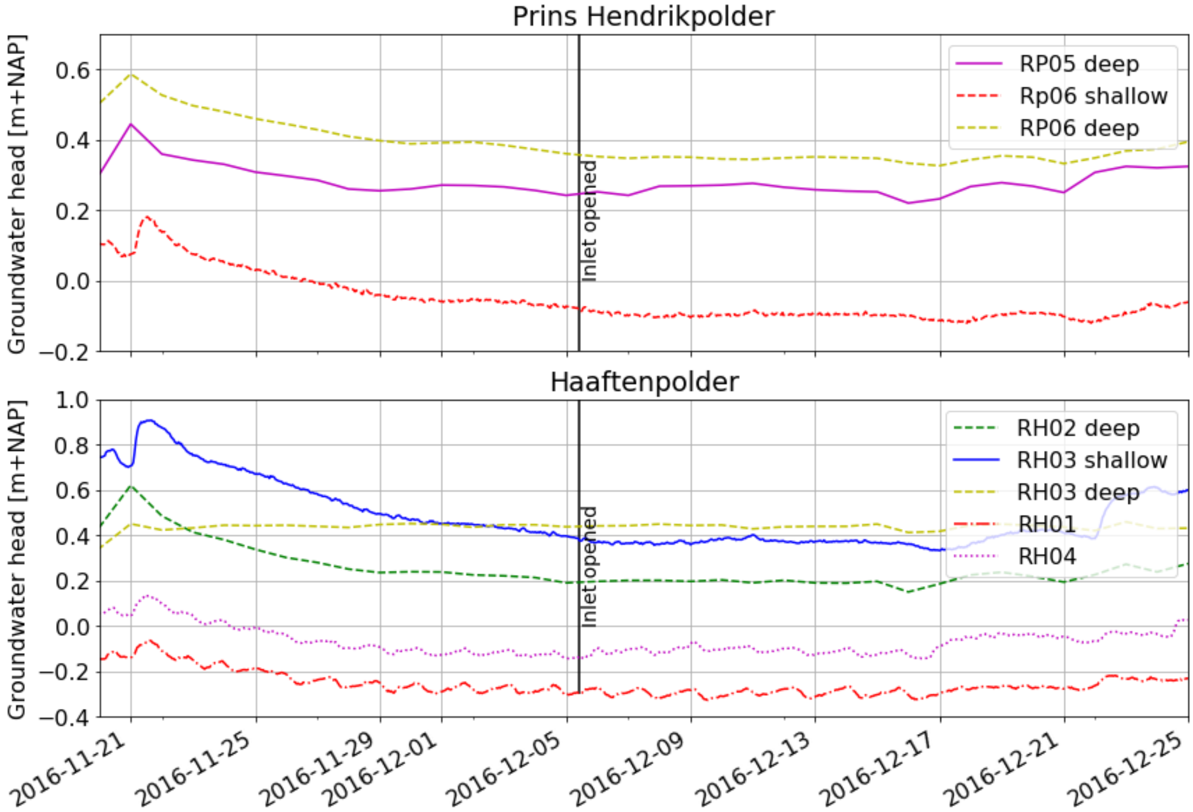


Figure 24. Groundwater heads in meter relative to NAP in the Prins Hendrikpolder and Haaftenpolder around the time of the opening of the inlet between the Eastern Scheldt and Rammegors.

Table 4. Measured EC values in the surface water before and after the opening of the inlet between the Eastern Scheldt and Rammegors.

EC [µS/cm]	Date	Wg1	Wg2	Rg zuid	BS1	BS2	Rg noord
Before opening	30-11-2015	1980	1760	>3999	2380	4000	
After opening	14-12-2018	>3999	1168	>3999	>3999	>3999	>3999

In 2017 and 2018 groundwater heads were also measured inside the Rammegors area itself. Figure 25 shows some of the measurements that were measured in the Rammegors area and in the surrounding polders. Note that the measurements are now shown relative to NAP. The groundwater heads in Rammegors show a large fluctuation as a result of the tides, which has two peaks and two minima per day.

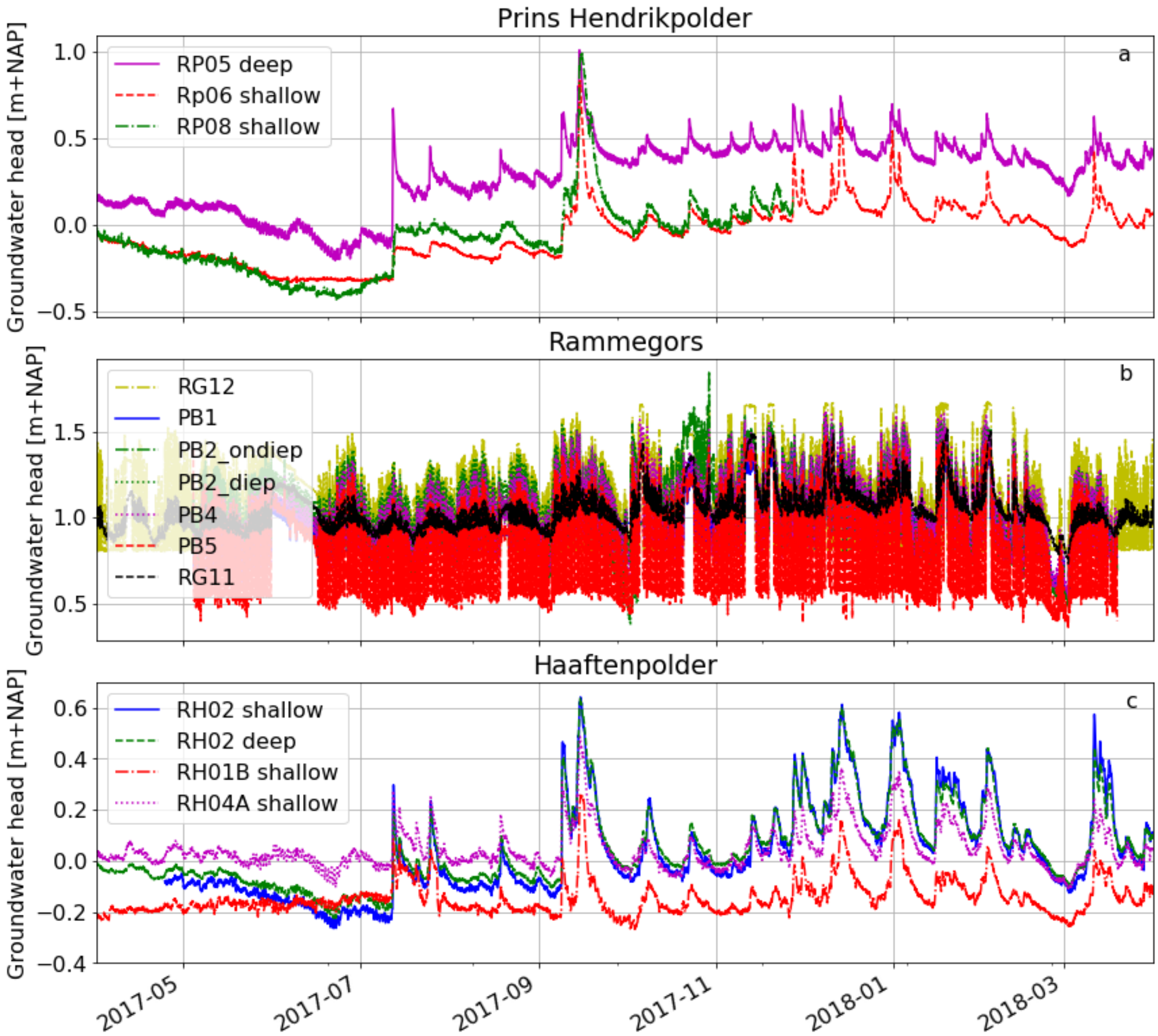


Figure 25. Groundwater heads in meter above NAP during the measurement period 2017-2018 in the Prins Hendrikpolder (a), Rammegors area (b) and Haaftenpolder (c).

At the end of May 2017, the inlet was closed for about 2 weeks due to construction works. As a result of this, a high-water situation was continued and (stagnant) water was covering almost the whole of the Rammegors area. This high-water level slowly decreased as water slowly infiltrated (Figure 26).

From this water level decrease, we can make an estimate of the infiltration within the Rammegors area. In a period of 15 days the water level decreased 243 mm, but about 50 mm of this was a step decrease on the 8th of June, which we did not include in the infiltration estimate. The evaporation was estimated to be about 5.5 mm/day, based on the daily KNMI Makkink reference-evapotranspiration and corrected with an open-water factor of 1.30 (Pouwels, 2018). Water may be leaking at the outlet of the Rammegors area, although this could partly be counterbalanced by reversed leakage during high tide situations. Infiltration is therefore considered to be the main part of the remaining water balance and from the numbers above is estimated at 7.4 mm/day.

,The groundwater heads in Rammegors maintained at a high level during closure of the inlet because of the high surface water level in the area (Figure 26b). Striking is that the groundwater heads still show influence of the tides, while the surface water doesn't. This shows that the groundwater system is still connected with the tides of the Eastern Scheldt, at no more than 200 m distance from the piezometers.

Figure 26a and c show the groundwater tables and heads in the surrounding polders during the closure of the inlet of the Rammegors area. There is no clear reaction of the groundwater system. Both the phreatic groundwater table and the heads in the deeper piezometers in the Haaftenpolder show a daily fluctuation of several centimeters as a result of evapotranspiration (Figure 26c). This shows that there is a tight connection between the phreatic groundwater system where evaporation takes place and the aquifer at a depth of 15 meter in the Haaftenpolder: there is hardly any resistance between the layers. In the Prins Hendrik polder the groundwater head measured in the deep piezometer RP05 is affected by the tides, while the shallow groundwater table measured in the other piezometers do not show tides or evaporation (Figure 26a), which indicates the presence of more resistance between the layers. The fact that the deep piezometer RP05 is affected by the tides during the closure of the Rammegors inlet shows that the aquifer at this location is more influenced by the Eastern Scheldt than by the Rammegors area. This piezometer also shows a trend over several days: the groundwater head rises between June 6th and June 9th followed by a decrease. This trend is caused by the springtide-neap tide cycle.

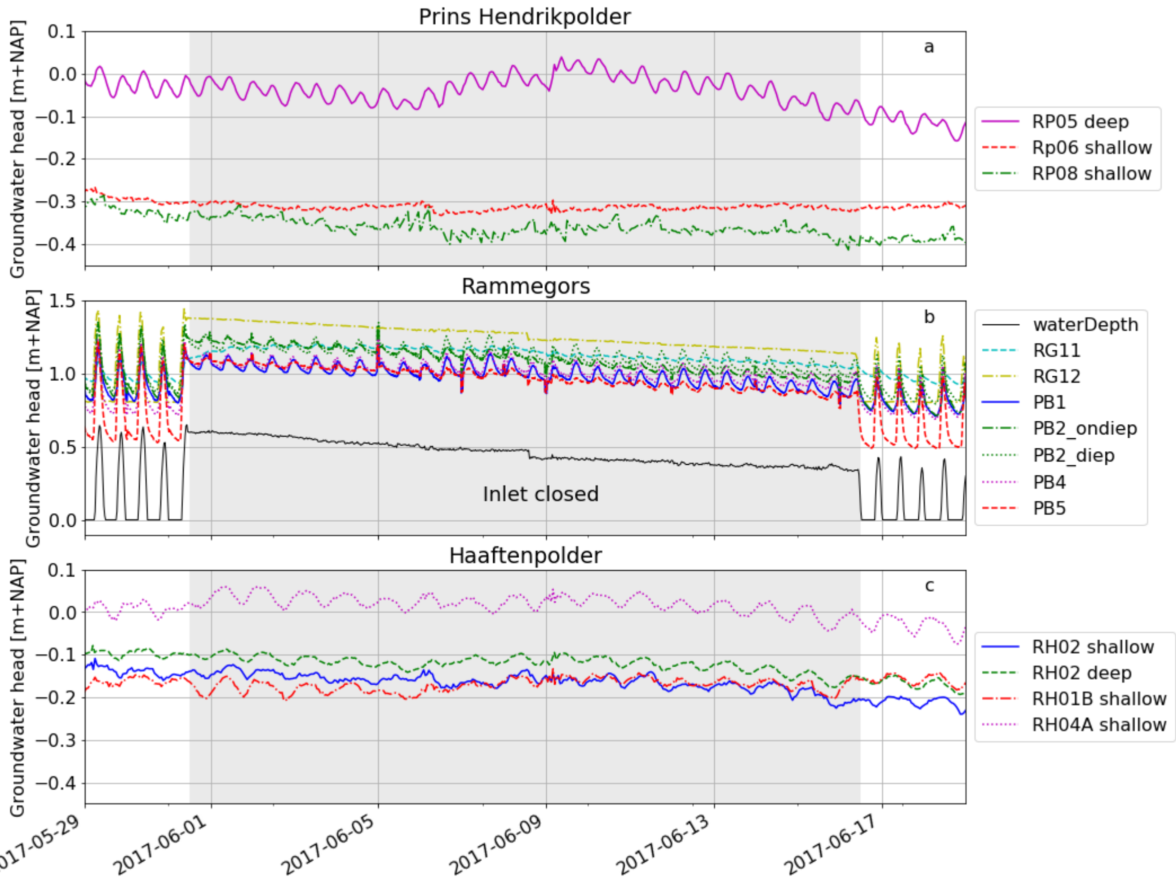


Figure 26. Groundwater heads in meter above NAP in the Prins Hendrikpolder (a), Rammegors area (b) and Haaftenpolder (c) during the closure of the inlet in June 2017. The unit of 'waterDepth' in panel b is meter above surface at the measurement point and the height of the line thus cannot be directly compared to the groundwater measurements.

In August 2017 the inlet of the Rammegors was closed once again, this time for a period of 3 days and like the previous time also during a high-water period. Like the closure in May/June, the groundwater heads continue showing tides during the closure (RP05 deep, Figure 27a). Unfortunately, at this moment we don't have measurements of the surface water levels during this period. Due to precipitation the groundwater tables are approximately 10 to 40 cm higher than during the period of the last closure in May/June. While the groundwater tables showed a daily fluctuation during the previous period (Figure 26), this trend is no longer present in August 2017 (Figure 27), for which no explanation has been found yet. Right around the closure of the Rammegors inlet on August 18th there is an increase in heads of 5 to 20 cm in both the deep and shallow filters. It is probable that this increase is caused by precipitation: between August 18th 8:00 and August 19th 8:00 there was approximately 6 to 9 mm rain in the area (Table 5). However, 18-28 mm of precipitation on August 15th only caused a minor and more slow increase in heads. Presumable this precipitation event was predominantly stored in the unsaturated zone.

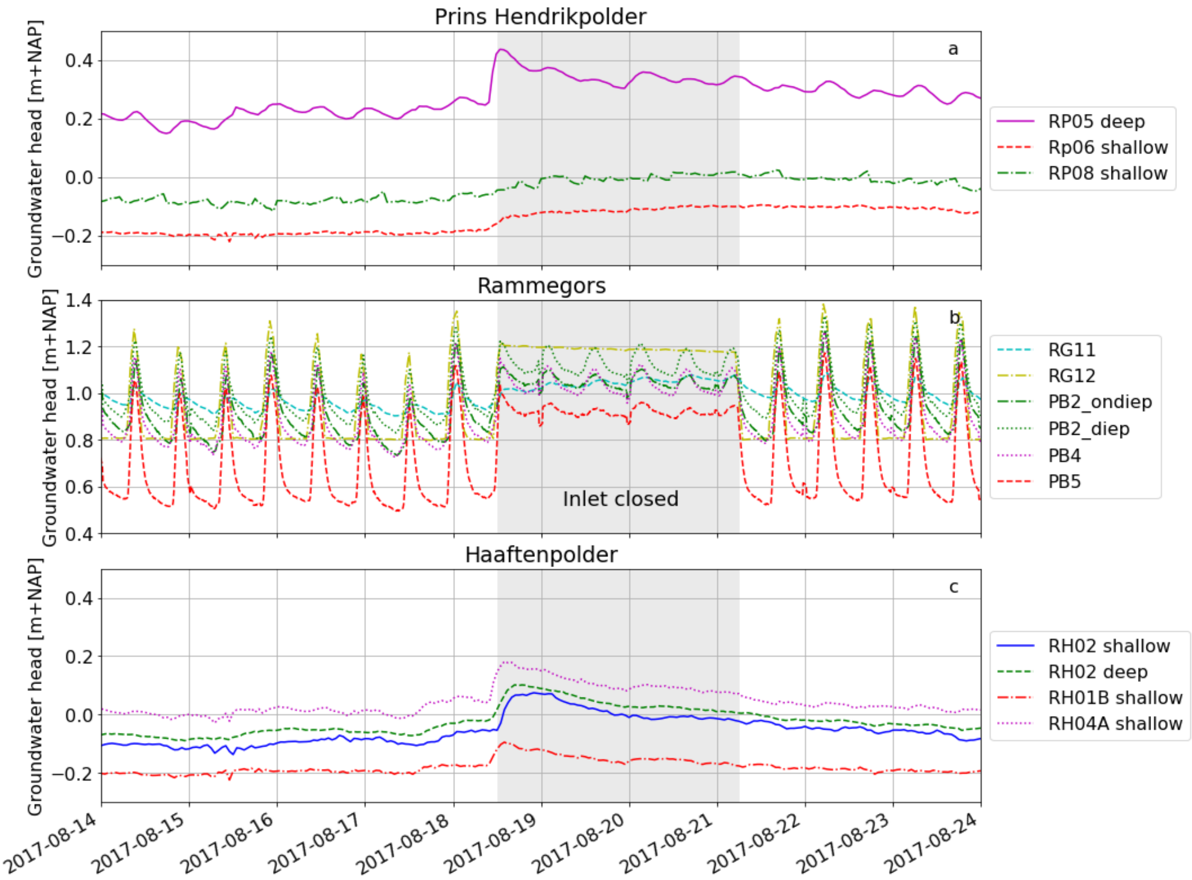


Figure 27. Groundwater heads in meter above NAP in the Prins Hendrikpolder (a), Rammegors area (b) and Haaftenpolder (c) during the closure of the inlet in August 2017.

Table 5. 24-hour precipitation of nearby meteorological stations in mm.

	Stavenisse	Anna Jacoba Polder	Wilhelminadorp
20170814	0	0	0
20170815	4.3	3.3	5.8
20170816	23.6	18.6	28.1
20170817	1.4	1.3	.3
20170818	8.4	9.1	6.1
20170819	8.2	6.3	9.2
20170820	3.6	6.4	7.1
20170821	0	0	0

In October and November 2017, the inlet of the Rammegors area was closed three times. Just like during the previous closures there was a stagnating high-water level in the area, while the groundwater was still affected by tides (Figure 28c). Likewise, in the Prins Hendrikpolder the groundwater head in the deep filter of RP05 is influenced by tides of the Eastern Scheldt, while the phreatic groundwater isn't (Figure 28b). Both the shallow and deep groundwater heads in the Polders (Figure 28b and d) show a clear reaction to precipitation events (Figure 28a).

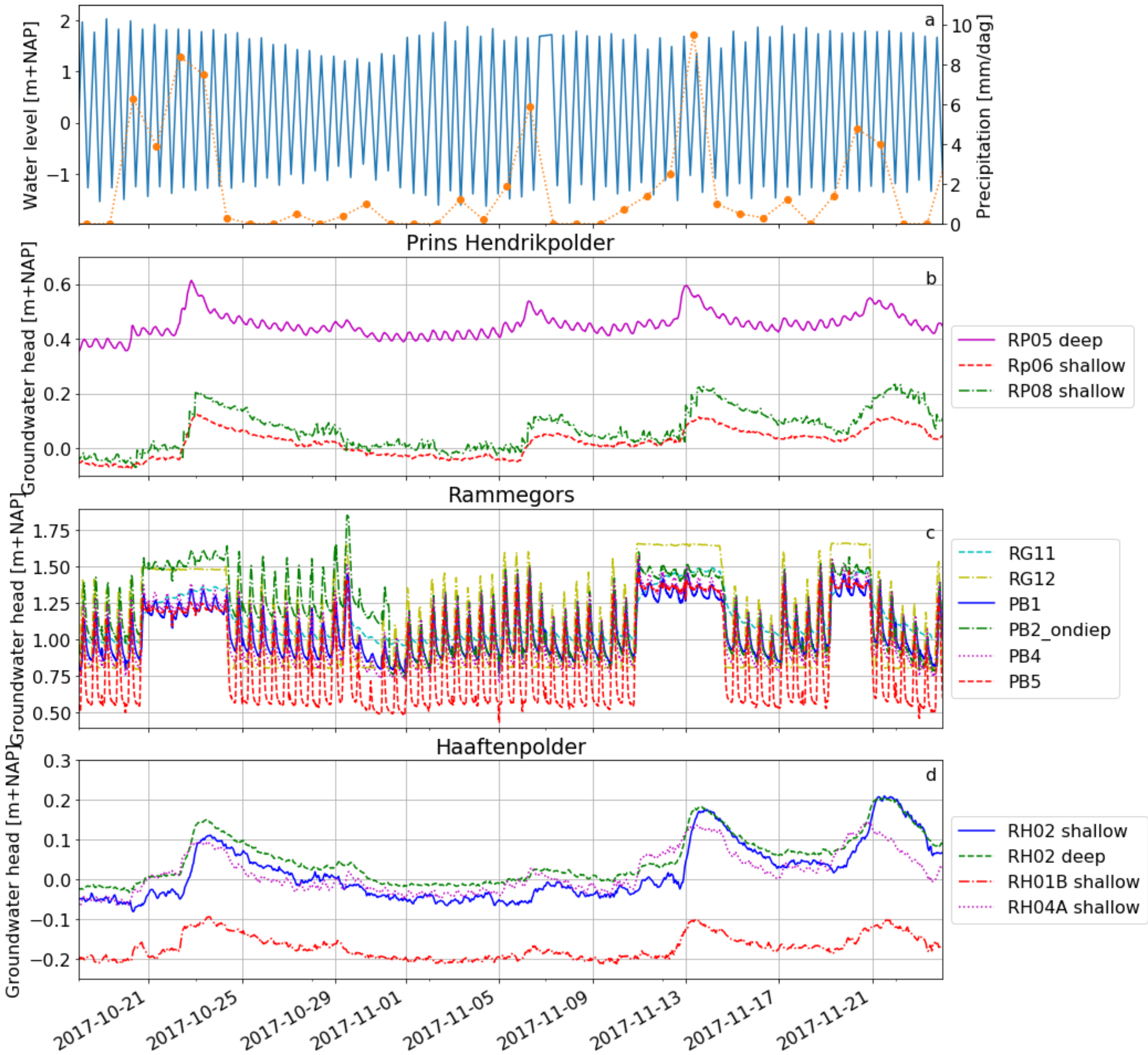


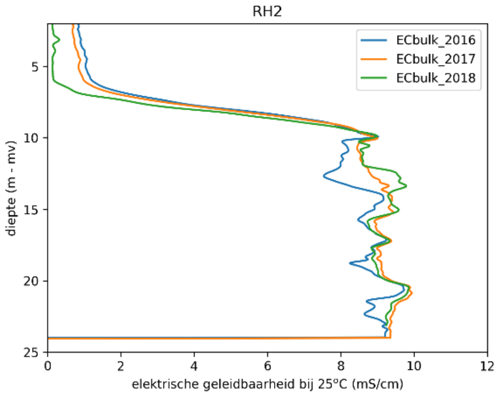
Figure 28. Groundwater heads in meter above NAP in the Prins Hendrikpolder (a), Rammegors area (b) and Haaftenpolder (c) in October and November 2017.

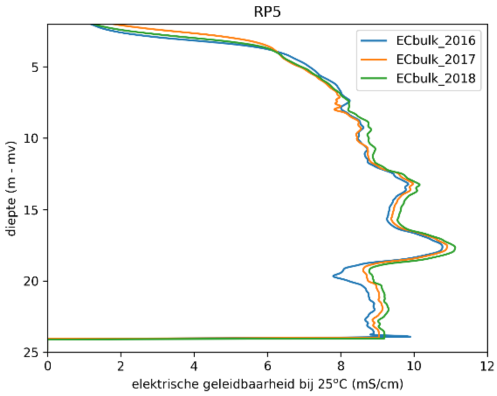
2.4.2 *FRESH-SALT INTERFACE (EM-SLIMFLEX AND ECPT)*

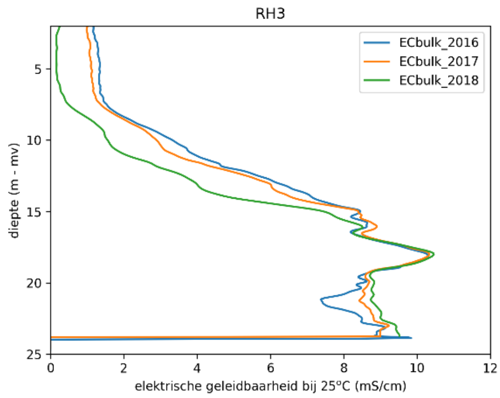
The EM-SlimFlex measurements are presented in Figure 29 and Figure 30. The measurements were corrected for temperature to a reference temperature of 25 C°, assuming a field temperature of 10.5 C° for the entire depth.

All locations in the agricultural area show a relatively shallow fresh-salt interface depth which is defined as the center of the transition between fresh and saline groundwater. In the Haaftenpolder, at RH-02 the interface depth is found at 8 m below surface and the transition zone is small. The interface at RH-03 is found at 12 m below surface but the transition zone is much wider, indicating that mixing processes have been more active. At RP-5 in the Prins Hendrikpolder, the interface is much shallower, i.e. 2.5 m below surface and for RP-06 at 8 m below surface level. The differences of the interface between the three measurement periods are within the accuracy of the measurements, except for RH3 which show a 2.5-

meter deeper interface for 2018 compared to 2016 and 2017. There is no reasonable explanation that the freshwater lens has grown during this period. Considering the restoration of the tidal area it is expected that freshwater lenses are decreasing.







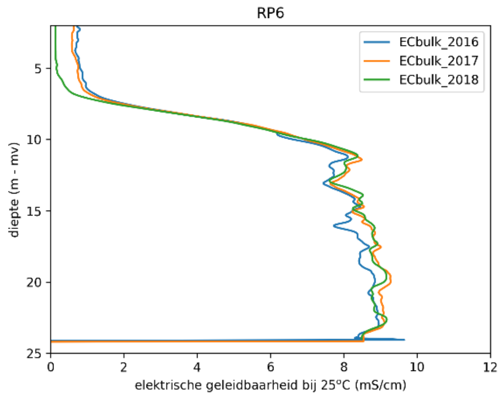
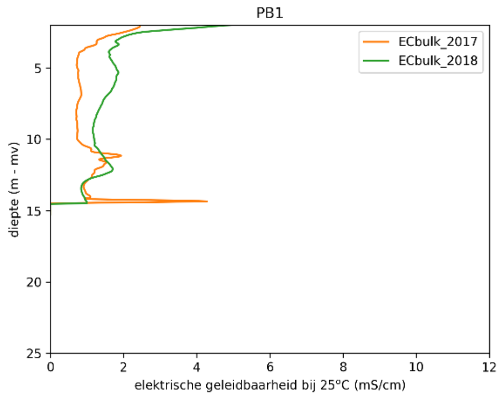
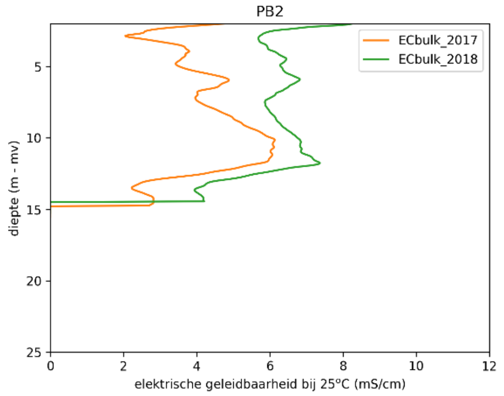
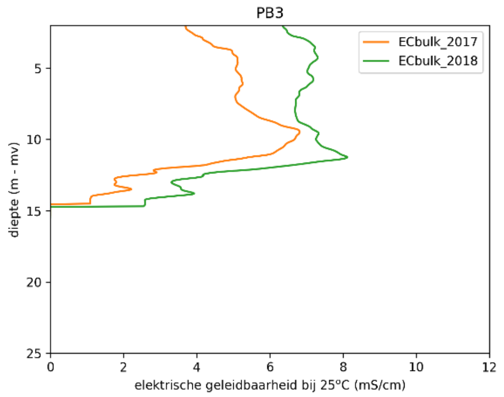


Figure 29. EM-SlimFlex-measurements for four locations in the agricultural area, for three periods (March 2016, May 2017, June 2018).

At five locations in the tidal area, the salt distribution with depth is measured two times. The monitoring locations are situated at different elevations which consequently result in differences in tidal flooding. Pb1 is situated at 1.42 m NAP and is only flooded a few times per month. As a result, the entire profile of pb1 is relatively fresh and only in the top 1-2 meter the salinity is increased indicating a salinization from above. There is a clear increase in salinity between 2017 and 2018 for the upper 12 meters. Pb2, pb3 and pb4 were already a bit salinized for the upper 10-11 meter which is probably the result of the incidental openings since December 2014. Since 2014 salt water has entered Rammegors and a stagnant salt water body was present for parts of the period between December 2014 and December 2016. It is clearly visible when comparing the 2017 and 2018 measurements that the salinization is actively taking place. For the entire depth the salinity has increased by a factor 1.2 to 2.0. The salinization is highest for the upper 10-11 meters. Pb5 is situated at an elevation of 0.60 m NAP, at the border of a permanent surface water body which contains salt water since the first opening in December 2014. However, the measurements show a relatively fresh top 5 meters and increasing salinity with depth, which is not what we expected.


PB1
ECbulk_2017
ECbulk_2018
diepte (m - mv)
elektrische geleidbaarheid bij 25°C (mS/cm)


PB2
ECbulk_2017
ECbulk_2018
diepte (m - mv)
elektrische geleidbaarheid bij 25°C (mS/cm)


PB3
ECbulk_2017
ECbulk_2018
diepte (m - mv)
elektrische geleidbaarheid bij 25°C (mS/cm)

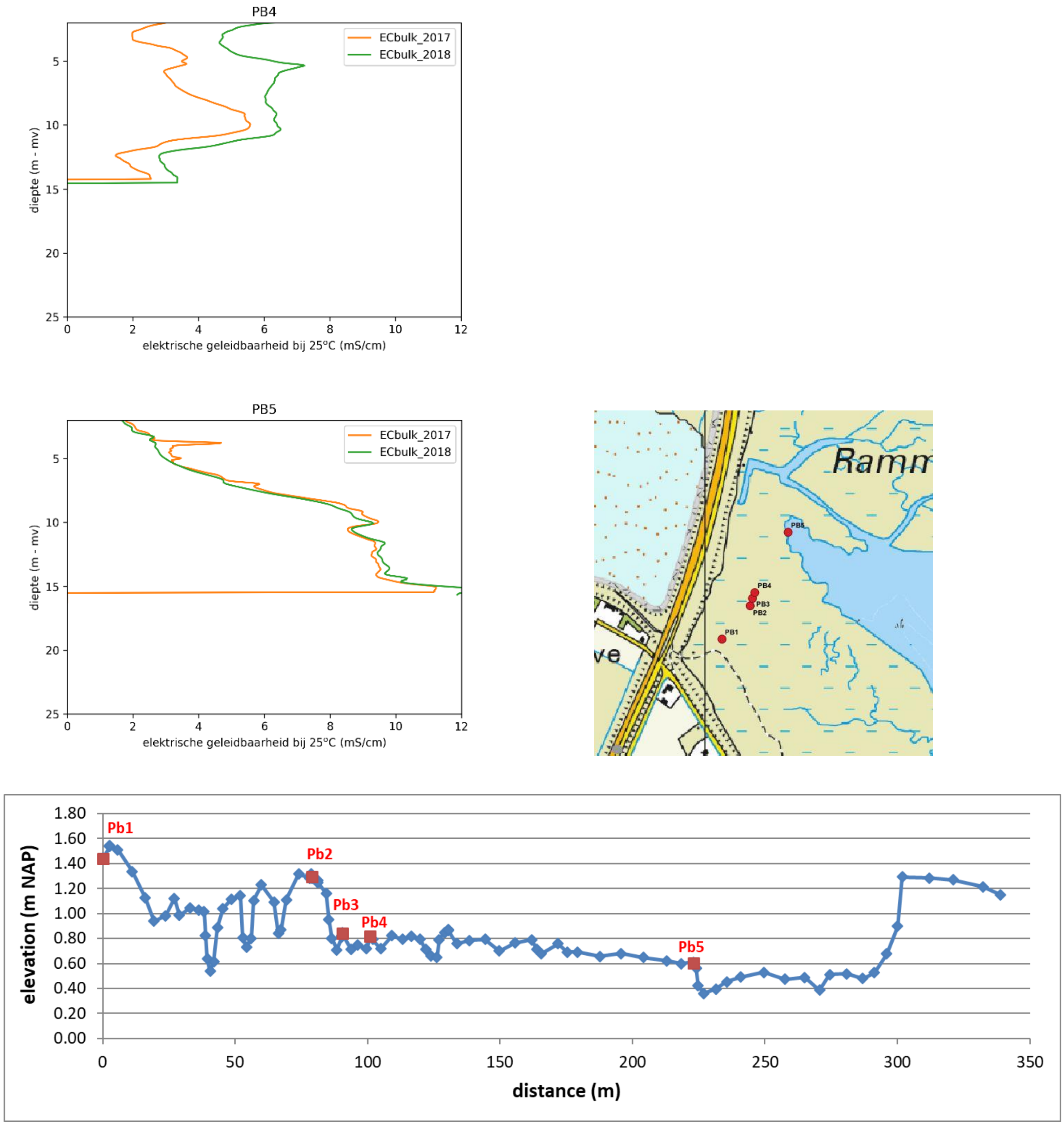


Figure 30. EM-SlimFlex-measurements for five locations in the tidal area, for two periods (May 2017, June 2018) and a profile of the ground level with the location of the monitoring locations.

Figure 31 shows the depth of the interface before the opening of Rammegors (ECPTs) and in 2016 (EM-SlimFLex). Clearly visible the thicker freshwater lens south of Rammegors, compared to the Prins Hendrik polder in the north.

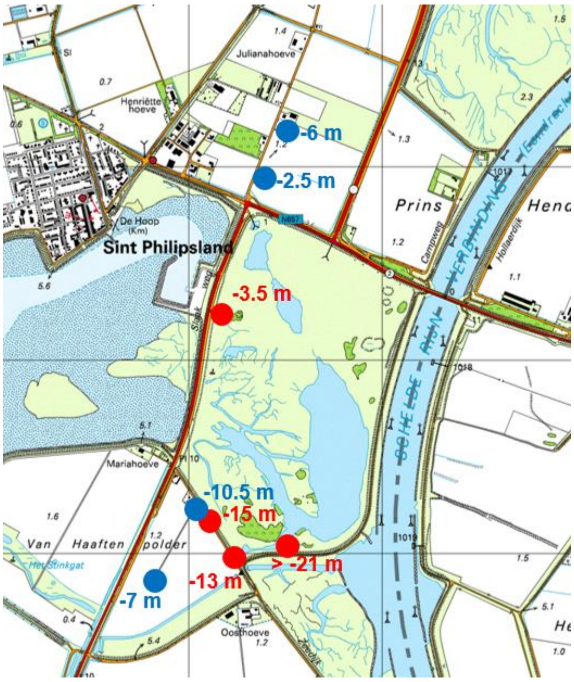


Figure 31. Depth of the fresh-salt interface from ECPTs (red dots) and EM-SlimFlex measurements (blue dots).

2.4.3 *FRESH-SALT DISTRIBUTION IN SUBSOIL: DUAL-EM*

At 20 June 2017 EM-dual measurements were carried for four lines in the tidal area. In Figure 32 two cross-sections of the soil-resistivity are shown which cross piezometers Pb1 (cross section 1) and Pb2-5 (cross section 2). The measurements show a very saline upper part of the subsoil (first meter) for Pb1. This piezometer is situated higher than the other piezometers at 1.5 m NAP which is seldom inundated with saline water, in contrast for the rest of the area which is inundated twice a day. It should be noted that the depth of investigation is only 2 to 2.5 meter because much of the signal has been lost in the saline upper part and the results below this depth could be unreliable. Below the saline upper part, a possible much fresher layer is found, according to the expectations and SlimFlex-measurements. In the north-part, much higher resistivities are found probably indicating a much fresher zone or the presence of coarser sand.

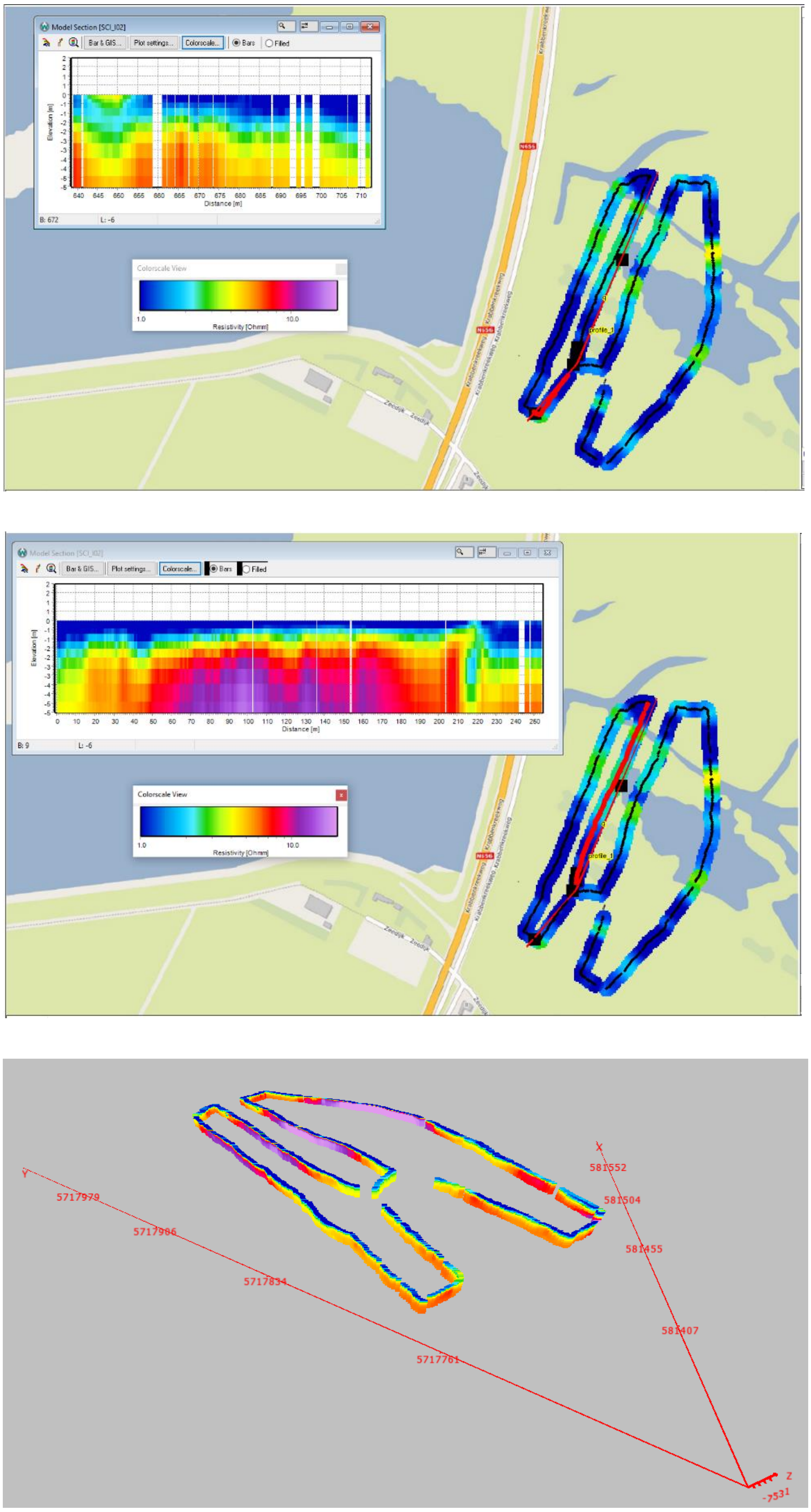


Figure 32. Dual-EM results (20 June 2017) with colors representing the soil-resistivity for the upper 5 meters. The top-figure shows a cross-section through Pb1 and the middle-figure through Pb2-5. Location of piezometers are indicated with black dots. The maps are representing the resistivity of the slice of 0.5 m depth. The lower panel shows the results in 3D for all the lines.

2.4.4 *FRESH-SALT DISTRIBUTION IN SUBSOIL: FRESHEM*

One of the FRESHEM-results is a 3D-voxel model which shows for every voxel of 25x25mx0.5m a Cl-concentration. This is obtained from the 3D interpolation of all the measurements at the flight lines (see Van Baaren e.a., 2017). Figure 33 shows the depth of the interface of the Cl-concentration of 1500 mg/l which can be seen as the interface between fresh (above) and saline groundwater (below interface). It therefore also gives an indication about the thickness of the freshwater lens. It can be seen that in a large area, the freshwater lens is thin (< 5 m), but in Rammegors de lens reach up to a depth 7.5 to 20 meters. With the exception of the gully in Rammegors which contain remnants of the earlier opening in Rammegors end of 2014 and beginning of 2015 (data survey FRESHEM was in March 2015). The freshwater lens in Rammegors extends for several hundreds of meters to the north (Prins Hendrik polder) and south (Haaftenpolder). The fresh water lens is probably the result of the freshening since closing of Rammegors from Eastern Scheldt. The results of FRESHEM correspond with the ECPT and EM-SlimFlex results.

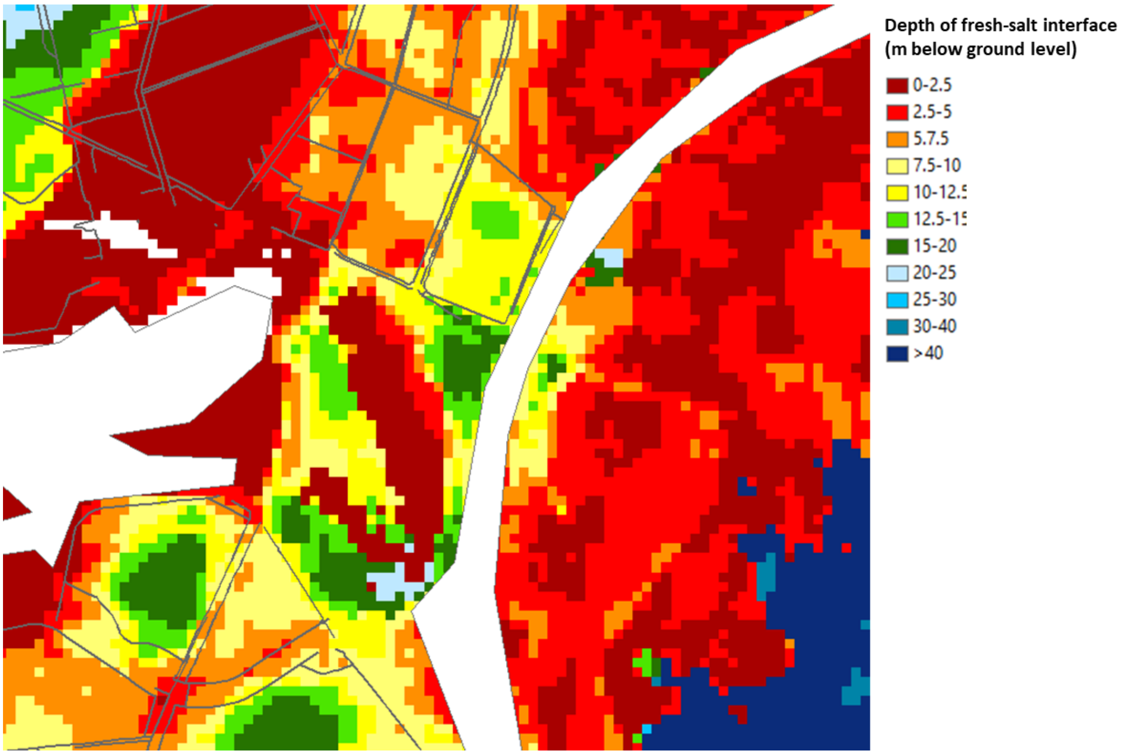
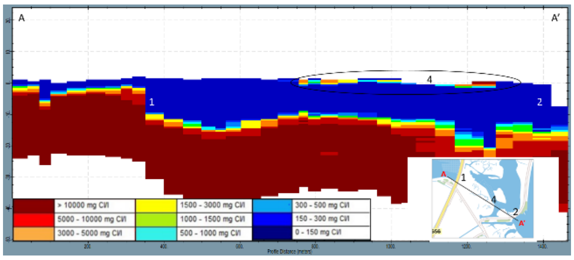
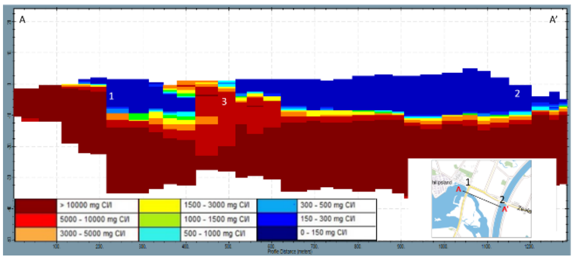
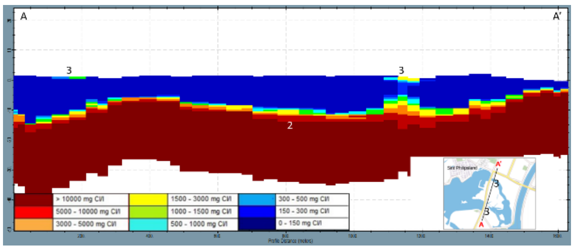


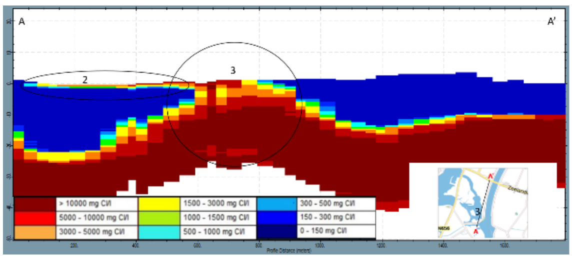
Figure 33. The depth of the fresh-salt interface (Cl = 1500 mg/l) below surface level (in m), derived from the FRESHEM-measurements.

From the 3D-model, different cross-sections have been derived to get a view of the salinity distribution with depth (Figure 34). Clearly visible is a well-developed fresh water lens till a depth of 15 meters floating on the saline groundwater below and the relatively sharp interface. At some location, the bottom of the lens corresponds with the presence of a high-resistant peat layer which probably blocked the infiltration of rainwater during the isolation of the Rammegors from the Eastern Scheldt. The thickness of the freshwater lens varies within Rammegors, and thicker lenses may be the result of the absence of the peat layer. The freshwater lens is absent at location where the cross sections cross the gully. The entire depth profile shows a high salinity which should probably be the result of the earlier openings when saline water had entered Rammegors and stayed there as a stagnant salt surface water body. However, this would mean that the infiltration of salt water over a depth of 10-20 meter was extremely fast and happened with a couple of months. Another possibility could be that the inversion of the FRESHEM-results was affected by a small (1-3 meter) thick shallow salt water layer on top of a freshwater body. At some locations, the FRESHEM results show a small 0.5 to 1 m thick saltwater layer on top of a freshwater body below which probably is the result of the earlier openings of Rammegors.









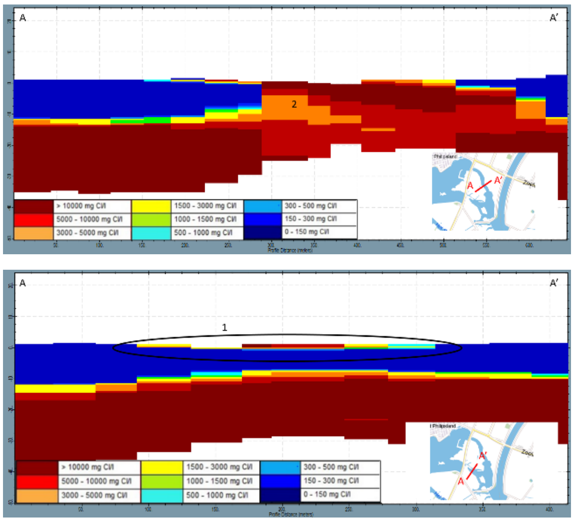


Figure 34. Cross-sections of the Cl-concentration derived from the 3D-FRESHEM result.

2.4.5 *SURFACE WATER SALINITY*

On 14th of March, field survey of the salinity of the surface water in the Haaftenpolder was carried out by direct measuring of the EC of the surface water with an EC-device (Figure 35). The field survey was carried out by students of the HZ. The results are given in the figure below. The large spatial variation of the EC in one ditch is visible. In the north, values lower than 3 mS/cm indicate fresh surface water while more to the south ECs are increasing up to 9 mS/cm. This corresponds with the depth of the fresh-salt interface which is found much more shallow in the south than in the north of the Haaftenpolder.

Figure 35. Results of a field survey of the Electrical conductivity (EC) of the surface water on 14-03-2016.

A TEC-probe was used in order to measure EC-depth profiles below a ditch bottom (Figure 36). In this way, saline seepage (upward flow of saline groundwater) can be detected without the influence of surface water flow through the ditch. In the Prins Hendrik polder, location 1 shows much higher salinities than location 2 indicating the presence of saline seepage. Location 1 is situated farther away from the Rammegors. These measurements also correspond with the depth of the fresh-salt interface, which shows a decrease with distance from Rammegors.

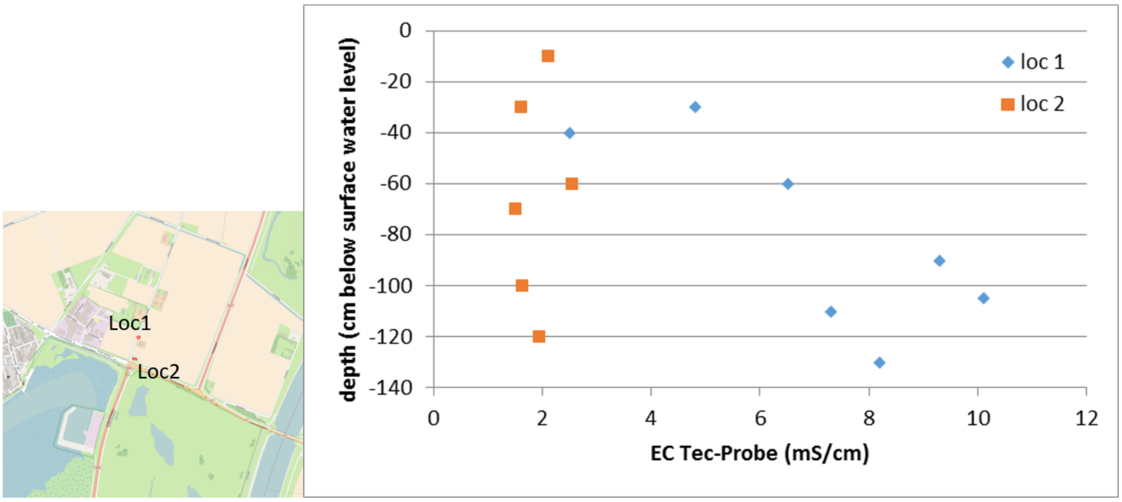


Figure 36. Results of two TEC-probe measurements on the bottom of a ditch, close to Rammegors.

2.5 MODELLING THE SALINIZATION PROCESS IN NATURE AREA THE RAMMEGORS

2.5.1 *INTRODUCTION*

Nature area Rammegors has recently been transformed from a fresh inner-dyke nature area to a salt tidal area to increase the ecological value of the Eastern Scheldt area. Due to this transformation, salt water is infiltrating in the freshwater lens which has been formed by a precipitation excess of 40 years, when Rammegors was still enclosed by dikes. This salinization process is studied in more detail by two- and three dimensional models which have been developed in a generic MODFLOW/MT3DMS-based computer program, named SEAWAT in a GMS environment. Zeeland project FRESHEM has provided detailed isohaline maps of the area. These data have been used to investigate which factors; bathymetry, lithology, tides or regional groundwater flow, will have the largest impact on the salinization process in Rammegors. Additionally, it was studied what the impact of the transformation of Rammegors into a tidal area has and will have in the future on the groundwater system in the surrounding agricultural polder areas.

The modelling study was part of a MSc-study which is described in detail in America (2018). In this section, the key findings from America (2018) are summarized.

2.5.1.1 **PROBLEM DEFINITION**

The nature area the Rammegors experiences an unstable water density stratification because heavier seawater lies on top of lighter freshwater. This freshwater lens was created by precipitation excess when the Rammegors was embanked by dikes (Pauw, 2015). The unstable density stratification can give rise to free convection (fingering), where salinization (in subsoil) occurs much more rapid because the advective flow is driven by density differences (Post and Kooi, 2003). Post and Houben (2017) indicated that there is a lack of data for fresh water lenses in temperate climates in unconsolidated sediments. Because of the general scarcity of high-resolution field data, the role of density-driven fingering triggered by seawater inundation, has not yet been fully assessed under field conditions. In this study high quality hydraulic data and salt distribution data is available. These measured data will be used to evaluate the simulated models, as they can be used to simulate future situations. Many studies have investigated the process of free convection in unstable conditions in the past (Wooding et al., 1997a,b; Simmons et al., 1999; Kinzelbach, 2000; Post et al., 2004). Most of them focused on small-scale problems and almost no aquifer scale investigations have been done, as small discretization sizes are required. Unfortunately, small discretization sizes cannot always be used, due to computational limitations (Kooi et al., 2000).

2.5.1.2 **OBJECTIVES AND RESEARCH QUESTIONS**

As Rammegors experiences an unstable density stratification, the free convection process will be investigated in great detail as it has a large influence on the salinization process. The salt fingers, which can form due to free convection, can create areas which contain more salt than other areas. Besides that, the heavier salt water can move faster downwards due to the salt fingering. The heterogeneous pattern of salt in an area can have a large influence on the specific flora and fauna, as the presence of salt is a dependent factor. Free convection can be influenced by many factors as it is dependent on the unstable density stratification. Factors which will be considered are:

- Bathymetry: Inside Rammegors height differences are small due to compaction and calving of sand marshes and sedimentation of sediments in creeks (Van der Reest and Van Haperen, 1996). The small height differences can be found at the mud-flats as they are still intact. These mud-flats can have a major influence in the convection process (Voss et al., 2010). In higher elevated areas, water will infiltrate more easily than in lower elevated areas where water accumulates during high tide. During low tide, water can be drained through the lower elevated areas (gullies), to the mainstream of the Rammegors.
- Lithology: As Rammegors was part of a tidal system with deep channels, tidal flats, and salt marshes before the embankment, a thick layer of moderate fine to silty sand was deposited by channels and creeks for several centuries (Arcadis and Rijkwaterstaat, 2013). Studies show that heterogeneity in lithology plays an important role in controlling convective instabilities (Prasad and Simmons, 2003; Simmons et al., 2001). Firstly, it can serve as the triggering mechanism. And secondly, it is the most important factor which controls whether instabilities, once they are generated, will grow or decay.
- Tides: During high tide, a larger area can be inundated and a larger water column can be present in the gully. During low tide, some parts of the area fall dry. These periodically inundated areas

can be of large influence on the free convection process (Cartwright, 2004; Mulligan et al., 2011; Pauw et al., 2014) and should therefore not be neglected.

- Regional groundwater flow: The regional groundwater flow influences the process of free convection as it has a large influence on the density distribution in an area.

As free convection could be very important in the salinization process, the overall objective of this modeling study is:

Investigate to what extent free convection influences the salinization process in Rammegors and to what extent it is influenced by bathymetry, lithology, tides, and regional groundwater flow.

Additionally, the following two research questions will also be answered using the numerical model results in combination with the obtained monitoring results.

- What is the effect of the initial salinity distribution obtained by paleo-modeling and by detailed measurements on the modeling results?
- What are the short-term and long term effects of the transformation of the Rammegors into a tidal area with average higher water level and an inflow of saline sea water?

2.5.2 *MODEL SET UP*

The models were made in a generic MODFLOW/MT3DMS-based computer program, named SEAWAT in a GMS environment. Figure 37 shows de location of the local and regional model.

The local model gives more understanding of the free convection process and how the different factors influence this process. The dimensions of the model is 300 meter in horizontal direction and 50 meter in vertical direction. First, the influence of the spatial discretization size on free convection was investigated, where several discretization sizes were used (0.5, 1.0, 2.0, 5.0, 10, 25m). The influence of bathymetry, lithology, tides and regional groundwater flow were investigated independently of each other but also in a coupled situation (Figure 38). The model is based on the transect AA' in the South-West of the Rammegors (Figure 37). This transect was chosen because of the large high density of monitoring data (ERT, SlimFlex, Hydraulic heads). The monitoring activities have been intensified for this transect because of the large spatial variation of the surface level and related inundation frequency and duration which differently impact the salinization process.

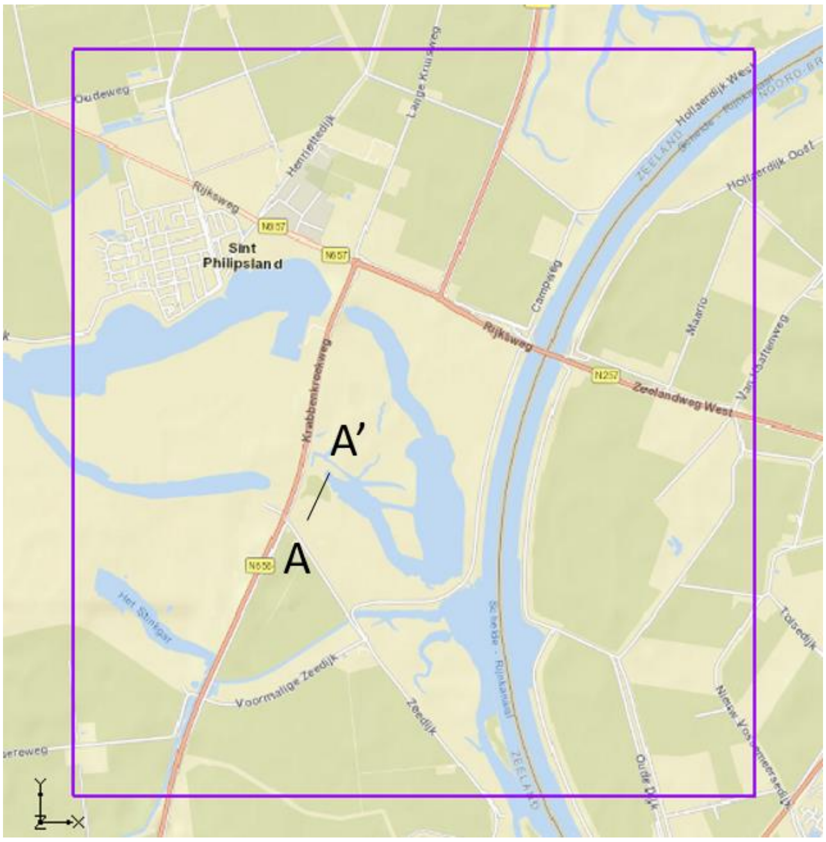


Figure 37. Overview of regional model (purple line). AA' line is transect location of local model.

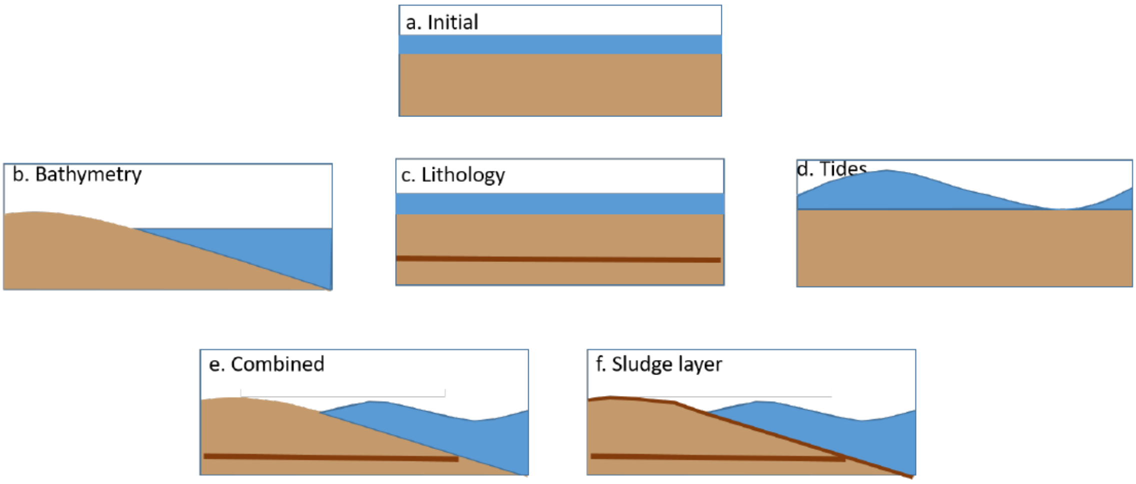


Figure 38. Schematic view of the 6 scenarios for the local model. a) Initial model, b) Bathymetry model, c) Lithology model, d) Tides model, e) Combined model and f) Sludge layer.

The regional model gives a more general overview of the salinization process in nature area Rammegors and effects outside the nature area. Figure 37 shows the spatial extent of the three-dimensional regional model, which is 50 meter in depth. The regional model has been divided in two smaller research phases. In the first phase (Freshening of Rammegors), the freshening of Rammegors was modelled for the embankment period. The end situation of this first phase was eventually used as initial situation for the second phase, the scenario analysis to understand possible future situations due to the opening in the Krabbenkreek in nature area Rammegors. Due to this opening, the Rammegors is influenced by tides and slowly salinizes. The tides could be implemented in different ways in the regional model. Besides that, the influence of different factors like precipitation, sea level rise and different initial saline conditions was investigated. Finally, two future scenarios were analyzed. The scenarios are:

1. Tides

- Fixed head: Tides were implemented with a fixed head.
- Tides 6 hours: Tides were implemented with an interval of 6 hours.
- Tides 10 days: Tides were implemented with an interval of 10 days.

2. Scenarios 2015

- Precipitation: Scenario where the influence of precipitation was investigated.
- Sea level rise: Scenario where the influence of sea level rise of 40 centimeters was investigated.
- FRESHEM: Scenario where the influence of initial concentration was investigated by implementing the measured chloride distribution from the FRESHEM data.

3. Future - 2066:

- Scenario where the situation in 2066 was critically analyzed with the ‘Tides 10 days’ and ‘FRESHEM’ scenarios.

For more detailed information of the set ups of the models, see America (2018).

2.5.3 *MODEL RESULTS*

2.5.3.1 **EFFECT OF CELL SIZE ON SALINIZATION BY FREE CONVECTION: 2D-MODEL**

In Figure 39, the concentration contours after 10 years are shown with different discretization sizes, ranging from 0.5 to 25 meter. A clear distinction in plume shapes between the smaller cell sizes (0.5- 2 m) and the larger discretizations (5 till 25 meter) can be observed, whereby the smaller cell sizes show more detailed plumes. There are more plumes in the situation with a discretization of 1 meter (Figure 39b), than in the situation with a discretization of 0.5 meter. The free convective plumes, which have developed with a cell size of 2 meter, are more emerged and are larger in length and width than the plumes formed at smaller scales.

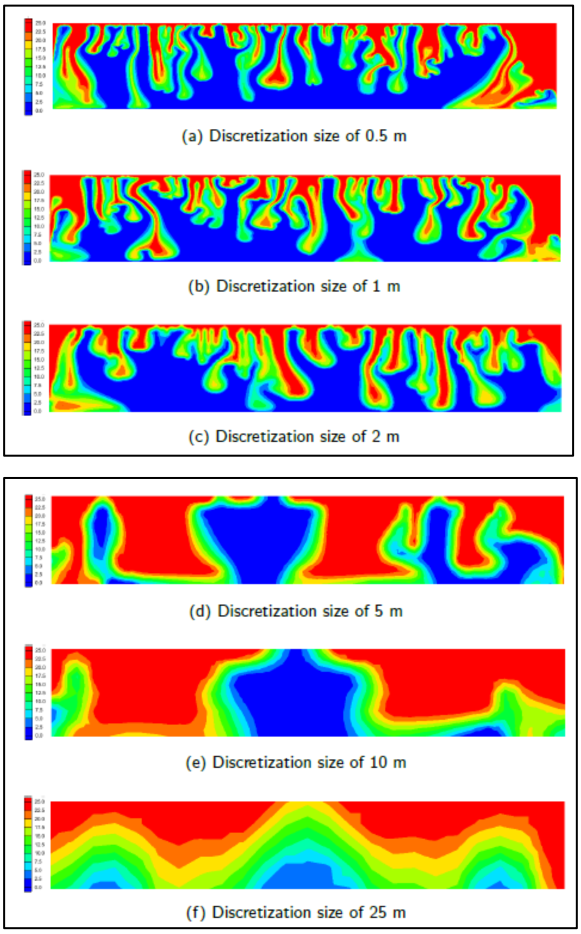


Figure 39. Concentration contours in TDS [g/l] after 10 years for different spatial discretization sizes.

Figure 40 shows the effect of cell size on the rate of the salinization process for DPF, COM and the total salt mass. DPF is the deepest position of the interface between the intruding solute plume and ambient groundwater and is defined using the concentration of C = 0.01. COM is the vertical center of mass, otherwise known as the mass midpoint of the salt plume which is integrated across the entire model domain. COM will provide slower but more reliable results than DPF because of its integrating effect.

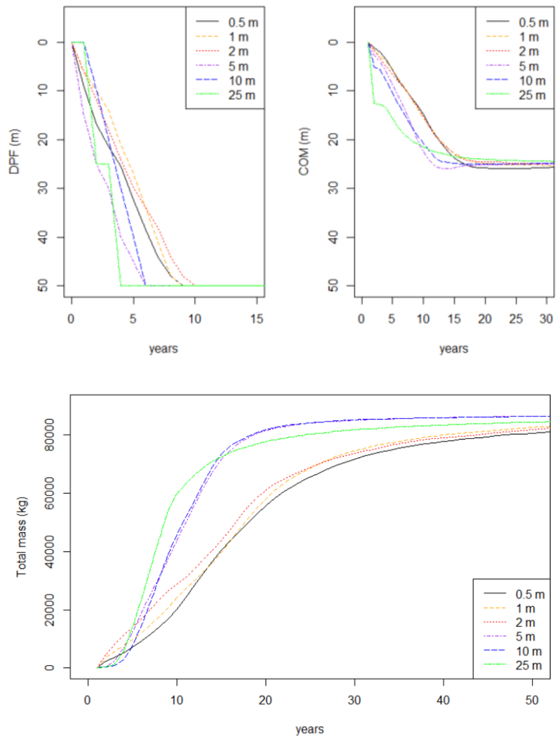


Figure 40. DPF and COM and total salt mass for different discretization sizes, boundaries excluded.

The differences between the small and large discretization sizes are clearly visible. The fingering process is well reproduced by the cell sizes of 2.0 m and smaller. Cell sizes of 5 m and larger show large plumes and this has clearly consequences for the velocity of the salinization process. The salinization process is faster when using larger cell sizes. This has large implications for regional groundwater models which usually using larger cell sizes than 25 m. With these large cell sizes the fingering process is not well reproduced and the rate of salinization by free convection could be exaggerated by a factor 2.

2.5.3.2 EFFECTS OF BATHYMETRY, LITHOLOGY AND TIDES ON SALINIZATION BY FREE CONVECTION: 2D-MODEL

In Figure 41, the concentrations contours for the different factors after 10 years, can be observed. When only bathymetry is implemented in the model, the plumes have changed to larger salt containing areas and the shape of the original plumes have diminished completely. Bathymetry influences mostly the shape of the plumes which are larger and move faster downwards. This could be caused by preferential start locations of plumes around the transgression zones to higher elevated areas.

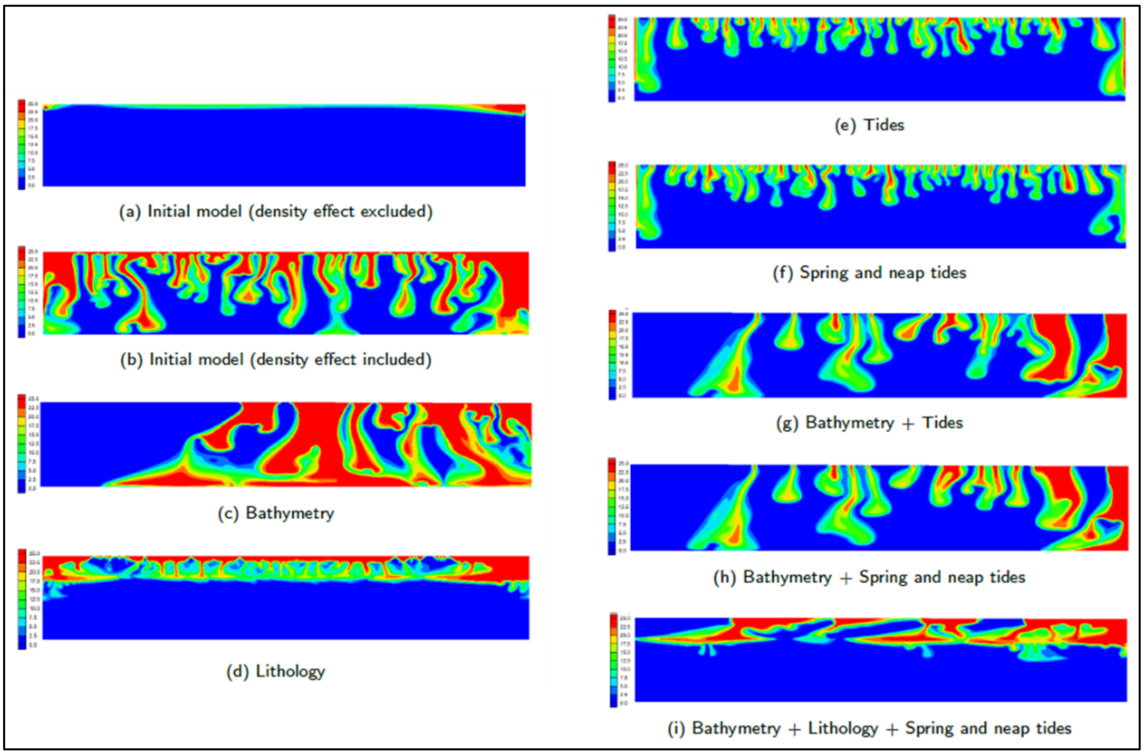


Figure 41. Concentration contours in TDS [g/l] after 10 years for different factors on the salinization process, with a discretization size of 1 meter.

Figure 41d shows clearly that lithology (in this case a large resistant compact peat layer at -12 to -14 m NAP) has a major impact on the salinization process. Figure 41e to Figure 41h show how spring and neap tides differ from a normal tide situation when bathymetry is taken into

account or not. When bathymetry is not implemented, the salinization process shows the same pattern as the initial situation. However, the plumes are smaller, thinner and less dense and the salinization process is slower. When spring and neap tides are implemented, slightly more and smaller plumes are shown but the effect on the salinization is nihil compared to two-daily tide.

Figure 42 shows that tides slow down the free convection process. When bathymetry is implemented this effect is less present. There is a small difference between the normal tides situation and the spring and neap tides situation. With spring and neap tides, the plumes move a little bit faster downwards but the center of mass of both situations are the same.

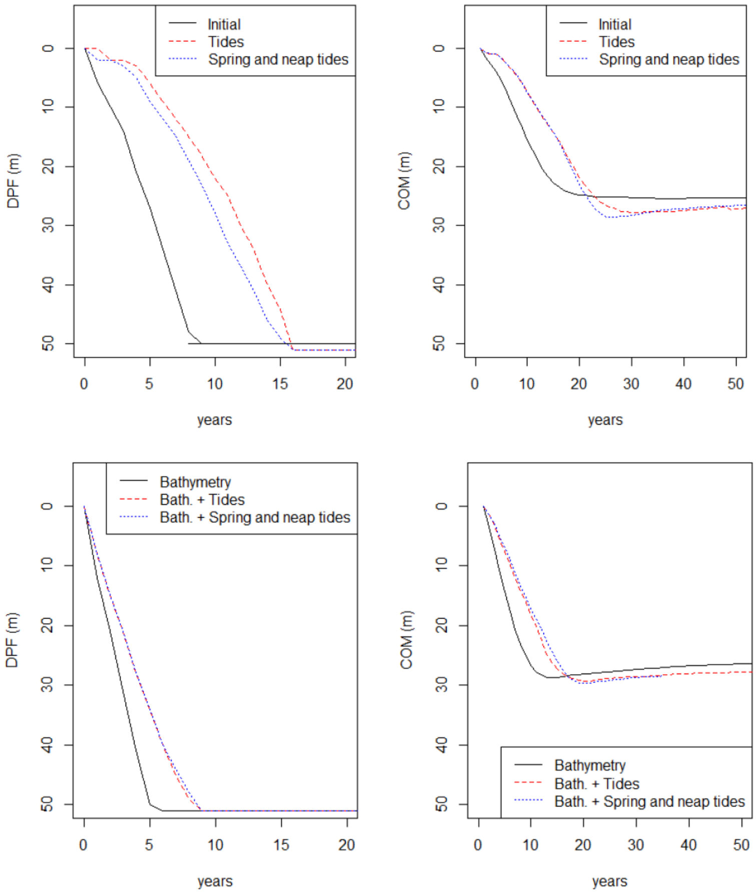
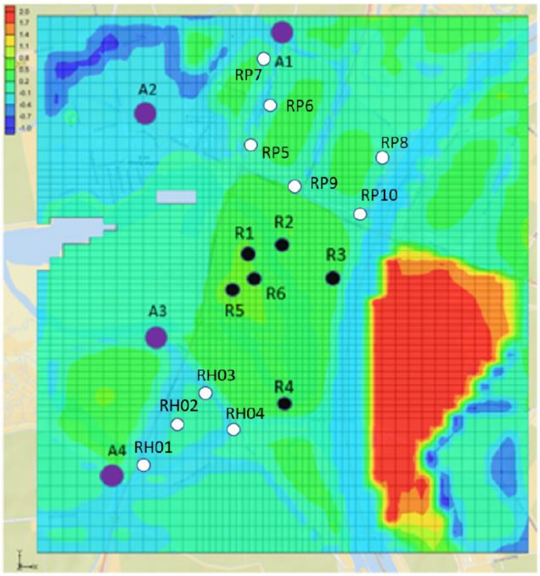


Figure 42. DPF and COM for the situations were tides and spring-neap tides and bathymetry are implemented, boundaries excluded.

2.5.3.3 SITUATION RAMMEGORS 2015: VALIDATION OF THE 3D-MODEL

The freshening process of Rammegors since the closure of the Krabbe-creek in 1972 until 2015 has been modelled with the 3D-model. Figure 43 shows the comparison between the modelled and measured heads. For most of the monitoring locations the modelled heads approach the measured heads. However, remarkable are the relative large differences for the newly installed deep piezometers RH02, RH03, RP5 and RP6. Now, there is no explanation for this large deviation.



Name	Average head (m NAP) (Rijkswaterstaat)	Head regional model (m NAP)	Difference (m)
R1	0.72	0.55	0.16
R2	0.65	0.40	0.15
R3	0.36	0.40	0.04
R4	0.32	0.33	0.01
R5	0.60	0.55	0.05
R6	0.59	0.58	0.01
A1	-0.20	-0.23	0.03
A1	-0.18	-0.16	0.02
A2	-0.35	-0.29	0.06
A2	0.09	-0.256	0.35
A3	0.37	-0.11	0.48
A3	0.21	-0.06	0.27
A4	-0.33	-0.3	0.03
A4	-0.42	-0.23	0.19

Phreatic groundwater level (-2 m NAP)

Deep groundwater level (-18 m NAP)

Name	Average head [m NAP] (Deltares)	Simulated heads regional model [m NAP]	Difference [m]
RH01	-0.34	-0.28	0.06
RH02	-0.02	0.01	0.03
RH02-deep	0.22	-0.17	0.39
RH03	0.30	-0.01	0.31
RH03-deep	0.50	-0.133	0.63
RH04	-0.03	-0.152	0.12
RP5	0.32	0.15	0.17
RP5-deep	0.28	-0.15	0.43
RP6	0.13	-0.045	0.18
RP6-deep	0.32	-0.166	0.49
RP7	-0.11	-0.082	0.03
RP8	0.12	0.151	0.03
RP9	0.40	0.07	0.33
RP10	0.25	0.07	0.18

Figure 43. Comparison between modelled and measured heads.

Figure 44 shows the comparison between the modeled and measured (FRESHEM) fresh-salt distribution. First, it should be noted that the simulated fresh-salt distributions has different units (in TDS) than the measured fresh-salt distribution (Cl g/l). Similarities can be seen in the freshwater lens which is present in Rammegors and the freshwater zone at the right-hand side of the figure. Differences are also visible, like (a) the difference in initial concentration of the subsoil, (b) the difference in freshwater lens thickness (large circle Figure 44) and (c) the presence of a salt gully inside in the Rammegors (small circle Figure 44).

a) Initial concentration 1972. This is caused by the assumption that the whole area was saline and has the same concentration as the North Sea (i.e. 16 g/l Cl or 35 g/l TDS). According to FRESHEM, Cl-concentrations are lower, between 10 and 16 g/L. The same holds for the freshwater area at the right hand side. It is likely that this area already contained freshwater in 1972.

b) Thickness of freshwater lens. The calculated lens is too thick compared to the FRESHEM-results. Multiple reasons could cause this difference in thickness and most likely it is a combination of reasons:
   - Lithology is different. Especially, the clay and peat layers could have a lower hydraulic conductivity.
   - Rammegors didn't have a fixed head in the open water area of 0.4 meter. Maybe it was 0.3 meter.
   - The precipitation excess is lower than simulated 0.6 mm/day.

c) The salt gully which is visible inside Rammegors. The FRESHEM measurements were taken after the two false openings in 2014 and 2015 which resulted in a stagnant salty surface water in the gully. This was observed by the FRESHEM-results but not implemented in the model.

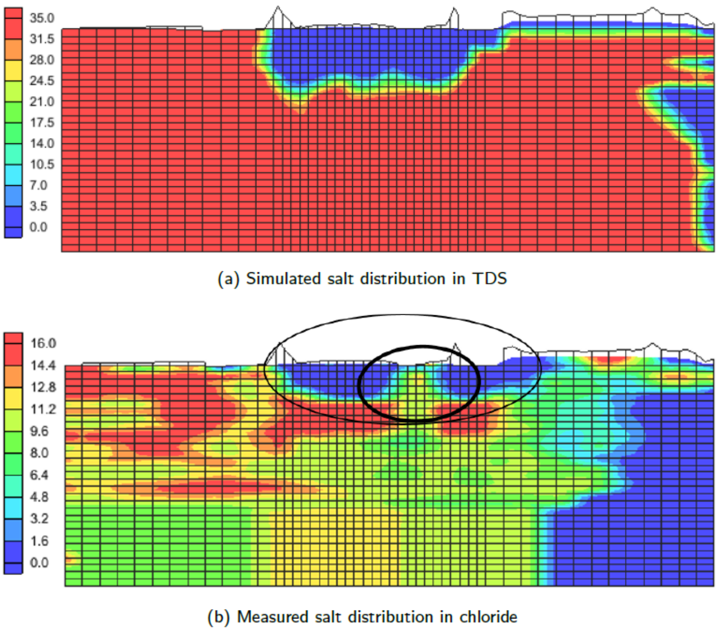


Figure 44. Concentration contours [g/l] in horizontal transect when freshwater lenses have formed.

2.5.3.4 EFFECTS OF TIDES: 3D-MODEL

Figure 45 shows the concentration contours after 10 years when tides are implemented in different ways: (a) fixed head, (b) tides with a time interval of 6.204 hours, (c) tides with a time interval of 10 days. There is a large difference between the changing tides with time and the constant head scenario. The changing tides scenario show much more salt plumes and more salt infiltrating into the subsoil with higher rates. There is only a small difference in model output between the 6 hours and 10 days time-intervals. This means that it is sufficient to implement the 10 days time-interval for simulating the salinization process, through which computational time is reduced significantly by a factor 40.

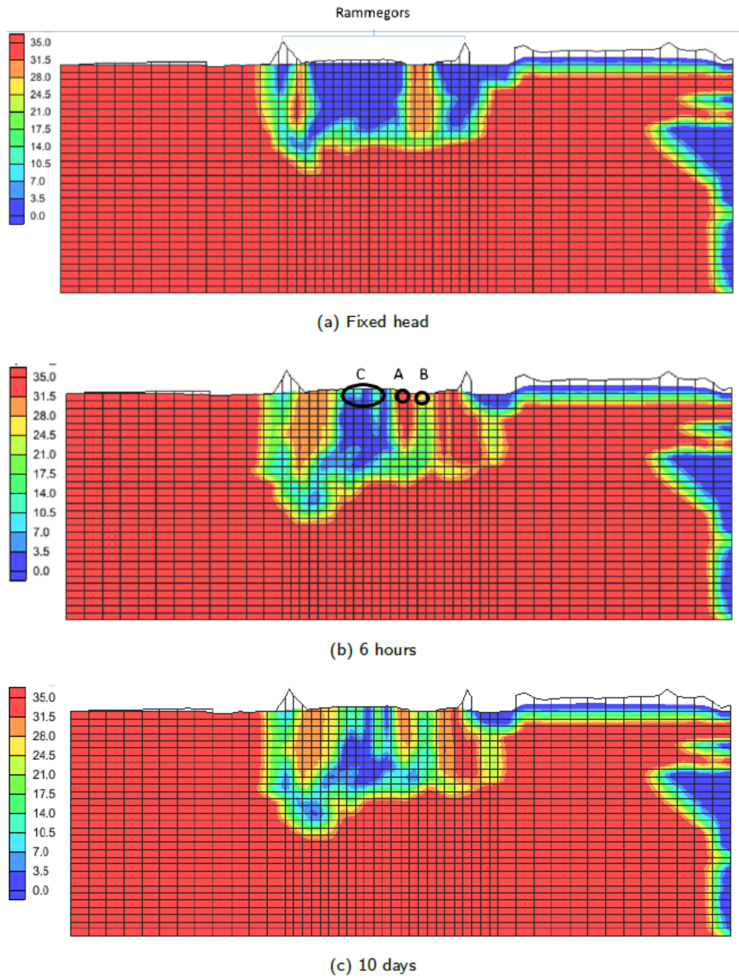
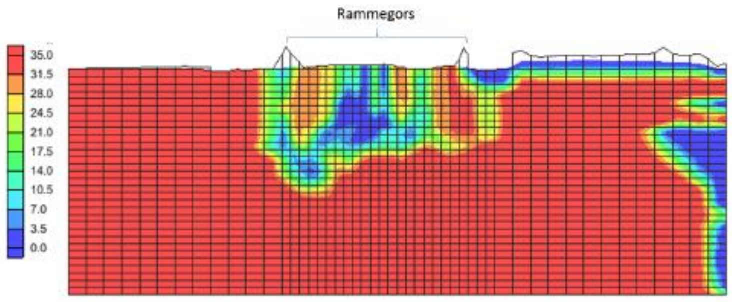


Figure 45. Simulated concentration contours in TDS [g/l], for horizontal transect (row 34) after 10 years when tides are implemented with a) fixed head, b) tides, 6 hours, c) tides, 10 days.

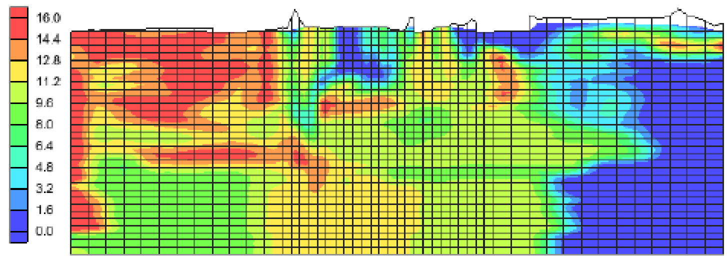
2.5.3.5 DIFFERENT IN INITIAL CONCENTRATION: PALEO-MODELLING VERSUS FRESHEM

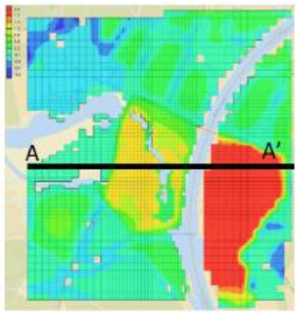
For the modeling of density dependent salt transport, the initial salt concentrations (density field) as initial conditions for calculating scenarios are extremely important. Density differences in the subsoil have a large impact on vertical groundwater flow due to the upward buoyancy force. When the initial density field is not in (dynamic) equilibrium with the hydrological model initial and boundary conditions, changes in salt distributions (and heads) in time are largely influenced by model artefacts. To study this, two different density fields are implemented as initial conditions: (1) through paleo-modeling and (2) FRESHEM-results. The method of paleo-modeling was already used for the previous model calculations and included the modeling of 40 years of freshening since Rammegors was isolated from the Eastern Scheldt. After 40 years, a relatively steady freshwater lens has been developed which was in dynamic equilibrium with the hydrological model boundary conditions.

Figure 46 shows the results of both methods after 10 years of re-opening the Rammegors nature area. In both transects, the plumes are at the same locations but they are of a lower intensity in the FRESHEM scenario. This is probably caused by the lower density difference in the FRESHEM scenario, as the area beneath the gully contained already saline water. Due to the lower density difference, the inflow of saline water will be less. Besides the lower downward flux, mixing will occur more quickly as the freshwater lens is thinner, which enhances the density difference to decrease. This scenario shows the importance of the initial concentration of an area when modelling density dependent groundwater flow. Another point which is worth to mention, are the freshwater areas that are still present in Rammegors, after 10 years. In the next paragraph, more differences in model results for the two different initial density fields will be presented and described.



(a) Tides, 10 day





(d) FRESHEM

Figure 46. Simulated concentration contours in TDS [g/l], for horizontal transect after 10 years with tides with a time interval of 10 days for (a) paleo-modeling to obtain initial fresh-salt distribution (d) measured chloride distribution (FRESHEM), used as fresh-salt distribution. Note the difference in legend, (a) TDS and (b) Cl-concentration (both in g/l).

2.5.3.6 FUTURE EFFECTS OF THE RESTORATION OF THE TIDAL AREA ON THE GROUNDWATER SYSTEM

The restoration of the tidal area Rammegors resulted in (1) a constant flow of salt surface water into Rammegors which may infiltrate into the subsoil, (2) an average higher water level in Rammegors and (3) a change from a constant water level to a tidal effect. These changes, may have consequences for the groundwater system in and outside Rammegors. Changes of the fresh-salt distribution resulting from interventions are relatively slow compared to effects on hydraulic heads and water fluxes. Salt transport is the results of the movement of water particles which is generally slow while the majority of the effects on heads and fluxes occur predominantly through pressure propagation.

Effects on fresh-salt distributions

Figure 47 shows the simulated concentration contours for a vertical transect for the first 50 years after the opening of Rammegors for both the paleo-modeling and FRESHEM approach. For the paleo-modeling, saltwater plumes remain visible, after 50 years. After 10 years, the plumes do not move that fast downwards anymore, as plumes are mixing with the more saline groundwater which is present below the freshwater lens. Small freshwater lenses remain present after 50 years (black circles, Figure 47c). However, they decrease in size. The polders outside Rammegors, stay fresh after 50 years. Only a small area of 150 meters at the south of Rammegors (black arrow, Figure 47c) will experience more saline conditions. By comparing the left and right sides of Figure 47, the difference of the initial salt concentration becomes clear. The salt plumes are less dense, which is caused by the lower inflow of saline water as density differences are smaller. The freshwater plumes inside Rammegors are larger in the FRESHEM scenario. The freshwater lenses in the FRESHEM scenario can persist longer, as there is less inflow of saline water and they receive the same amount of freshwater from the precipitation excess. The lower inflow of saline water is caused by smaller density differences, as mixing occurs earlier.

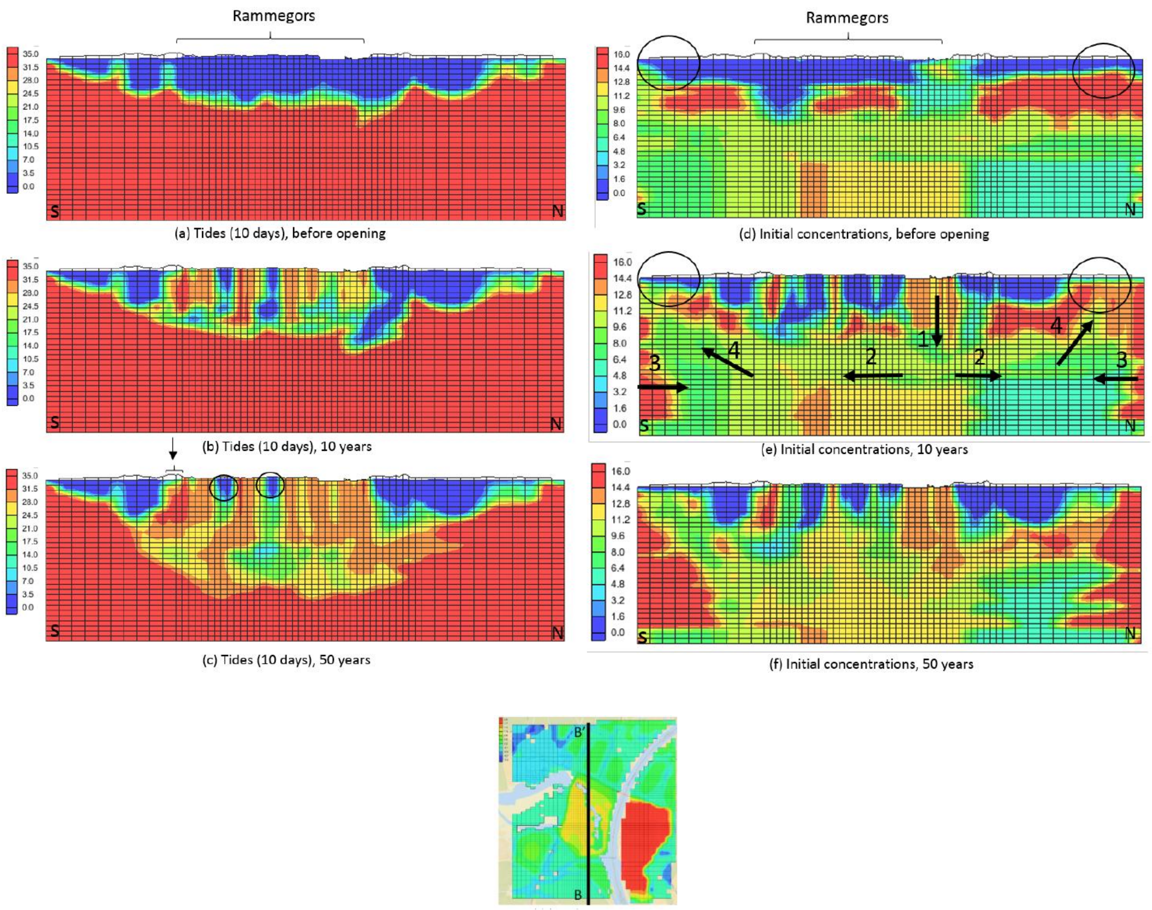


Figure 47. Simulated concentration contours for (a, d) the situation just before opening, (b, e), 10 years and (c, f) 50 years. Left: paleo-modelling (in TDS g/l). Right: FRSEHEM as initial condition (in CL g/l).

Figure 48 and Figure 49 show the depth of the freshwater lens before the opening of the Rammegors and 50 years after opening, for both the paleo-modeling and FRESHEM case. For the paleo-modeling case, the simulated freshwater lenses are thinner than the measured ones (compare with FRESHEM-results for the situation before opening). In the bottom right corner (1) (Figure 48a and Figure 49a), saline water can be found at shallow depths for both approaches. This is caused by the shallow resistant clay layer which reduces the formation of a freshwater lens. The measured saline area inside the Rammegors (number 2 in Figure 49a) is caused by salt water from the two earlier openings of the Rammegors.

After 50 years, the freshwater areas will decrease inside Rammegors for both cases. However, some freshwater areas remain still present after 50 years. These areas never inundate and experience a precipitation excess of 0.6 mm/year. Due to higher water groundwater levels a freshwater lens persists in a saline environment. Noteworthy is the fact that, the freshwater areas are not influenced by the surrounding salt plumes by horizontal salinization. This indicates that vertical processes are dominant, inside Rammegors.

Unfortunately, there are some side effects for the area outside Rammegors. The polders south and north of Rammegors will experience more saline conditions in the ditches and shrinking of the freshwater lenses, after 50 years (black circles, Figure 48b and Figure 49b). These saline conditions are caused by the upward flow of saline groundwater (saline seepage) which is induced by:

- Salinization of Rammegors where saline water infiltrates and moves downwards (black arrow (1), Figure 47e).
- Horizontal groundwater flow of the saline water below the freshwater lens (black arrow (2), Figure 47e). This is caused by mixing of the downward moving saline plumes from Rammegors with their environment. The water below Rammegors tends to move to the sides as it cannot move downwards.

As a result, the saline water will move upwards which reduces the freshwater lens in the southern and northern regions (black circles, Figure 47e). With the above mentioned results, it becomes clear that there is a vertical salinization from top to bottom, inside Rammegors. The surrounding areas experience a horizontal and vertical salinization from bottom to top. These effects of salinization are much larger for the Haaftenpolder in the south than for the Prins Hendrikpolder in the north.

Although clearly differences in salinization between the paleo-modeling and FRESHEM-approach are visible, the overall processes are comparable.

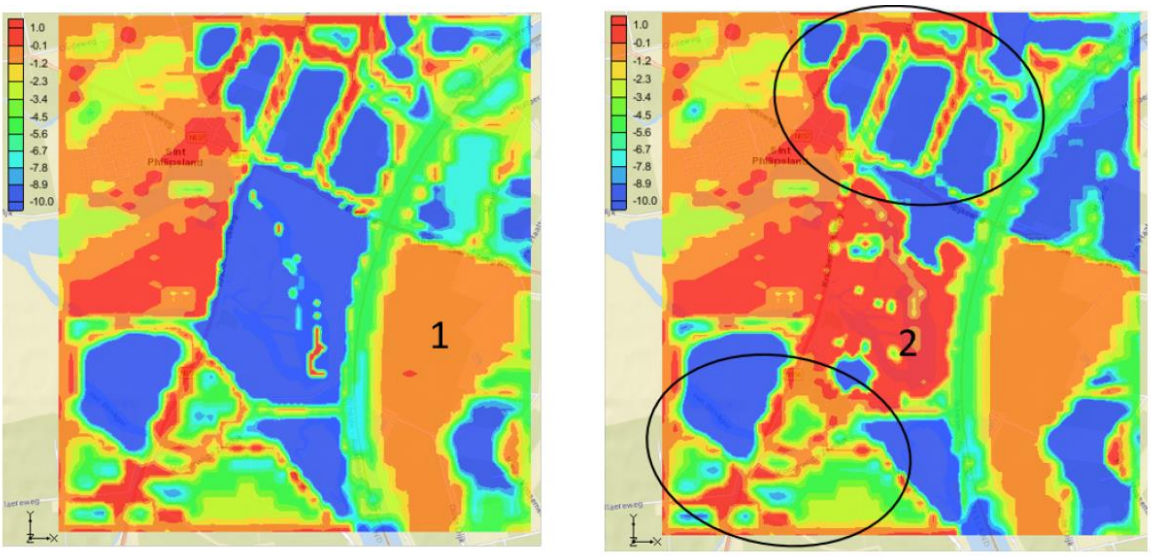


Figure 48. Depth [m NAP] of the fresh-salt interface before opening (left) and 50 years after opening (right), for the paleo-modeling case. The fresh-salt interface is defined as the depth where salt concentrations (TDS) of 1.80 g/l are found. Numbering: 1) Elevated polders and 2) Rammegors.

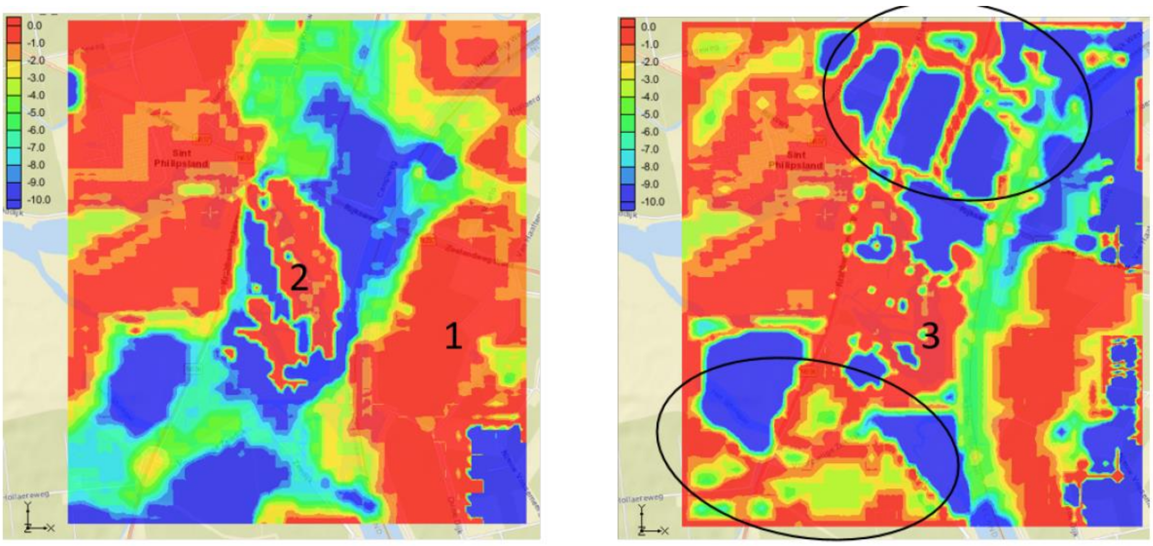


Figure 49. Depth [m NAP] of the fresh-salt interface before opening (left) and 50 years after opening (right), for the FRESHEM case. The fresh-salt interface is defined as the depth where chloride concentration of 1.0 g/l are found. Numbering: 1) Elevated polder, 2) gully inside Rammegors and 3) Rammegors area.

Figure 50 shows for a location inside and outside Rammegors the measured salt distribution with depth (with EM-SlimFlex) and the calculated salt distribution with depth for different years after opening Rammegors. For both location there is a good agreement between the modelled (timestep 0 years) and measured salt distribution. The simulated salinization process is very much different for the tidal area inside Rammegors (PB1) and the polder area outside Rammegors (RH2). In the tidal area the salt water in intruding the subsoil from the surface, pushing down the fresh water lens. After 50 years the upper 30 meters are totally salinized and just a small relict of the freshwater lens is visible. Although absolute salt concentrations and patterns differ between the paleo-modeling and FRESHEM-approach, the salinization processes and its magnitude are comparable with each other for the tidal area.

The salinization in the adjacent agricultural area is not coming from the surface but from the deeper part of the subsoil. Due to higher hydraulic heads caused by the average higher water levels in Rammegors and the infiltration of saltwater, the upward flow fluxes increased outside Rammegors, causing an upward movement of the fresh-salt interface. For this location RH2 there is a clear difference between the salinization process between the paleo-modeling and FRESHEM-approach. The upward movement for RH2 has stabilized after 10 years while for FRESHEM-approach this continues. The latter is probably due to an model artefact caused by the fact that the initial density field wasn't yet in dynamic equilibrium with the hydrological model boundary conditions. Therefore, the effects of the paleo-modelling are judged to be more realistic.

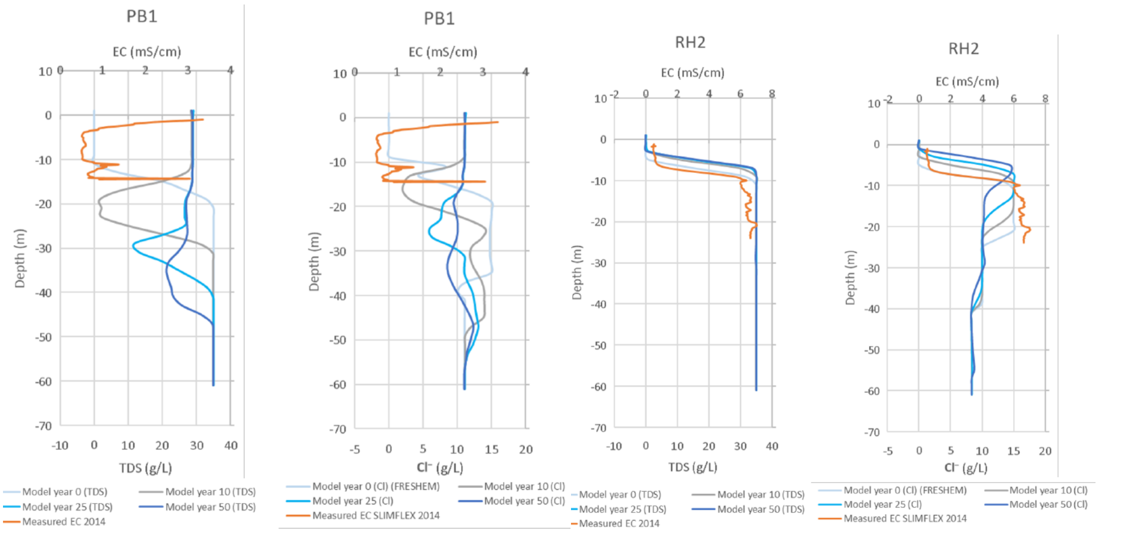


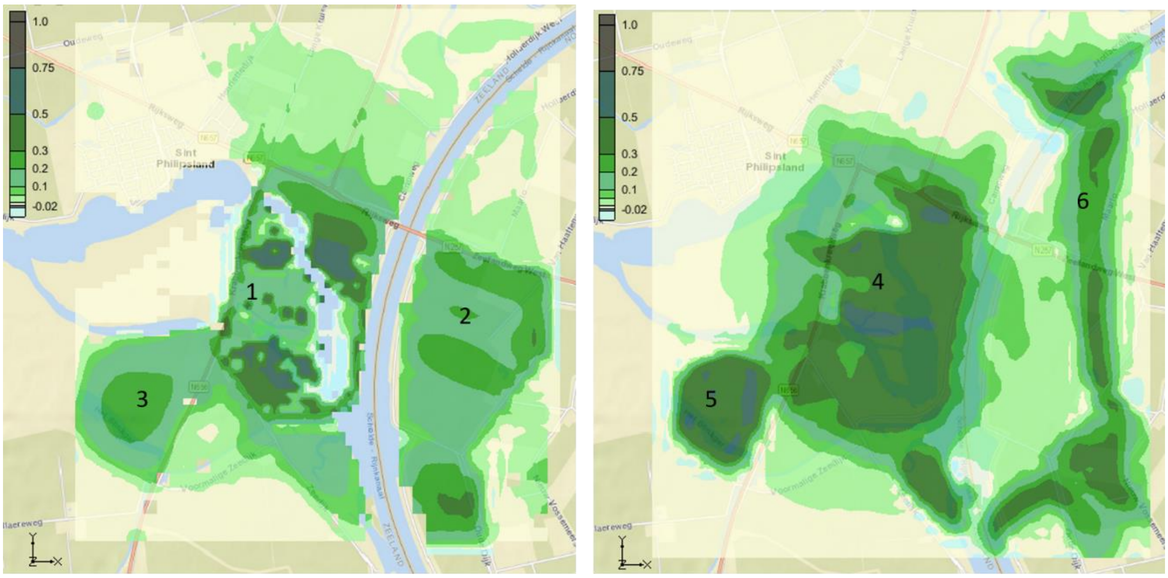
Figure 50. Modelled and measured (SlimFlex) salt distribution for a location in Rammegors (PB1) and in the Haaftenpolder outside Rammegors (RH2). The left-hand graphs of PB1 and RH2 are the results of paleo-modeling and the right-hand graphs are the results from the FRESHEM case modelling. The orange line represents the measured EM-Slimflex observatios in EC(mS/cm), blue colours indicate the simulated salt distribution after 0, 10, 25 and 50 years.

<u>Effects on groundwater levels and hydraulic heads</u>

Figure 51 shows the effects of the opening of Rammegors on the phreatic groundwater level and hydraulic heads. The largest effect at -18 m NAP after 50 years, can be found inside Rammegors (4) followed by the polder which is located southwest of Rammegors (5) and the elongated area at the right side of the area (6) (Figure 51b). The latter two are not the result of the opening of Rammegors but the effect of 50 years replacing saltwater with freshwater by the inflow of freshwater from the east (6) and the infiltration of precipitation (5, 6). It is not clear if these effects will really happen after 50 years or that the effects are model artefacts.

The focus will therefore be on the effects of the opening of Rammegors (4) causing average higher surface water levels and the infiltration of saltwater. These effects propagate via the hydraulic head and it is clearly visible that the effect decreases with distance from Rammegors. Effects larger than 1 cm are visible at a distance of 350 m in the Prins Hendrikpolder and 500 m in the Haaftenpolder. This is also the area where an increase of seepage fluxes and shrinking of freshwater lenses can be expected. The effects on the phreatic groundwater level are less pronounced (smaller effects) but the 1 cm effect line is found at larger distance. Only for a small zone of approximately 50-100 meters effects on the phreatic groundwater level may reach 10-20 cm.

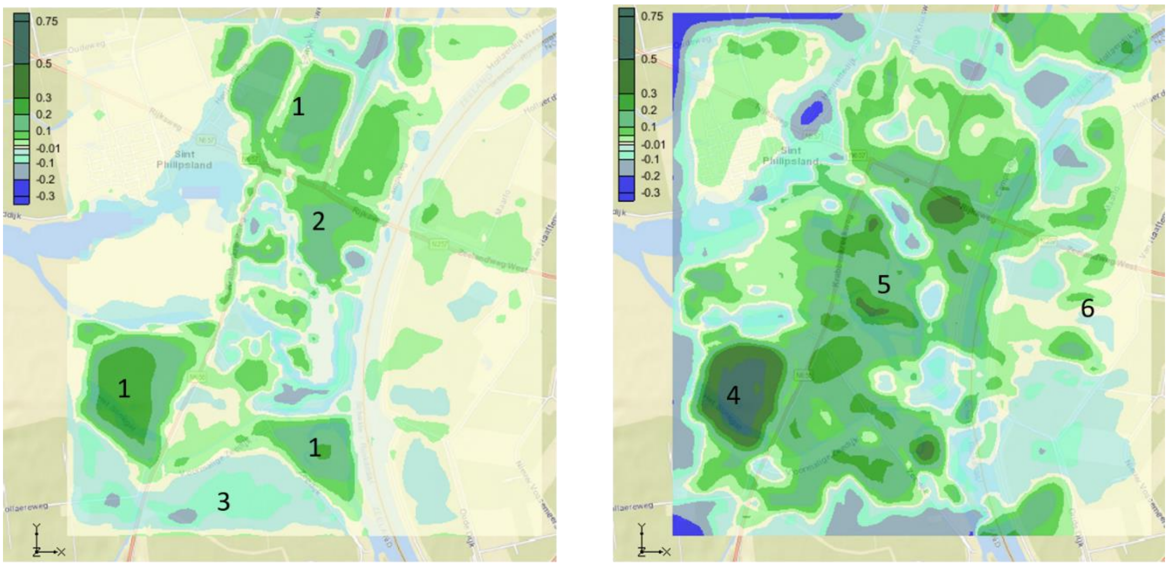
The calculated effects on groundwater level and hydraulic head with the FRESHEM-approach after 50 years is mainly caused by changes of the density fields. These changes are probably the results of the fact that the initial salt distribution wasn’t in dynamic equilibrium with the hydrological model boundaries. Therefore, the results of this approach will not be discussed and should not be intreprated as possbile future effects. This indicates that it is always important to bring your model in dynamic equilibrium with the initial salt distribtuion.



(a) Phreatic groundwater level

(b) Deep groundwater level (-18 m NAP)

Figure 51. The effect on the phreatic groundwater level and the hydraulic head (at -18 m NAP) resulting from the opening of Rammegors. Modeling results of the paleo-modeling approach. Numbering: 1) Rammegors, 2) elevated polder, 3) polder southwest of Rammegors, 4) Rammegors, 5) polder southwest of Rammegors and 6) elongated area, east of Rammegors.



(a) Phreatic groundwater level

(b) Deep groundwater level (-18 m NAP)

Figure 52. The effect on the phreatic groundwater level and the hydraulic head (at -18 m NAP) resulting from the opening of Rammegors. Modeling results of the FRESHEM approach. Numbering: 1) Surrounding polders, 2) northern part Rammegors, 3) southern polder, 4) polder southwest of Rammegors, 5) Rammegors and 6) elongated area, east of Rammegors.

2.5.4 *CONCLUSIONS MODEL STUDY*

The local model shows that discretization size has a large influence on the speed and spatial distribution of salt plumes. Fine discretization shows the process of free convection in detail, whereas for the models with discretization larger than 5 meters, no salt plumes are visible. Lithology has the largest influence on the salinization process, followed by bathymetry. Tides should not be forgotten in the model as they reduce the amount of infiltrating saline water. Bathymetry and tides together, determine which areas are inundated and with that the locations were saline water can infiltrate. The effect of the formation of a sludge layer is very limited as the reduction in salt plume formation is small.

Based on this research, it can be concluded that fine discretization is needed when modelling the process of free convection in detail. The influence of discretization is different in two- and three-dimensional settings, as large plumes were visible in the regional model with a discretization of 50 meter, whereas they were not visible in the local model with a discretization of 25 meter. Bathymetry and tides together, determine which areas are inundated and with that the locations were saline water can infiltrate. Lithology on the other hand, determines the rate of infiltration.

From the regional model it can be concluded that saline plumes still form and that the implementation of bathymetry and tides are crucial for the amount of saline water that will infiltrate, in Rammegors. The modeled heads show good agreements with the measured hydraulic heads with differences between 0.02 and 0.35 meter. Areas with fresh groundwater persist at locations which never inundate in the next 50 years. The largest part of Rammegors will be saline in 10 years. Surrounding Southern and Northern polders could experience more saline conditions, especially in ditches where saline seepage fluxes increase.

The modeling exercises show that tides should not be standardized with an average constant value. To reduce the computation burden, tides could be implemented with a time interval of 10 days in the case of Rammegors, instead of 6 hours.

When modelling variable density groundwater flow, special attention should be given to the initial conditions of the model because they are decisive for the final results. There is a large difference between the paleo-modeling approach (modeling the relevant history of the area concerning the fresh-salt distribution) and using measurements like FRESHEM as initial conditions. When using measurements as initial conditions, the fresh-salt distributions are most likely not in dynamic equilibrium with hydrological model boundary conditions. When calculating future effects of interventions, model artefacts will blur the real effects of interventions. With paleo-modeling the risk for this is less, however, deviations from the real fresh-salt distributions may be larger. Therefore, a combination of both method would be an appropriate method.

Besides that, it is worthwhile to pay attention to forcing like precipitation and the water levels during low and high tides, as they influence the amount of saline water that will infiltrate. However, these influences are minor compared to the influences of the initial conditions.

According to the models in this research, effects of the opening of Rammegors for the surrounding Southern and Northern polders may be expected. Saline seepage will increase for a zone 100-300 m from Rammegors with largest effects close to Rammegors. Freshwater lenses will slowly decrease for the same zone adjacent to Rammegors. Significant increases of phreatic groundwater levels of 10-20 cm are only expected for a zone 50-100 from Rammegors.

2.6 MONITORING OF VADOSE ZONE SALINITY CHANGES

2.6.1 *RESEARCH AIM*

The main idea of this research project is to further understand the process of salinization due to tidal change and its effect on the coastal ecosystems. This research will contribute to better understanding of salinization process and its effect on vadose zone; hence it may serve as a basis from which water management can benefit. This research aims at (*i*) identifying the extent and distribution of soil salinity over the time in the upper soil horizons, (*ii*) understanding the dynamics of the ecosystem (*e.g*. reeds and benthos species) development due to changing soil salinity, and (*iii*) determining temporal evolution of soil and phreatic water salinity due to seawater intrusion.

2.6.2 *MATERIAL AND METHODS*

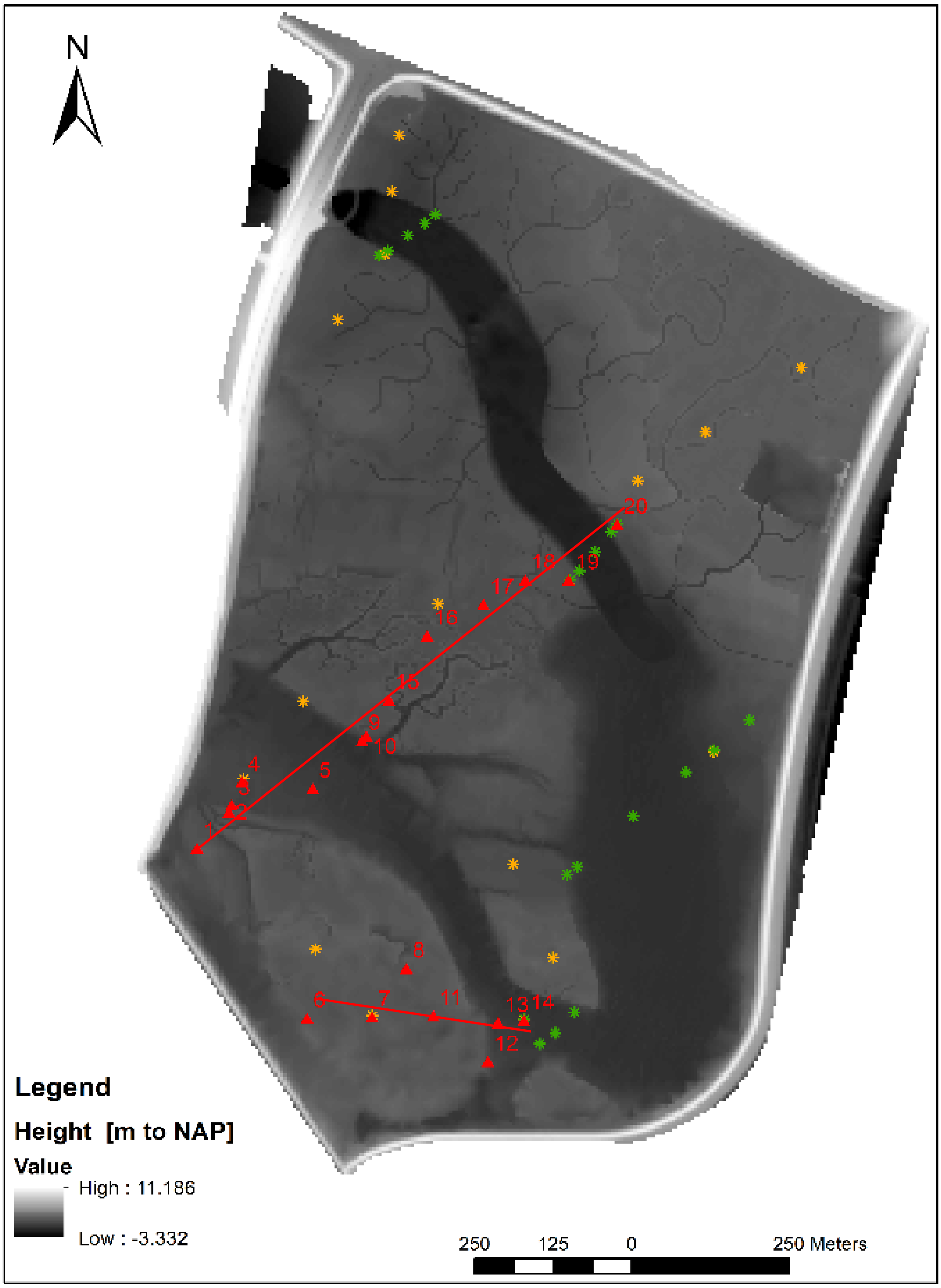


Figure 53. Rammegors GIS map with defined experimental paths, and monitoring location (red points) including the monitoring locations of Royal Netherlands Institute for Sea Research – NOIZ (orange points) and Wageningen Marine Research – WMR (green points) and Deltares (red points 1 and 2).

The first step considered in the monitoring program involved selection of representative experimental pathways along which sampling locations will be defined (Figure 52). The experimental pathways in

Rammegors were selected with intension that they overlap, or pass close by, several sampling locations of Royal Netherlands Institute for Sea Research (monitoring vegetation), Wageningen Marine Research (monitoring benthos species) and Deltares (monitoring groundwater salinity). Moreover, variation in elevation and habitat characteristics along the experimental trajectory were taken into account during selection. Finally, two experimental routes are defined (Figure 52): Pathway I with 13 sampling location (approximately linear pathway); and Pathway II with 7 sampling location (to some extend dispersed pathway).

At each sampling location were installed groundwater observation wells (HDPE pipes, Ø 32x25mm with an average well depth between 1.3 and 1.5 m from surface) to quantify the water levels (Figure 54). Precise coordinates of the well were obtained using Leica Viva GS08plus DGPS with accuracy of 3 mm (see, Leica Viva GS08plus Data sheet). Further, water level data-loggers Micro-Divers and Cera-Divers (see, Van Essen Instruments Pruduct Manual Divers) were installed at 10 sampling locations. The diver is an autonomous data-logger (measurements are stored in the diver's internal memory) that were programmed to measure water pressure and temperature. Divers measure the water pressure using the built-in pressure sensor, and measure the temperature using a semiconductor sensor. They are installed below water level using the vectran cable attached to well cap. Both of the used diver types are capable of storing a maximum of 48,000 measurements and measuring up to 10 m of water column. Divers are set to take a measurement on every 10 min. They can tolerate temperatures between -20 and +80 °C. Micro-Divers and Cera-Divers pressure accuracy is ±3 cm H_2O and ±2 cm H_2O respectively, while temperature accuracy for both divers is ±0.2 ^{o}C (according to manufacturer specifications).

Figure 54. Sampling location 2 and monitoring well (a); Macro-Rhizon soil moisture samplers monitoring location 12 (b).

Next to the observation wells at each location were installed 3 Eijkelkamp Macro-Rhizon soil moisture samplers (MR) at 3 deferent depth ranges *i.e*. 0-10 cm, 15-25 cm and 35-45 cm bellow surface level (see, Figure 4). Rhizon field samplers are reliable equipment for sampling of all dissolved components in the soil solution. Dissolved organic and inorganic matter will not absorb on the soil moisture sampler. The sampler porous plastic material length of 9 cm, Ø 4.5 mm wets spontaneously and has standard pore size of 0.15 µm which assure a high bubble point pressure creating a complete vacuum. The hollow porous part is reinforced with a glass-fibre reinforced core. MR are housed in PVC tubing and at the sampling locations are installed samplers of 3 different housing lengths i.e. 30, 60 and 90 cm. Installation at an angle of around 45° in a drilled and gouged out small-diameter hole guarantees good contact between the soil and the porous element (see, Eijkelkamp Soil Moisture Catalogue). A sample is obtained by placing the sampler under vacuum using a 30 ml syringe.

Diver operation, data display, processing and storing is done with the help of the Diver-Office® software package. Acquired raw data is absolute pressure at sampling location. This pressure is equal to the 'weight' of the water column above the measuring instrument plus the prevailing air pressure. Consequently, these air pressure measurements should be compensated, due to air pressure variations, from the absolute pressure measurement. This barometric compensation in done using Diver-Office®. Atmospheric pressure and temperature data from the neighbouring Royal Netherlands Meteorological Institute (KNMI) Wilheminadorp meteorological station are assigned to each (barometric) monitoring point/well. Water levels are compensated with respect to a vertical reference datum (*i.e*. cable length and a top of casing).

Further, pore water is sampled by the MR and the pore electrical conductivity (EC) was measured using the Hanna HI-98195 Multi-parameter Waterproof Meter. Besides EC other water quality parameters were measured *i.e.* pH, temperature (T), total dissolved solids (TDS) and oxidation reduction potential (ORP). The measurement accuracy are ±0.02 pH, ±0.15 °C, for EC ± 1 µS/cm, for TDS ±1 ppm and for ORP ± 1.0 mV (see, Hanna HI-98195 Multi-parameter Waterproof Meter Manual). Samples taken by MR syringe are placed in sampling cups and instantly measured by the HI-98195 meter. Moreover, because the electrical conductivity is strongly dependent on the temperature of the sample the measuring results from the different temperatures need be corrected to 25 °C (the reference temperature) by using temperature correction coefficients. Conversion to the EC at 25 °C, is made by using the equation (SFS-EN27888, 1994):

$$EC_{ref} = \frac{EC_T}{1 + \frac{\theta}{100} \cdot (T - T_{ref})}$$

where θ = temperature correction coefficient of natural waters taken from the SFS-Standard; T = measuring temperature; EC = electrical conductivity of the sample at T, Tref = Reference temperature 25 °C; ECref = electrical conductivity of the sample at Tref.

2.6.3 *RESULTS AND DISCUSSION*

2.6.3.1 HYDRAULIC HEAD

Figure 55 shows the observed hydraulic heads during August 2018 for three piezometers (1, 5 and 18) on the Pathway I and observed tides at nearby Stavenisse harbour. The piezometer *i.e*. observation well 18 is closest to the lock/inlet structure, while piezometer 5 is further from the lock and piezometer 1 the furthest. Consequently, from Figure 55 it can be seen that there is difference in the heads from piezometer 18, 5 to 1 due to time delay of inundation that depends on local bathymetry and tides together. This determines the locations were saline water can infiltrate. Further, it can be seen that head in the observation wells does not drop below approximately 45-46 cm NAP during the neap tide Figure 56. Therefore, it can be assumed that at this elevation is the separation point between vadose and phreatic zone in Rammegors. Moreover, while looking at the water level fluctuations in the wells it can be noted that the permeability at observation well 5 is higher in comparison to the well 1 and 18. Local lithological characteristics determines the rate of saltwater infiltration. Figure 7 shows lithological cross-section of the Pathway I that was made with the help of lithological borehole descriptions of the HCL derived from the Geological Survey of the Netherlands' database (www.dinoloket.nl). The cross-section is derived from a detailed 3D geological model of Zeeland based on 5 drillings per 1 km2 that were classified into geological units (GeoTOP, Stafleu *et al*., 2011). Overall, different factors influence salinization process *e.g*. bathymetry, lithology, tides and local groundwater flow.

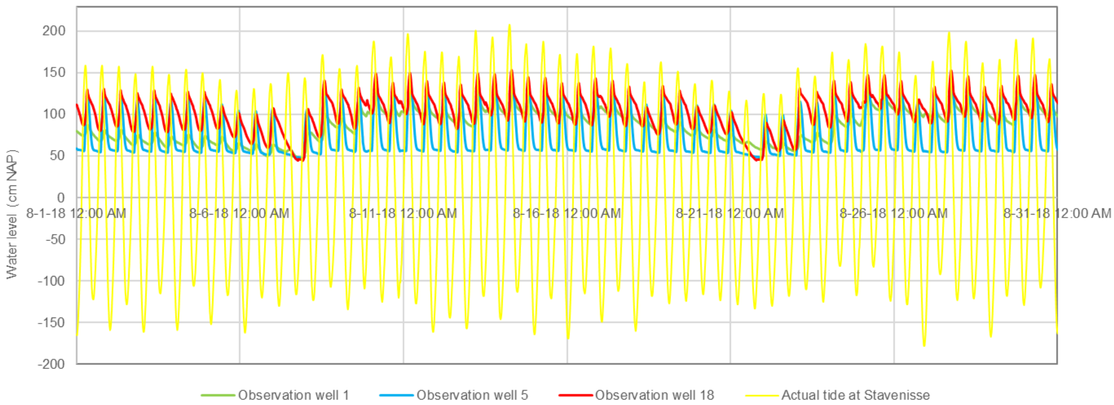


Figure 55. Observed heads in the monitoring wells (1, 5 and 18) and observed tides at Stavenisse harbour during August 2018.

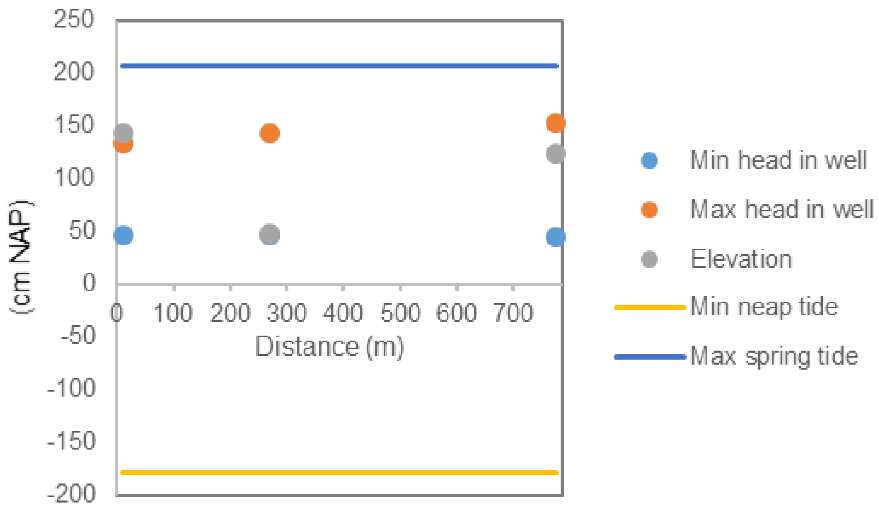


Figure 56. Maximum and minimum water levels at the piezometers 1, 5 and 18 vs. max and min tides and the elevation of the wells.

America (2018) investigated the salinization process in Rammegors with the help of 2D and 3D models and came to conclusion that lithology has the largest influence on the salinization process (Figure 57), followed by bathymetry and tides respectively. Also, model results contributed to a better understanding of the free convection process. Overall, farmers from surrounding polders should be concerned because in the near future ditches will become more saline due to saline seepage.

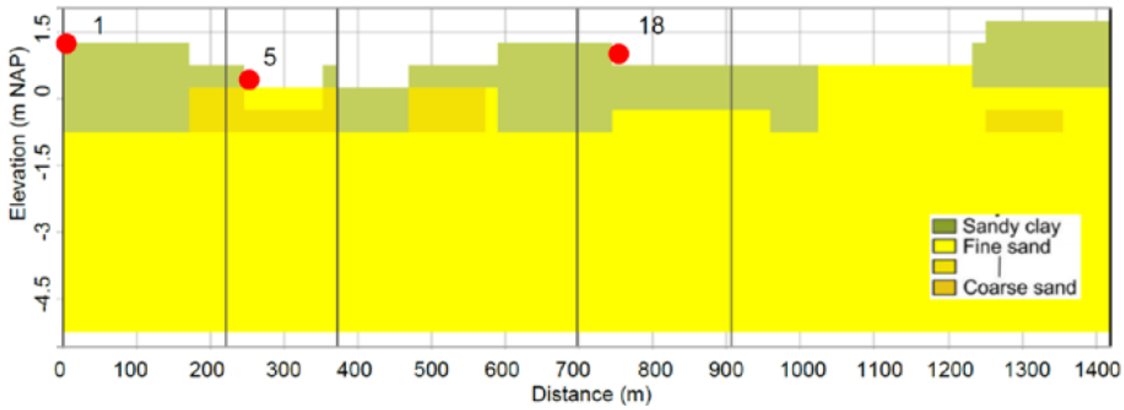


Figure 57. A lithological cross-section of the of the experimental Pathway I in Rammegors with indicated locations (red points) of observation wells 1, 5 and 18.

2.6.4 *SOIL SALINIZATION*

Figure 58 shows the correlation between conductivity and total dissolved solids of pore water samples in Rammegors. It can been seen that there is strong linear correlation between EC and TDS. This implies that this is natural water *i.e.* uncontaminated, especially by human activities. Furthermore, these two parameters are correlated, however, this relationship is not always linear; it depends on the activity of specific dissolved ions average activity of all ions in the liquid, and ionic strength (Hem, 1985; Hayashi, 2004; Siosemarde *et al*., 2010). TDS analysis explain the groundwater quality in a more complex manner, particularly in understanding the effect of salinization better than EC analysis (Khaki, *et al*., 2015).

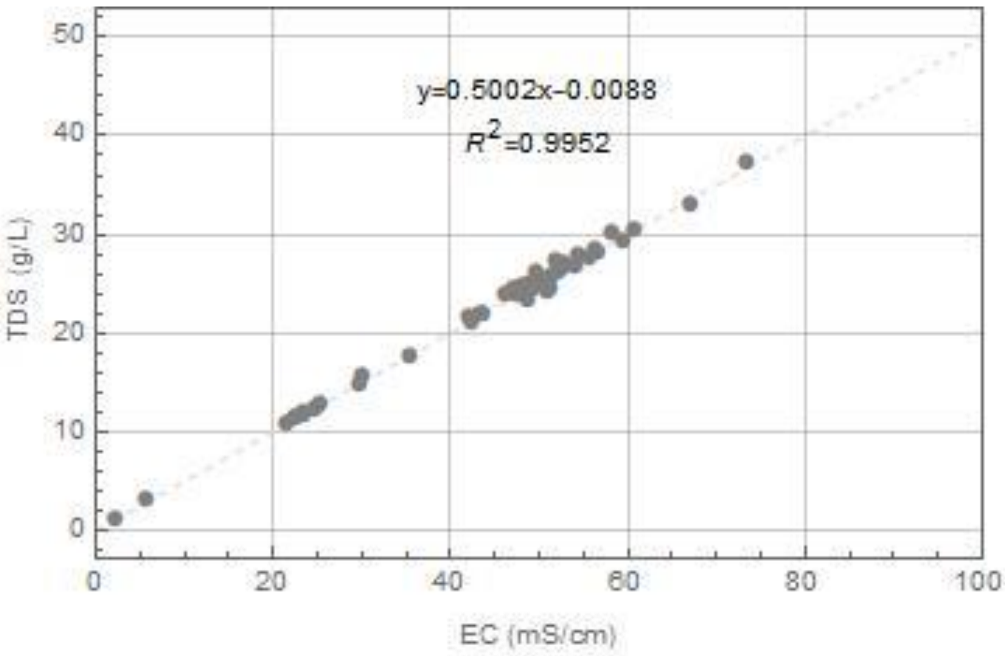


Figure 58. Electrical conductivity – total dissolved solids correlation of pore water in Rammegors.

Figure 59 shows box plots for the EC results for 3 different MR sampling depths at the monitoring locations. As can be seen there is large spatial and temporal variability. The ranges for the EC indicate that EC drops with depth, at most of the locations, implying that the salt concentration increases in the uppermost soil layer, which forms a dense saline layer (Figure 59). Probably, lithological characteristics at locations lead to this phenomenon; however, with time this influence will diminish. Further, this drop of EC with depth is more obvious for the measurements from August then from the ones in July (Figure 59 and Figure 59). This was to be expected due to a long dry summer periods *i.e*. no precipitation during June and July. On the other hand, August had somewhat days with precipitation. Data about the precipitation was obtained from the local Stavenisse KNMI precipitation station. Overall, it can be noted that precipitation can influence soil salinity concentrations in the area, however, this influence is minor on long term.

Further, there are few EC result outliers and they are located at the sampling location 5 and 9. Monitoring locations 5 and 9 are neighboring locations along Pathway I and at relatively low elevation; hence implying that they are inundated for a long period of time. Consequently, water should be more saline, but this is not the case. Assuming that top layer at this locations is clayey *i.e*. of low-permeability free convection slows down, thus preventing the entry of saline water at the top of the aquifer system and obstructing the vertical passage of saline water as it moves through the aquifer (Post *et al*., 2004). However, lithology at this monitoring sites imply that soil is sandy and less clayey; hence with higher permeability. Therefore, it is possible that a freshwater seepage phenomenon takes place in the vicinity of piezometer 5 and 9. Probably local lithological characteristics, salt water progression and positon of freshwater lens lead to freshwater discharge. In order to confirm this hypothesis additional study of the area needs to take place.

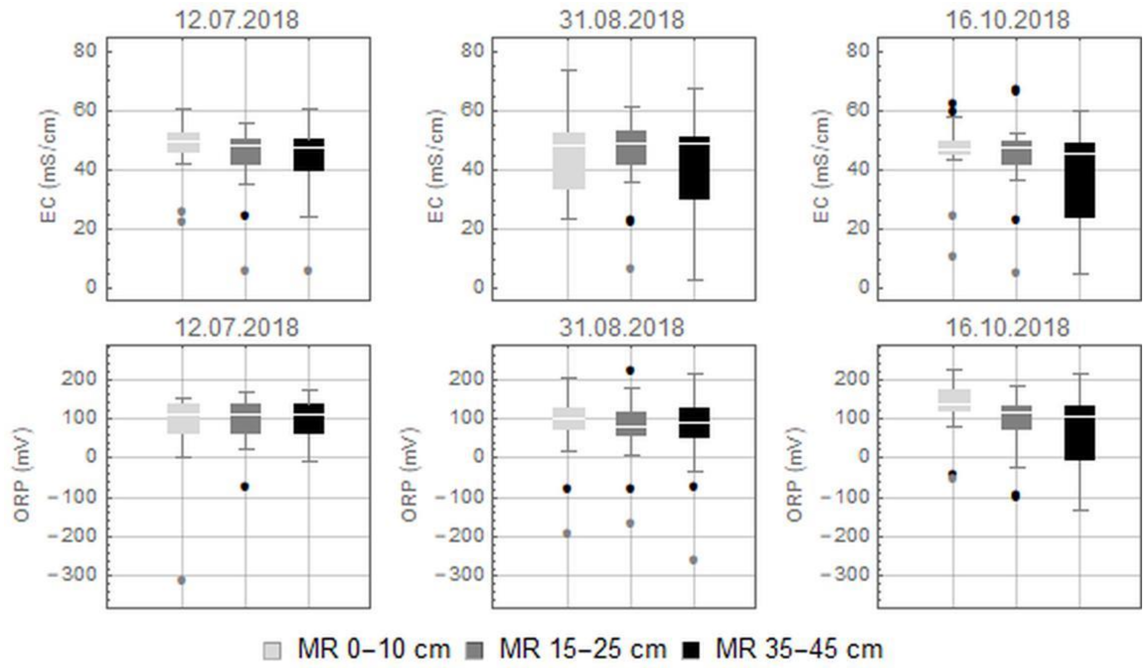


Figure 59. Boxplot for the EC and ORP measurements at the 3 different MR sampling depths on two sampling events. On each box, the central mark is the median, the edges of the box are the 25th and 75th percentiles, the whiskers extend to the most extreme data points not considered outliers (approximately ±2.7σ), and outliers are plotted individual.

Further, while looking at the boxplot (Figure 59) it can be noted that there is a rather large variability of ORP results. ORP measures an aqueous systems capacity to either release or accept electrons from chemical reactions *i.e*. measures oxidising or reducing potential of water. Depending on the ORP values different physical, chemical and biochemical processes can occur in soil, thus having different impact on abiotic and biotic factors. Overall, ORP results suggest that in Rammegors soil predominate aerobic conditions. ORP values from August drop slightly with MR depth, which is expected due to decrease of oxygen content with depth. However, opposite trend was noticed for the values from July. At some monitoring locations, conditions are anoxic (between +50 and -50 mV), while negative outliers in boxplot suggest anaerobic conditions in the soil. Measurements from July and August suggest that these anaerobic soil conditions move with location and depth. Consequently, suggesting that aerobic and anaerobic processes are shifting in soil over period of time. Probably this shift is occurring due to local biome activity in water and soil. These processes depend of multiple abiotic and biotic factors. For instance, a lot of parts of Rammegors are covered with biofilm that obviously contains oxygen producing diatoms (common saltwater species) that reaerate water. Further, Van Colen (2012) notes that activity of bioturbating organisms (e.g. benthic species) can have a great impact on soil reaeration and thus on the several ecosystem processes.

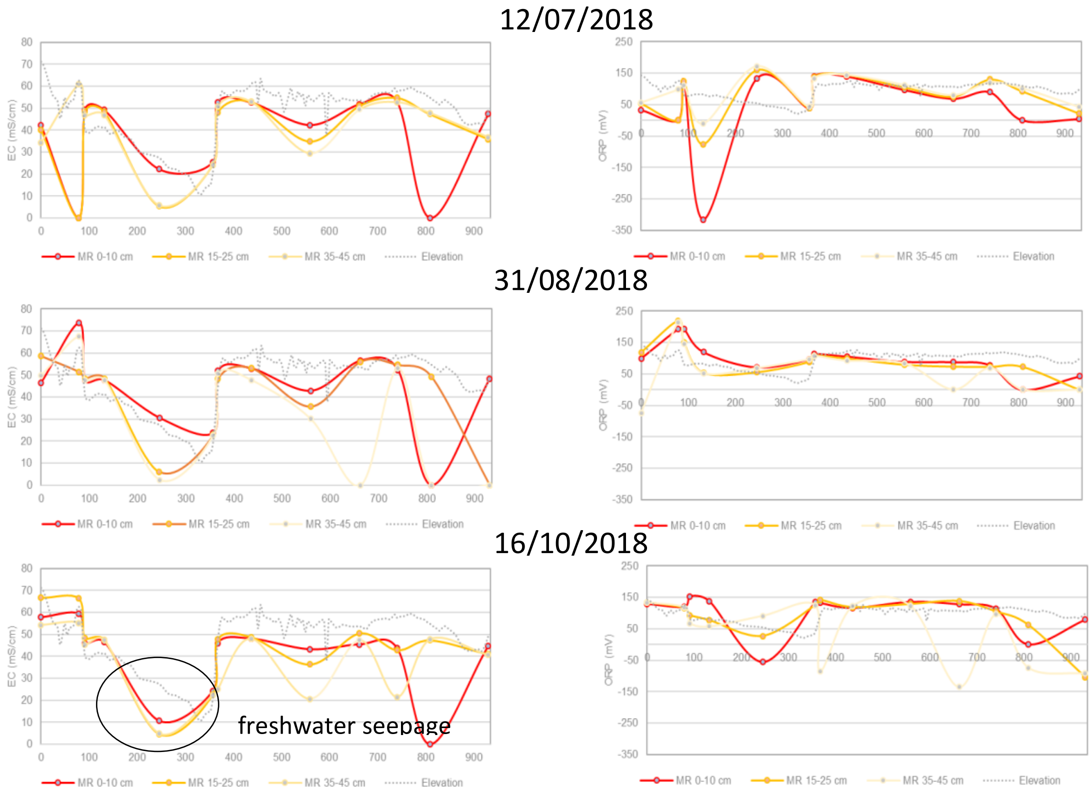


Figure 60. Change of EC measurements (left hand) and ORP values as a function of the distance and elevation along Pathway I during sampling event on: (a) 12/07/2018; (b) 31/08/2018; and (c) 16/10/2018. Zero values are the missing measurements.

At some locations with measured maximum ORP values was seen colloidal iron in the collected samples and a red tint in water. This implies that pore water and soil are rich with iron, suggesting also the presence of iron-oxidizing microorganisms. Furthermore, the soil at these locations is visibly reddish and in the areas where there is stagnant water a rainbow-like or iridescent sheen can be seen. With poke test it was confirmed that this is a bog sheen *i.e*. naturally produced thin film on top of the water is a combination of bacteria and oxidized iron or manganese. On the other hand, at locations with measured minimum ORP values water samples were greenish and with a ‘rotten egg’ smell implying presence of H_2S gas. Overall, the ‘rotten egg’ smell was notices at these locations.

In addition, soil at this location had the dark colour of sludge. This suggests that sulfate-reducing microorganisms are present in water and soil. Moreover, because of possible seasonal hypoxia (*i.e*. oxygen depletion) it is likely that ‘cable bacteria’ are present in the Rammegors. They strongly influence the sediment geochemical properties of the coastal systems. Electrogenic metabolism of cable bacteria promotes the oxidation of iron at the surface of the sediment. Also, they are capable to transport electrons, derived from sulfide oxidation, to oxygen as the final electron acceptor. Further, the iron oxides can act as a ‘firewall’, which can substantially impact iron-sulfur-phosphorus cycling, and thus marine ecosystems in coastal areas (Seitaj *et al*., 2015; Sulu-Gambari *et al*., 2016). Overall, in order to prove these assumptions it is necessary to carry our additional chemical and microbiological sample analysis in laboratory.

2.6.5 *SYNTHESIS AND RECOMMENDATIONS*

Already, after two monitoring events results have contributed to better understanding of salinization process and its effect on the vadose zone in Rammegors. With time freshwater lens will become more saline via process of infiltration. Rate of saltwater intrusion depends on the various local area characteristics (*e.g*. lithology) and on tidal fluctuation. Furthermore, different physical, chemical and biochemical processes influence the soil water quality in the studied vadose zone. Overall, the predominating processes will have an effect on the local ecosystem.

In addition, to this increased knowledge about Rammegors environment also it is important to monitor ecosystem performance. Information and knowledge will be shared between institutions (*i.e*. HZ University of Applied Sciences, NIOZ, WMR and Deltares) that are carrying out different types of research in Rammegors. Overall, understanding of how do biotic and abiotic factors interact in the ecosystem will contribute to the increased confidence in the decision making process on future water management needs.

2.7 CONCLUSIONS AND RECOMMENDATIONS

2.7.1 *CONCLUSIONS*

- In 1972 part of the Krabbekreek was dammed and isolated from the Eastern Scheldt by building the Krabbekreekdam and this resulted in a fresh-brackish nature area, called Rammegors. Since then, no saltwater has been flooded the area and due to the constant input of fresh rainwater and the increased stagnant water level in Rammegors of 0.3-0.,5 m NAP, resulted in the replacement of the saltwater by freshwater.
- A freshwater lens of about 10 to 20-meter thickness have been developed below Rammegors which extent for several hundreds of meters outside Rammegors. The EM-SlimFlex measurements and the FRESHEM have shown their strength by accurately mapping the fresh-salt distribution in the subsoil.
- The lens has a thickness of about 3 to 6 m in the Prins Hendrikpolder and 7 to 10 m in the Haaftenpolder. The freshwater lens is not used by the farmers for irrigation.

- From the monitoring results, no effect of the restoration of Rammegors on the hydraulic head and phreatic groundwater level was visible. This does not mean that there is no effect but anyhow effects would be very small, as shown by the groundwater model.
- According to the groundwater model simulations, some effects of the opening of Rammegors for the surrounding Southern and Northern polders may be expected. Saline seepage (and increase of hydraulic heads) may increase for a zone 100-300 m from Rammegors with largest effects close to Rammegors. Significant increases of phreatic groundwater levels of 10-20 cm are only expected for a zone 50-100 from Rammegors.
- The model also shows that the freshwater lens in both polders will slowly decrease for the small zone of 100-300 m adjacent to Rammegors. Changes in salinity (hence also thickness of freshwater lenses) occur slowly because it involves the transport of water with salt which is a slow process (order of tens of meters per year horizontally). On the other hand, changes in hydraulic heads, phreatic water table and seepage fluxes occur instantaneously (or with a small delay) by the process of pressure propagation.
- The isolation of Rammegors from the Eastern Scheldt for a period of 43 years caused a freshening of Rammegors and small zone in the adjacent polder areas. With the fact that salinization processes from the surface occur faster than freshening due to the free convection processes, it is expected that salinization of the freshwater stock by the opening of Rammegors will take place in the same time span or even faster. Model results confirm these conceptual thoughts about the salinization process.
- No effects on the freshwater lens in de polder areas haven been detected by the EM-SlimFlex measurements, which was expected for this short period after opening of Rammegors.
- The salinization in the tidal area is taking place much faster by the process of free convection due to the unstable situation of the denser salt water on top of freshwater. Both model results and SlimFlex-measurements show the relatively fast salinization process in the tidal area. The model shows the largest part for Rammegors is salinized within 10 years. However, the model also shows that even after 50 years, there are still small freshwater patches present below areas which never (or sporadically) inundate.
- The effect of the tides in Rammegors are clearly visible in the hydraulic head measurements at 15 meters depth and the phreatic groundwater level in the tidal area.
- The effect of different factors like bathymetry and lithology on the salinization process was examined with the local-2D and regional-3D groundwater models. The most important findings are:
    - Discretization cell size has a large influence on the speed and spatial distribution of salt plumes. Fine discretization shows the process of free convection in detail, whereas for the models with discretization larger than 5 meters, no salt plumes are visible.

- With small cells (<5 m), the salinization occurs up to a factor 2 slower than for cells larger than 5 m. This is an important finding considering regional groundwater models which usually use larger cell sizes due to calculation times. These regional groundwater models may exaggerate the salinization by free convection by a factor 2.
- Lithology has a large influence on the salinization process when a high-resistant clay or peat layer is present and blocking the infiltration of salt water. The combination of bathymetry and tides determine which areas are inundated, the inundation frequency and duration and with that the locations were saline water can infiltrate, how much and for which period.
- The modeling exercises show that tides should not be standardized with an average constant value. The salinization process goes faster with the implementation of tides. To reduce the computation burden, tides could be implemented with a time interval of 10 days in the case of Rammegors, instead of 6 hours (results are comparable).
- When modelling variable density groundwater flow, special attention should be given to the initial conditions of the model because they are decisive for the final results. There is a large difference between the paleo-modeling approach (modeling the relevant history of the area concerning the fresh-salt distribution) and using measurements like FRESHEM as initial conditions. When using measurements as initial conditions, the fresh-salt distributions are most likely not in dynamic equilibrium with hydrological model boundary conditions. When calculating future effects of interventions, model artefacts will blur the real effects of interventions. With paleo-modeling the risk for this is less, however, deviations from the real fresh-salt distributions may be larger. Therefore, a combination of both method would be an appropriate method.

2.7.2 *RECOMMENDATIONS*

- From both the system analysis and the modeling, it is expected that salinization will continue for both the tidal area and the surrounding polders. It is therefore recommended to continue the hydrological monitoring for the coming 5 to 10 years.
- The recommended hydrological monitoring exists of:
    1) Yearly EM-SlimFlex monitoring for the 4 deep piezometers in the Prins Hendrikpolder and Haaftenpolder.
    2) Yearly EM-SlimFlex monitoring for the 5 deep piezometers in the tidal are Rammegors.
    3) Monitoring hydraulic heads in these 9 deep piezometers with a hourly frequency using so-called Divers.
    4) Monitoring phreatic groundwater levels in the shallow piezometers.

5) Monitoring the salinity of the surface water of the three most important locations (i.e. inlet water Haaftenpolder, Rammegors) using CTD-divers with an hourly frequency.
6) Every 6 months, manual measurements in all piezometers and reading out the dataloggers.
7) Every 6 months, a visual inspection of the status of the monitoring.

- The monitoring data should be analyzed on a yearly basis and presented in a small report.
- Furthermore, it is recommended to make the monitoring network robust and well protected for damage using iron protection caps. Recovery of damaged piezometers or dataloggers should be done as soon as possible after
- Preferably the monitoring data should be made available online for the general public.

3. BENTHIC ORGANISMS

The results described in this chapter are also available as a WMR report (Walles, 2019).

3.1 RESEARCH QUESTIONS

A central question of the Rammegors tidal restoration project is how the habitat will develop in the area. Estuarine habitats will develop over time, but little is known about the spatial and temporal characteristics of this development. This chapter focusses on the development of the benthic macrofauna. Intertidal and shallow subtidal habitats are important habitats for many species of macrobenthos, including polychaetes, molluscs and crustaceans. These organisms are central elements of the estuarine foodweb, as they are important consumers of phytoplankton and micro-phytobenthos, and on the other hand are a crucial food source for higher trophic levels such as birds and fish.

The intertidal benthic biota have to survive in a harsh and variable environment. Temperature, light, emersion time and water saturation vary not only according to tidal and diurnal rhythms, but also with seasonal and short-term weather variations. Physical stress is exerted by tidal currents and waves, the impact of which varies in space and time.

The main questions related to the Rammegors project are:

1. How do benthic macrofauna communities develop in relation to:
    - the elevation gradient;
    - the presence of the existing (remaining) freshwater vegetation;
    - the presence of the developing salt marsh vegetation;
    - the sedimentation rate in the area?
2. Are benthic communities in Rammegors similar to benthic communities in similar ecotopes in the Oosterschelde?
3. How do the developments of Rammegors compare to the developments of Perkpolder in the Westerschelde? What can be learned about the design of de-polder areas?

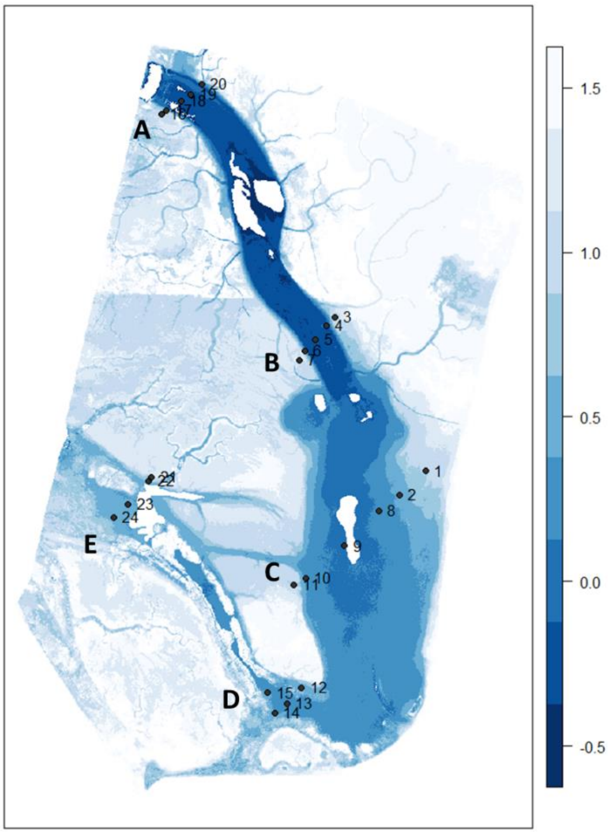
3.2 MATERIAL AND METHODS

3.2.1 *BENTHIC SAMPLING*

To quantify the colonisation of macrobenthic infauna and their community structure twenty stations, along four transects with varying distances from the inlet, were sampled within Rammegors in 2017 (Figure 61, A, B, C, D). In 2018 an additional transect (E, Figure 61) was added at the end of the creek. The transects cross the main tidal creek and include the creek and creek banks without vegetation. Large parts of Rammegors were still covered with reed (Elschot et al. 2016) or remnant plant parts. Sampling stations were located between remnant plant parts (station 7 and 10), areas with newly established plants (*Salicornia europaea*) (station 3 and 11), permanently submerged areas (station 5, 9, 13 and 23) or on the unvegetated tidal flat (stations 1, 2, 4, 6, 8, 12, 14, 15, 16, 17, 18, 19, 20, 21, 22 and 24). None of the sampling stations were located in areas covered in reed due to sampling difficulties. These twenty-four stations were sampled on May 17th (spring) 2017, September 5th (autumn) 2017, June 14th (spring) 2018 and September 3th (autumn) 2018 (Figure 65).

Macrobenthic infauna was sampled using a cylindrical 10 cm in diameter corer, i.e. 78 cm^2 surface area to a maximum depth of 35 cm. Due to plant remains and roots we could not sample up to 35 cm in depth at most locations. Three replicates were taken randomly at each station, pooled and sieved in the field through a 1 mm mesh sieve. The residue was preserved in 4% buffered formaldehyde solution and stained with Rose Bengal. In the lab specimens were sorted and identified to the lowest possible level, counted, wet weighted and preserved (in 4% buffered formaldehyde solution). The amount of individuals per species found at each station was converted to density (number of species m^{-2}). Worm counts were bases on the number of heads found in a sample. When only tails were found they were recorded as one individual of this species. Biomass was calculated by converting total wet weight per station per species to total ash free dry weight (AFDW) in g m^{-2} using species specific conversion factors as described in Craeymeersch and Escaravage (2014). In addition, *Arenicola marina* densities were counted by counting heaps in the field within 0.25 m^2 (n=10) at each sampling station. At each station a single sediment sample (18.5 cm^3) was collected from the upper 3 cm (using a 1.4 in diameter syringe from which the tip was cut off) and stored in a preweighed sample bottle. In addition salinity of the surface water was measured at each transect in the main gully in spring 2017.

Samples were wet weighted and placed in a freezer for a minimum of 3 days before opening the bottles and freeze dry (Christ® Alpha 1-4) the sediment samples for 4 days (-50ºC). Samples were reweighed after freeze drying. Bulk density of the sediment (g cm^{-3}) was calculated as ratio dry weight to the sampled volume. Sediment particle size distribution was determined by laser diffraction (Malvern Mastersizer 2000), from which the median grain size of the sediment D_{50} (µm) as well as the size distribution (percentage coarse, medium, fine and very fine sand, and silt) was derived. Elevations (m NAP) were measured using a differential GPS device with a horizontal and vertical measure accuracy of 8 and 13 mm, respectively (Leica GS12, Leica Geosystems AG, Switzerland, correction signal: SmartNet, Leica Geosystems, the Netherlands). Additional, Chlorophyll *a* (µg cm^3), as a measure for food availability for benthic animals, was measured by three pooled sediment samples collected from the upper 1 cm of the sediment, using a 1 cm in diameter syringe from which the tip was cut off. The samples were stored in the dark at -80ºC after which they were freeze dried and analysed spectrophotometrically according to Aminot and Rey (2002).



transect	station	x	y	z
A	16	71316.0	403461.7	0.70
A	17	71327.6	403470.4	0.38
A	18	71358.6	403490.2	-0.53
A	19	71380.2	403505.0	-0.56
A	20	71403.7	403528.0	-0.04
B	3	71694.9	403018.4	0.87
B	4	71676.3	402999.0	-0.18
B	5	71652.5	402968.5	-0.30
B	6	71629.1	402944.7	-0.13
B	7	71617.2	402924.4	1.04
C	1	71893.2	402681.7	0.80
C	2	71836.1	402630.0	0.37
C	8	71790.7	402594.4	0.16
C	9	71715.8	402517.6	0.09
C	10	71631.5	402447.1	0.28
C	11	71605.1	402433.3	0.93
D	12	71622.3	402207.4	0.46
D	13	71589.9	402172.9	0.27
D	14	71564.0	402152.8	0.43
D	15	71548.2	402196.5	0.49
E	21	71295.0	402667.5	0.91
E	22	71288.9	402659.4	0.57
E	23	71242.8	402608.4	0.43
E	24	71211.6	402579.5	0.49

Figure 61. The twenty four benthic sampling points, along 5 transects (A till E), in Rammegors (2 by 1 km) (left). X, Y, Z coordinates of the benthic sampling stations (Z in m NAP, situation September 2018) are presented in the right table. **Stations 21 to 24 were only sampled in 2018.**

Based on the benthic macroinfauna samples, several biological indicators were defined and linked to abiotic parameters. We defined:

(1) Species richness, which is a measure of the diversity (number of different taxa) of the macrofauna community at each sampling station. Species richness is the number of taxa found in the sample. As this is dependent on the sampled surface it is not expressed per m^2 but per station.

(2) Density, which is the amount of individuals per species found in the cores, converted to number of individual species m^{-2}.

(3) Biomass, which is the total wet weight per station per species converted to the total ash free dry weight in g m^{-2} using species specific conversion factors as described in Craeymeersch and Escaravage (2014).

Figure 62. Benthic macrofauna sampling in the Rammegors area, May 2017 (top photos) and September (bottom photos) 2017. Notice the thick peat layer (top right photo). First cockels (C. edule and C. glaucum) observed in autumn 2017 (bottom right photo). Photos: Tom Ysebaert and Brenda Walles.

3.2.2 *STATISTICAL ANALYSIS*

Multivariate

Changes in macroinvertebrate community composition was analysed with NMDS ordination (with the package "vegan" in R) which was run for 20 iterations at k=2 (decreased number of dimensions) before obtaining a solution. Abundance was square root transformed, and then submitted to Wisconsin double standardization to down-weight the importance of the highly abundant species allowing for the mid-range and rare species to exert influence on the calculation of similarity. Rare species, of which only one individual was found, were removed. Twenty-one taxa were included in the multivariate analysis.

Regression analyses were performed for species richness, density and biomass in relation to the abiotic data (elevation, d_{50}, % silt, chlorophyll a, bulk density and organic matter).

3.3 RESULTS

3.3.1 *ENVIRONMENTAL CONDITIONS*

Throughout the sampling period elevations did not change when considering all sampling stations in the Rammegors area (Figure 63, Table 6). However, when zooming in on the separate transects (Figure 64), lowering in elevation was observed near the inlet (transect A to C), whereas an increase was observed at a greater distance from the inlet (transect D, E). Figure 64 also shows that sampling stations near the inlet are lower positioned than those at the end or the creek. Overall median grain size decreased over time (Figure 63). Median grain size decreased with distance from the inlet (Figure 64). Near the inlet a decrease in grain size was observed in spring 2018 (Transect A and B) followed by an increase in autumn 2018 (Figure 64). At a greater distance from the inlet the opposite was observed. Changes in median grain size coincide with changes in silt content (Figure 63 and Figure 64). Percentage silt increased with distance from the inlet (Figure 64) and overall increased in time (Figure 63). Bulk density shows a decrease with distance from the inlet. After the first sampling in spring 2017 bulk density increases throughout the whole area which might indicate compaction of the sediment. It is however unknown why bulk density decreases again after this increase. Overall organic matter did not show changes over time. Chlorophyll *a* decreases over time. However, looking at the separate transects a small increase in both organic matter and chlorophyll *a* can be observed near the inlet (Transect A and B) whereas a decrease occurred at some distance from the inlet (transects C, D and E). Both parameters show an increases form the inlet to the end of the creek. Salinity of the surface water was high being 31 at each transect.

Table 6. Summary of mean values and their standard errors between brackets for abiotic characteristics and biological indicators of the Rammegors area in 2017 and 2018.

Parameter	Rammegors area			
	2017 (n=20)		2018 (n=24)	
	spring	autumn	spring	autumn
Abiotic characteristics				
d_{50} (mm)	101.6 (11.2)	102.4 (10.8)	91.4 (9.3)	93.1 (9.1)
Coarse sand (%)	0.3 (0.2)	0.1 (0.1)	0.4 (0.1)	0.4 (0.1)
Medium sand (%)	6.8 (1.4)	5.6 (0.8)	5.9 (0.9)	5.6 (0.1)
Fine sand (%)	34.1 (4.5)	35.8 (4.9)	29.7 (3.7)	29.6 (3.8)
Very fine sand (%)	27.7 (1.5)	27.6 (1.5)	27.0 (1.9)	28.5 (1.4)
Clay/silt (%)	31.3 (5.5)	31.0 (6.0)	37.2 (4.6)	36.1 (4.5)
elevation (m NAP)	0.37 (0.09)	0.37 (0.09)	0.38 (0.08)	0.33 (0.09)
Chlorophyll-a (µg g^{-1})	36.4 (8.3)	30.2 (7.6)	25.2 (4.0)	24.4 (3.4)
Organic matter (%)	9.0 (2.0)	7.2 (1.7)	5.8 (1.3)	8.7 (1.6)
Bulk density ()	1.08 (0.10)	1.93 (0.11)	1.54 (0.07)	1.66 (0.08)
Macrofauna				
No. of taxa	10.0 (0.9)	5.9 (0.7)	7.8 (0.7)	7.4 (0.7)
No. of ind. (m^{-2})	8049 (1779)	3028 (653)	3149 (819)	4122 (735)
Biomass (g m^{-2})	6.14 (1.21)	5.66 (1.01)	5.61 (0.94)	11.23 (1.46)

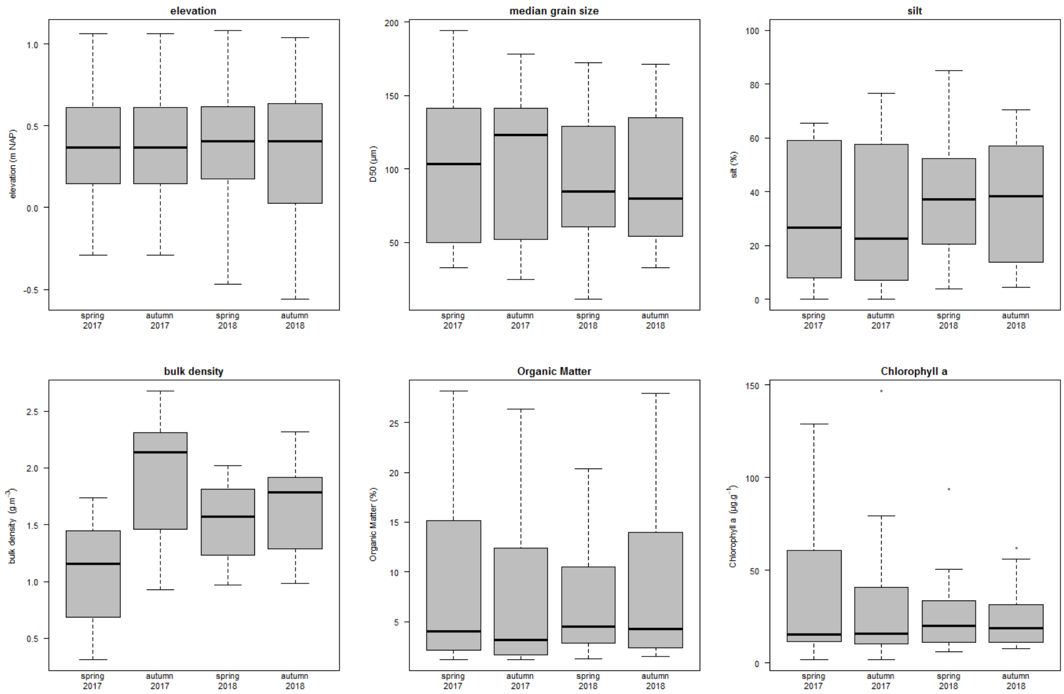


Figure 63. Changes in elevation (m nap), median grain size (%), silt (%), bulk density (g cm-3), organic matter (%) and chlorophyll-a (µg cm3) in time in the whole Rammegors area.

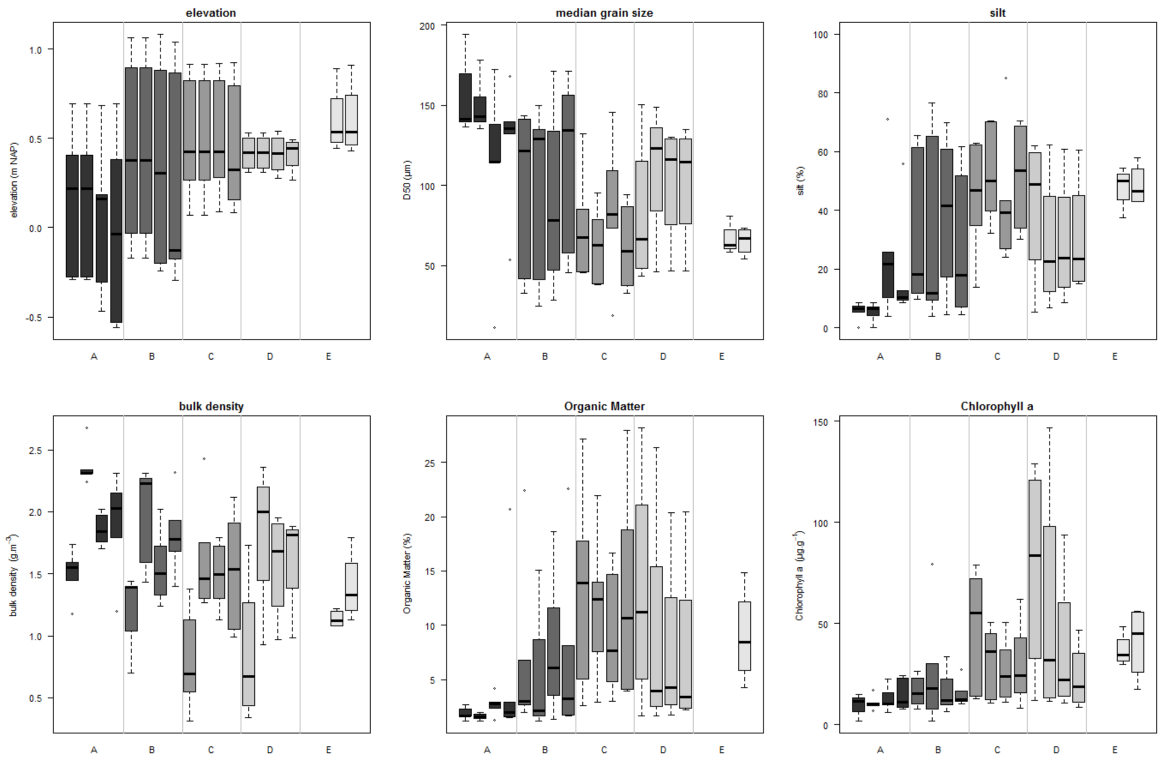


Figure 64. Changes in elevation (m nap), median grain size (%), silt (%), bulk density (g cm-3), organic matter (%) and chlorophyll-a (µg cm3) with increasing distance to the inlet (panels) over time (spring 2017, autumn 2017, spring 2018, autumn 2018).

3.3.2 *BENTHIC MACROFAUNA*

A rapid colonization was observed as 22 species colonized the Rammegors area within five months after the third opening. During each subsequent sampling campaign new species colonize the area (Table 7). In spring 2017, the brackish mud shrimp *Monocorophium insidiosum* (Crawford 1937) occurred in 80% of the sampling stations and was by far the most dominant species in abundance (Table 7). *M. insidiosum* declined in autumn 2017 to only 1.5% of the density found in spring and disappeared completely from the area in autumn 2018. From autumn 2017 onwards the marine *Corophium volutator* increased in abundance. The observed decrease of *M. insidiosum* combined with an increase of *C. volutator* indicate that the Rammegors area was still brackish five months after the third opening but transferred to a marine system. Also the occurrence of the brackish cockle *Cerastoderma glaucum*, as well as high occurrence of Chironomidae in 2017 followed by a decline in 2018 indicates this transition. In autumn 2018 the Rammegors area was dominated by gastropoda and polychaeta of which *Peringia ulvae* and *Corophium volutator,* respectively contributed most to the total abundance (Figure 65B). Biomass (Figure 65C) increased over time, with polychaetes contributing most to the total biomass.

Table 7. Occurrence (% of the total sampled stations) and density (ind. m-2, mean ± se) of the observed species/taxon in the Rammegors area.

species/Taxon	Occurrence %			
	Spring 2017	Autumn 2017	Spring 2018	Autumn 2018
Monocorophium insidiosum	80	10	20	
Chironomidae	75	10	10	10
Hypereteone foliosa	75	50	50	25
Arenicola marina	70	25	30	5
Capitella capitata	70	30	15	50
Hediste diversicolor	65	80	105	115
Nereis	65	60	80	60
Polydora cornuta	65	10	70	35
Oligochaeta	60	5	30	15
Pygospio elegans	55	20	45	20
Peringia ulvae	45	45	75	80
Gammarus	35			
Microdeutopus gryllotalpa	35	5	10	5
Streblospio benedicti	35	30	45	50
Eteone	30	5	5	15
Gammarus locusta	30		5	
Arenicola	20	15	10	5
Heteromastus filiformis	20	60	50	85
Idotea	15			
Insecta	5	10	10	5
Phyllodoce mucosa	5	5		
Praunus	5			
Alitta virens		40	30	65
Limecola balthica		20	30	40
Aphelochaeta		10	40	55
Carcinus maenas		10	5	10
Cerastoderma edule		10	10	5
Actiniaria		5		
Alitta succinea		5		15
Cerastoderma glaucum		5		
Corophium volutator		5	75	35
Crangon crangon		5	15	10
Bivalvia			10	15
Nemertea			10	15
Tapes			10	5
Arthropoda			5	
Cerastoderma			5	
Gastropoda			5	
Melita palmata			5	
Scrobicularia plana			5	5
Spio martinensis			5	
Mya arenaria				10
Glycera tridactyla				5
Magelona				5
Nephtys hombergii				5
Ruditapes philippinarum				5
Spionidae				5
number of species	**22**	**28**	**34**	**34**

species/Taxon	Density (ind. m^{-2})			
	Spring 2017	Autumn 2017	Spring 2018	Autumn 2018
Monocorophium insidiosum	3735 ± 1066	446 ± 74	2143 ± 716	
Chironomidae	1949 ± 531	106 ± 20	191 ± 34	64 ± 7
Hypereteone foliosa	195 ± 43	115 ± 26	59 ± 7	93 ± 16
Arenicola marina	340 ± 80	119 ± 21	50 ± 4	42 ± 0
Capitella capitata	243 ± 42	156 ± 30	71 ± 11	110 ± 27
Hediste diversicolor	405 ± 123	899 ± 194	594 ± 89	961 ± 205
Nereis	552 ± 216	509 ± 134	180 ± 38	453 ± 138
Polydora cornuta	274 ± 63	127 ± 27	224 ± 44	218 ± 44
Oligochaeta	2278 ± 762	4923 ± 0	85 ± 8	42 ± 0
Pygospio elegans	293 ± 56	64 ± 12	292 ± 57	212 ± 40
Peringia ulvae	292 ± 57	2735 ± 669	993 ± 332	2546 ± 736
Gammarus	194 ± 61			
Microdeutopus gryllotalpa	770 ± 263	212 ± 0	1528 ± 416	42 ± 0
Streblospio benedicti	449 ± 99	212 ± 55	141 ± 33	127 ± 21
Eteone	71 ± 10	0 ± 0	42 ± 0	28 ± 5
Gammarus locusta	78 ± 7		42 ± 0	
Arenicola	64 ± 5	42 ± 16	21 ± 7	42 ± 0
Heteromastus filiformis	74 ± 21	258 ± 114	68 ± 12	135 ± 39
Idotea	71 ± 11			
Insecta	42 ± 0	42 ± 0	64 ± 7	127 ± 0
Phyllodoce mucosa	85 ± 0	85 ± 0		
Praunus	42 ± 0			
Alitta virens		80 ± 15	71 ± 10	98 ± 16
Limecola balthica		53 ± 5	42 ± 0	58 ± 7
Aphelochaeta		64 ± 7	101 ± 13	278 ± 68
Carcinus maenas		42 ± 0	42 ± 0	42 ± 0
Cerastoderma edule		42 ± 0	42 ± 0	85 ± 0
Actiniaria		42 ± 0		
Alitta succinea		42 ± 0		14 ± 5
Cerastoderma glaucum		42 ± 0		
Corophium volutator		42 ± 0	1092 ± 478	2213 ± 718
Crangon crangon		42 ± 0	57 ± 5	64 ± 7
Bivalvia			21 ± 7	424 ± 75
Nemertea			42 ± 0	99 ± 22
Tapes			42 ± 0	85 ± 0
Arthropoda			5093 ± 0	
Cerastoderma			42 ± 0	
Gastropoda			42 ± 0	
Melita palmata			42 ± 0	
Scrobicularia plana			42 ± 0	42 ± 0
Spio martinensis			85 ± 0	
Mya arenaria				64 ± 7
Glycera tridactyla				42 ± 0
Magelona				0 ± 0
Nephtys hombergii				0 ± 0
Ruditapes philippinarum				42 ± 0
Spionidae				0 ± 0
average abundance	**8049 ± 1779**	**3028 ± 653**	**3150 ± 819**	**4122 ± 735**

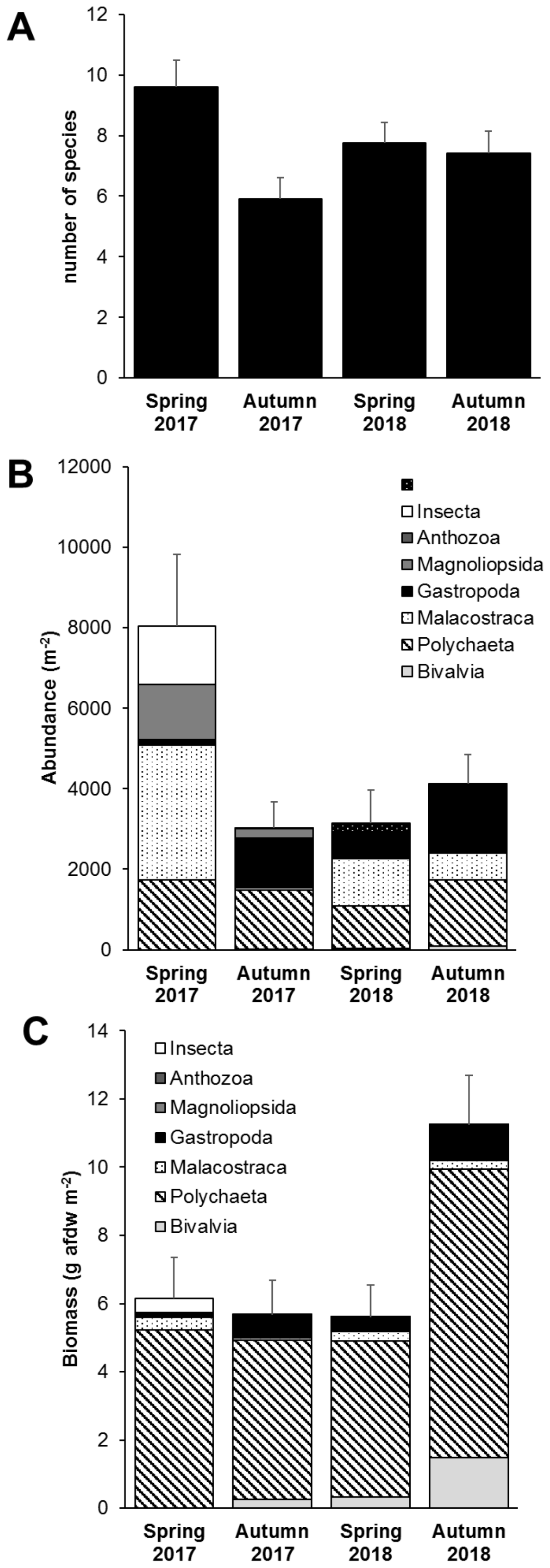


Figure 65. Variation in the mean (± se) species richness (A), total abundance (B) and biomass (C) with proportional representation of the taxa in the Rammegors area.

All biological indicators show a significant relation along the elevation gradient with an optimum around +0.4m NAP and lower values at both lower and higher elevations (Species richness: polynomial regression: R^2 = 0.11, p=0.006; total density: polynomial regression: R^2 = 0.18, p=0.000; total biomass: polynomial regression: R^2 = 0.30, p=0.000) (Figure 66). Total density significantly increases with an increase in chlorophyll *a* (linear regression: R^2 = 0.23, p=0.000), silt content (linear regression: R^2 = 0.10, p=0.003) and organic matter (linear regression: R^2 = 0.08, p=0.009). A significant decrease in total density (linear regression: R^2 = 0.29 p=0.000) and species richness (linear regression: R^2 = 0.05, p=0.030) was observed with increasing bulk density (Figure 67). All biological indicators show a significant linear increase with distance from the inlet (species richness: R^2 = 0.08, p=0.007; total density: R^2 = 0.16, p=0.000; total biomass: R^2 = 0.12, p=0.001) (Figure 68). No relation between sediment composition and benthic macrofauna was found.

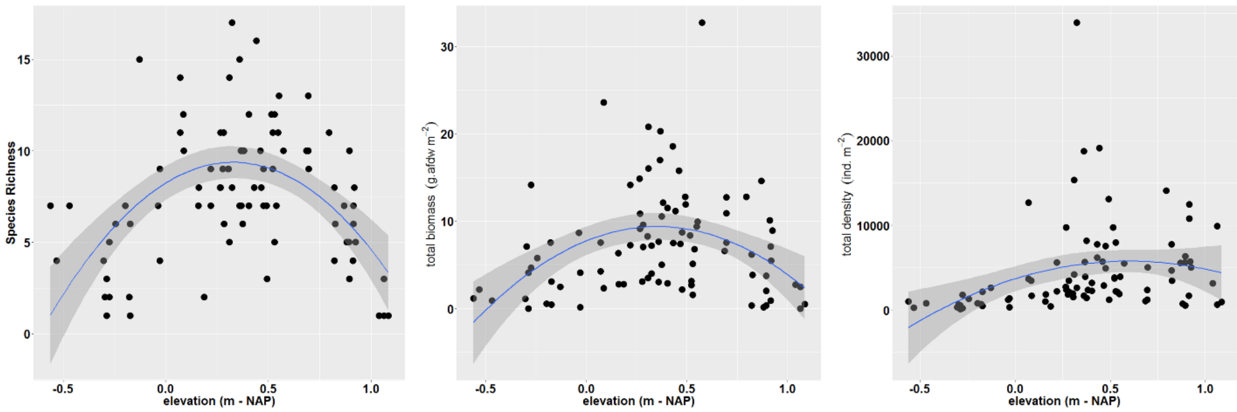


Figure 66. Species richness, total biomass and total density along an elevation gradient (in m nap). Lines represent polynomial regression lines for the macrofauna community in the Rammegors area. Grey area indicates the 95% confidence interval.

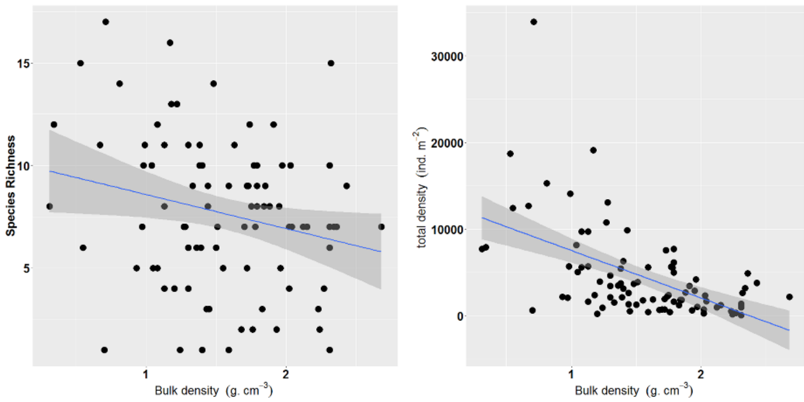


Figure 67. Species richness and total density versus bulk density (g cm-3). Lines represent polynomial regression lines for the macrofauna community in the Rammegors area. Grey area indicates the 95% confidence interval.

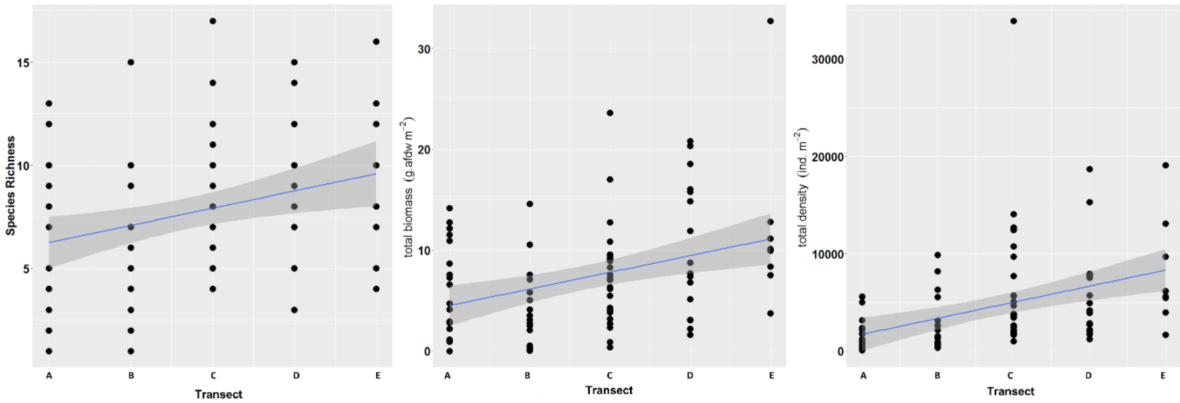


Figure 68. Species richness, total biomass and total density at the different transects increases with increasing distance to the inlet (transects a near the inlet). Lines represent linear regression lines for the macrofauna community in the Rammegors area. Grey area indicates the 95% confidence interval.

3.3.3 *COMMUNITY STRUCTURE*

The benthic community composition showed high dissimilarity between the first sampling moment in spring 2017 and the other sampling moments. From autumn 2017 onwards community is not changing that much and showing a relatively stable community (Figure 69).

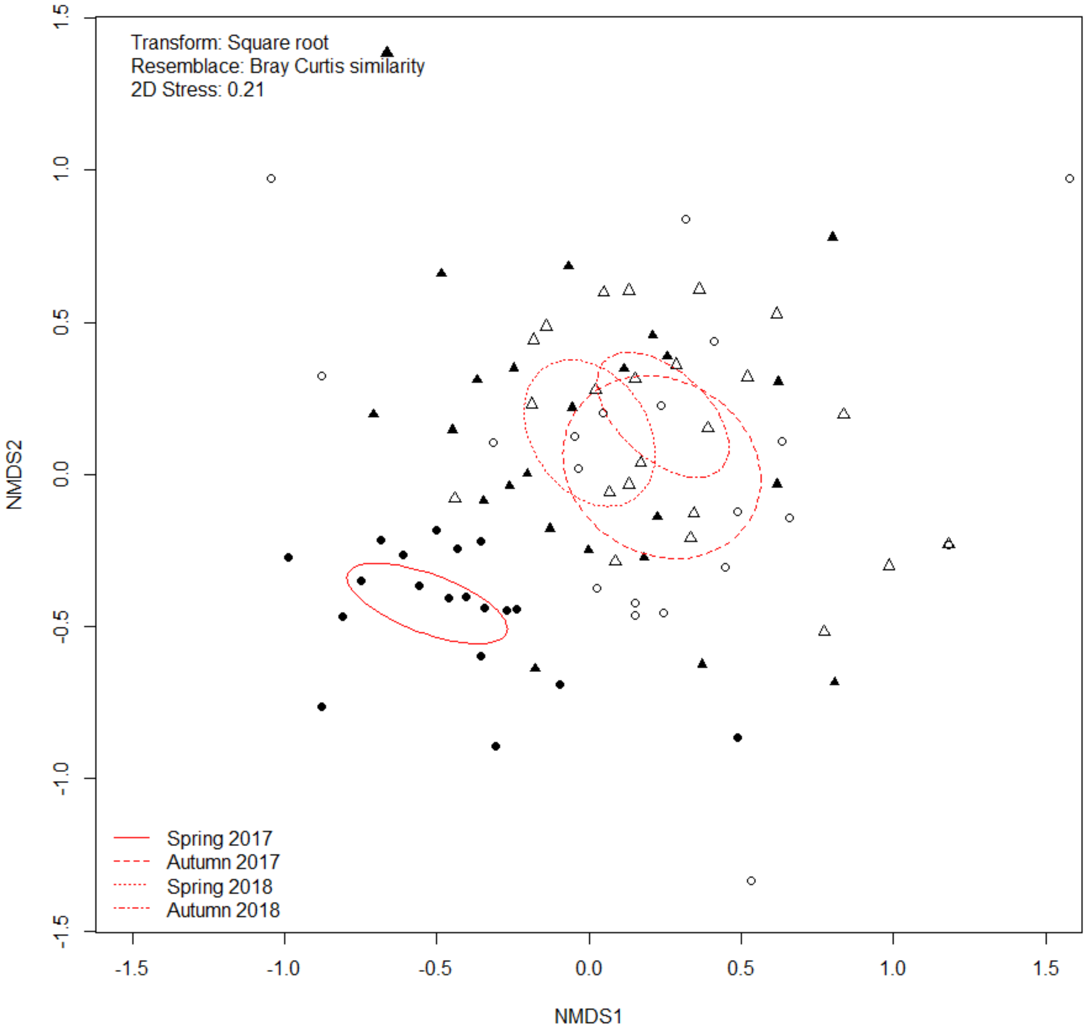


Figure 69. nMDS-plot showing changes in benthic community composition from spring 2017 till autumn 2018 at the Rammegors area based on abundance data. Each point represents a sampling station. The different symbols indicate the different sampling moments (closed circles: spring 2017; open circles: autumn 2017; closed triangles: spring 2018; open triangles: autumn 2018). Distance between points is a measure of dissimilarity in benthic community composition. The eclipse (red) denote the 95% confidence interval for each sampling moment.

3.4 CONCLUSIONS

A fast colonization of the benthic macrofauna was observed in Rammegors. The communities significantly differed between spring and autumn 2017 but did not show significant changes after autumn 2017. In spring densities reached high values, especially for the brackish mud shrimp *Monocorophium insidiosum* and mosquito larvae *Chironomidae*. In autumn these brackish species almost disappeared from the area. Their presence in autumn, even in low numbers, as well as the observation of the brackish cockle *Cerastoderma glaucum* indicate that, almost a year after the tidal restoration, parts of Rammegors are still under influence of brackish water. In spring a further decline occurred among the brackish species indicating the transition into a marine environment. The occurrence of brackish conditions a year after tidal inundation could be explained by model simulations of groundwater salinity by Deltares (America et al. 2018). Before inundation, a freshwater lens was present in the Rammegors area. Inundation by saltwater influenced the groundwater. Saltwater is heavier then freshwater. The saltwater on top of the freshwater lens does not drain down homogeneous, but in plumes. As a response, also upward plumes of freshwater occur, resulting in locally seepage of freshwater to the surface. This could locally effect the benthic community as the ground water could be brackish at these spots whereas the overlaying water is saline.

Benthic macrofauna shows a relation with elevation. An optimum of species richness, total density and total biomass was found around +0.4m NAP with lower values at both lower and higher elevations.

As sedimentation does not take place in the Rammegors area, no relation with sedimentation rate could be made. With an increase in chlorophyll *a* and organic matter an increase in total density was observed. A significant decrease in total density and species richness was observed with increasing bulk density, indicating that more compact sediments contain less species in lower abundances. With increasing distance from the inlet benthic macrofauna increases in richness, density and biomass. The elevation near the inlet was on average lower than the other transects, below the elevation at which an optimum in macrobenthic was observed. Sediment composition changes are larger near the inlet, perhaps calmer conditions further from the inlet facilitate the benthic macrofauna. Also retention time could be longer further from the inlet, affecting colonization processes. More knowledge on the hydrodynamics within the Rammegors area is needed to confirm this.

No comparison was made with a comparable ecotope in the Oosterschelde as it is at this moment unclear which ecotope is comparable with the Rammegors area due to the different tidal range in the Rammegors area compared to the Oosterschelde. A detailed inundation map of the area could help identifying with which area the Rammegors area could be compared.

Tidal restoration area Rammegors in the Oosterschelde developed different from the managed realignment Perkpolder located in the Westerschelde (van de Lageweg et al. 2019b). Biggest differences were (1) no sediment input in Rammegors, whereas a fast ongoing sedimentation occurs in Perkpolder and (2) the development of vegetation in Rammegors (Van de Lageweg *et al.* 2019a) compared to a lack of vegetation in Perkpolder (Van de Lageweg et al. 2019b). Besides those differences, both areas were initially colonized by a high numbers of Corophidae and showed a high biomass of Polychaeta. The community composition at Perkpolder is still showing large changes after five years and develops in the direction of a community generally found at the mid-litoral low-dynamic ecotoop at the transition zone between marine and brackish water of the Westerschelde. It is unknown after two years if the community in Rammegors reaches stability or that changes are too small to observed a development in a certain direction. Development of the benthic macrofauna community should be monitored over a longer period and compared to a community found in a comparable natural habitat.

4. VEGETATION & SOIL

4.1 INTRODUCTION

To protect the South-western delta in the Netherlands from flooding, the Delta works were constructed. Due to the building of a series of dams, the estuarine water bodies have radically changed. Before the construction of the Delta works, gradients of salinity were found throughout the delta area. Due to the building of dams, water bodies became compartmentalized into lakes and sea-arms, with much less riverine inputs. The Eastern Scheldt was also disconnected from riverine influence, while maintaining a connection to the sea via a permeable storm-urge barrier, turning the system effectively into a sea arm. The storm-urge barrier is only closed if storms are predicted to increase water levels to +3m NAP. This construction allowed maintaining valuable intertidal flats with a high biodiversity of benthos, which among others serves ass food for (migratory) birds, and the persistence of tidal salt marshes, which harbour a unique plant community and offer habitat to various animals.

The Rammegors project focuses on extending the area of valuable ecological areas in the Eastern Scheldt, by creating additional salt marsh area, intertidal area and low energetic shallow sub-tidal area. Due to the construction of the Krabbekreekdam (part of Scheldt-Rhine channel) about 40 years ago, the Rammegors salt marsh area became disconnected from tidal seawater influence. At first this area was a designated sludge depot, but developed into a fresh water marsh. Recently, a tidal inlet was constructed in the Krabbekreekdam to generate a reduced tidal influence that should allow the development of typical tidal salt marsh vegetation. However, it is unclear at what rate salt-marsh development will take place, as *i)* seed exchange with other salt marshes might be limited due to the tidal inlet, and *ii)* growth conditions may hampers salt marsh vegetation establishment.

Gaining an in-depth mechanistic insight into the processes that affect the rate of conversion from fresh water marsh into a tidal salt-water marsh area is important, as similar conversion/restoration projects might take place in the future. We aim to provide the 1st basic insights, by using the Rammegors project as an unique opportunity to validate and extent on previously at NIOZ developed concepts (e.g., Window of Opportunity theory).

4.2 MAIN QUESTIONS AND OBJECTIVES

To gain better mechanistic insight into how fresh marsh areas develop into tidal salt marshes we focused on the following generic questions:

1) What is the role of seed (including propagules) availability and dispersal for the potential of marsh vegetation to develop?
   a) Is the seed (including propagules) supply into the area sufficient to enable the establishment of marsh vegetation?

b) Is the seed (including propagules) dispersal within the area sufficient to enable colonization of all areas?

2) Which process controls the colonization process of the lower marsh :

a) Does the Window of Opportunity theory provide an applicable framework that allows predicting which parts will become vegetated?

b) What is the relative importance of seed (propagule) dispersal versus clonal spreading, for colonization in space?

3) How does the colonization occur along the inundation (⬄ elevation) gradient:

a) Do the remaining plant parts have a positive (by trapping seeds / propagules) or negative (via the soil chemistry) effect on the colonization?

b) Is the effect of the remaining plant parts on the colonization depended on the inundation frequency (⬄ elevation gradient)?

4.3 RESEARCH APPROACH

The followed approach is mainly empirical making use of various field surveys and manipulative experiments.

- To understand the effect of the inlet on the exchange and distribution on salt marsh propagules, seeds will be trapped at various plots in the Rammegors area. Nets are used to quantify the propagule flux in and out via the tidal inlet.
- Sediment accretion/erosion, soil chemistry and inundation frequency (tidal gauges) are measured at various plots.
- Planting experiments will be used to investigate the effects of soil properties on the survival and development of seedlings and tussocks. This experiment was relocated to areas across the Eastern and Western Scheldt, as technical problems with the dam at the inlet of Rammegors, required the inlet to be closed over a prolonged period of time.

4.4 RESULTS

4.4.1 *BACKGROUND INFORMATION ON NIOZ RESEARCH*

In anticipation of the large amount of (field) work within the Rammegors project, and given the opportunity that an excellent candidate was available for carrying out this task, NIOZ hired a field assistant for the Rammegors project. Within this context, we had planned on carrying out the seedling experiment in 2015, rather than 2016, so that we would be ahead of the time schedule. Unfortunately, this did not work out as planned, as technical problems with the broken dam near the inlet of Rammegors, the fieldwork could not be carried out as was foreseen. Eventually this field experiment with planting of seedlings was carried out in 2017. 2018 was used to keep monitoring the local 18 points.

Table 8 provides a concise overview of most important fieldwork that we did carry out in 2015 within the Rammegors project.

- The locations where “vegetation measurements” were taken have been indicated by the “green” points in Figure 70. The “vegetation measurements” include at this point in time (with no new vegetation established yet) the following measurements of the abiotic environment: (1) a sediment sample of the top 3cm, (2) measuring changes in sediment elevation, using erosion pins, (3) seed dispersal by (re)placed seeds traps and (4) tidal inundation using automated tidal gauges. A detailed description of the various field measurements is given below.
- In order not to waste all the seedlings that were germinated and cultivated for the Rammegors field experiment, we decided to use them for an alternative experiment with relevance for the project. A detailed description of this seedling experiment is given below.

In addition to the fieldwork described in this report, 4 students have been appointed on the project in 2015: 2 students from the HZ and 2 students from the RU Groningen. The students of the HZ (co-supervised by Carla Pesch and Tjeerd Bouma) have made an inventory of the (death) above and below-ground standing biomass of the original vegetation, and tried to make a long-term, prediction of the future marsh, based on the elevation map. The students of the RU Groningen (co-supervised by Jim van Belzen and Tjeerd Bouma) have analysed flooding data and measured soil properties. The results of the student work are not described in full detail in this report, as these t0 measurements are no longer regarded very useful given the delays in opening Rammegors, and the management that resulted from this.

Table 8. Concise overview of the fieldwork carried out by NIOZ in 2015, 2016, 2017 en 2018 within the Rammegors project.

Visiting date	Seed traps		dGPS	Diver	Sediment sample	Penetrologger	Shear vane	Erosion pins	Mapping vegetation	Wildcams	Seedling experiment	Seedling experiment
	Mats	Nets									Eastern Scheldt	Western Scheldt
2015-03-12	Placed		X	Placed	X			Placed	X			
2015-04-29	Re-Placed			Re-Placed	X			X	X			
2015-06-23											Setup (biweekly follow up)	
2015-06-24												Setup (biweekly follow up)
2015-10-16				Collected					X			
2015-11-25	Re-Placed			Placed	X			X				
2016-01-18										Placed		
2016-04-01										Battery/card		
2016-09-26	Re-Placed			Collected	X				X	Battery/card		
2016-11-24				Placed	X					Battery/card		
2016-12-14	Re-Placed	X										
2017-01-26	Re-Placed	X		Re-Placed						Battery/card		
2017-05-17	Re-Placed		X	Re-Placed	X	X	X			Battery/card		
2017-06-27											Planted	
2017-07-05											Monitoring grow/survival	
2017-07-21					X		X				Monitoring grow/survival	
2017-08-09	Re-Placed			Re-Placed						Battery/card	Monitoring grow/survival	
2017-11-06	Re-Placed			out	X		X			Battery/card	Monitoring grow/survival	
2018-01-31	Out				X + Core		X			Battery/card		
2018-04-30			X		X	X	X			Removed		
2018-07-30					X		X					
2018-10-30					X		X		X			

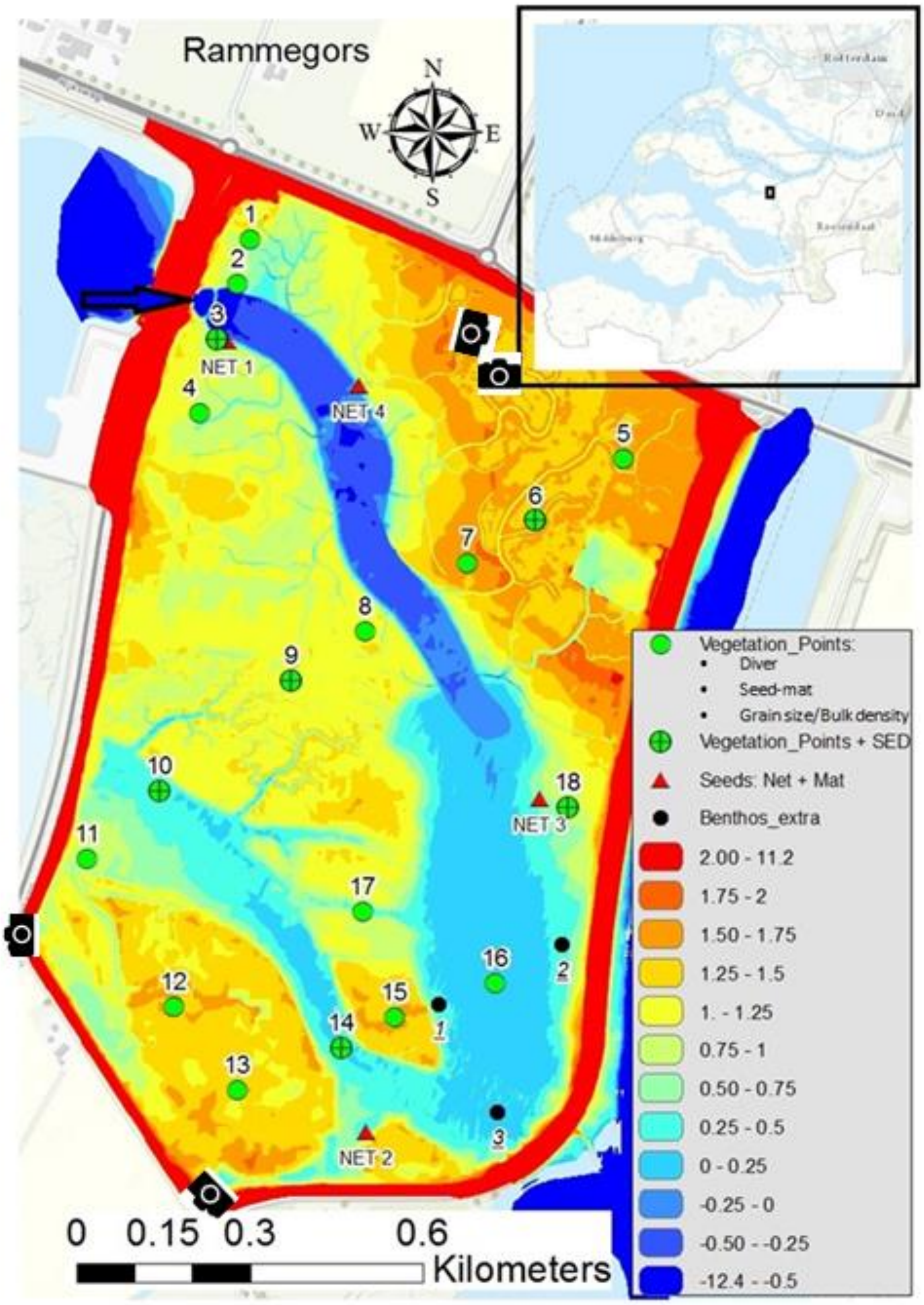


Figure 70. Overview of the locations where measurements are taken within the Rammegors project. As a starting point, the remaining fresh water marsh vegetation was mapped (i.e., at start of project, there has no new vegetation established yet). During this inventory by the HZ-students (co-supervised by Carla Pesch and Tjeerd Bouma), areas covered by Phragmites, grass, bare spots without vegetation and areas with permanent water were tracked with a GPS and converted into a map. At the "vegetation measurements" locations (indicated by the by green dots), the following biotic & abiotic parameters were measured: (1) above and below ground biomass of decaying vegetation, (2) a sediment sample of the top 3cm, (3) seed dispersal by (re)placed seeds traps and (4) tidal inundation using automated tidal gauges. At four locations the availability of floating seeds will be monitored. Wildcams with a timelaps setting of one hour have been placed on four locations.

4.4.2 *SEED TRAPS*

Astro-turf mats of 50 by 50 cm were placed at all 18 points (Figure 71) to trap seeds that arrive in Rammegors. These mats are regularly replaced, depending on the season. Within the lab these mats are cleaned, where after the number of seeds can be quantified and determined at the species level. By deploying the Astro-turf mats in a spatial explicit pattern, we can map the seed arrival for different species arriving this area.

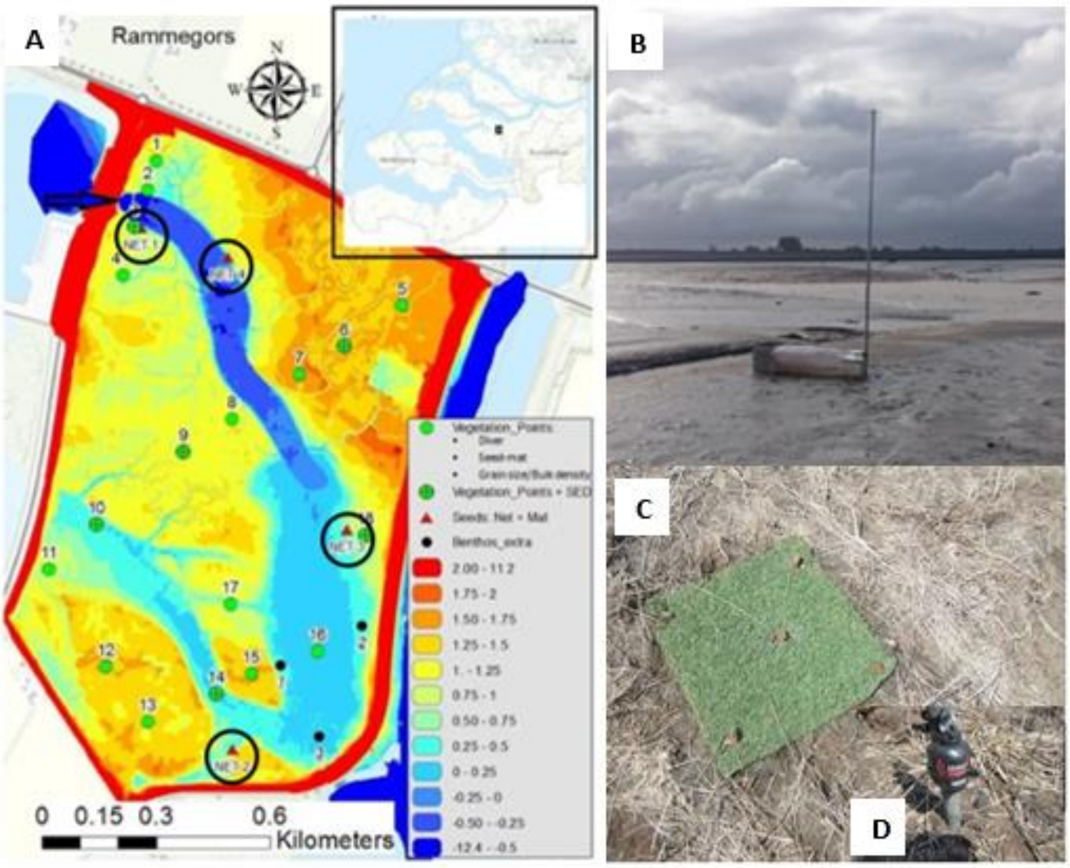


Figure 71. a) Locations of the 18 points, pictures of b) floating net, c) seed traps a 50*50 cm seed trap (Astro-turf mat) and d) a Reefnet sensus ultra diver.

Besides these mats we also placed ‘floating’ nets of 1 meter at four point shown in Figure 71b. In this way the seed availability coming in from the Eastern Scheldt during one (spring) tide can be quantified. At the lab these seeds are determined and tested for vitality.

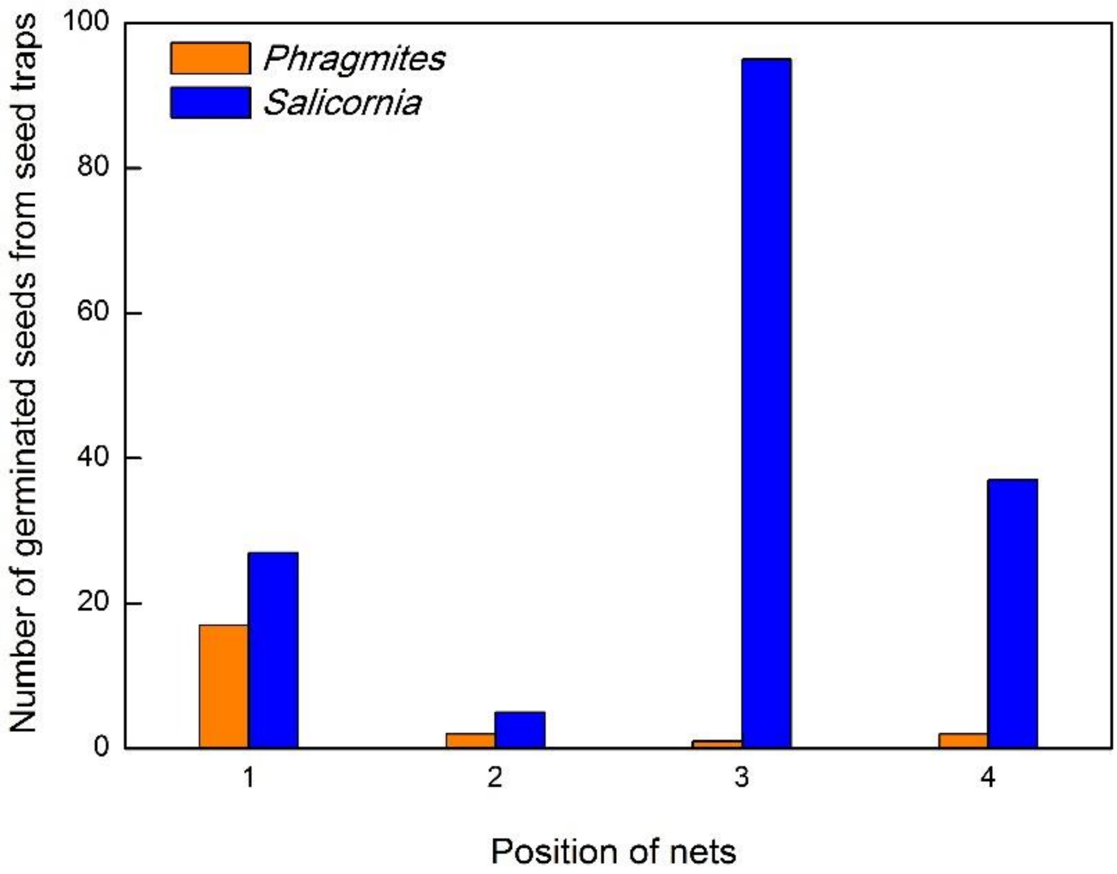


Figure 72. Number of seeds present in floating net deployed at Rammegors for 1 day (= 2 tidal cycles) in December 2017.

4.4.3 *MEASURING INUNDATION PERIODS AT DIFFERENT LOCATIONS OF RAMMEGORS*

To study the flood propagation and spatial pattern of inundation period within the Rammegors area, we placed pressure sensors (Sensus Ultra by Reefnet, shown in Figure 71) that measure and logs the pressure every 30 minutes. This pressure can then be converted into a water level, enabling us to make spatial analyses of the flooding. Following results are the average of the period between January 2017 and May 2017.

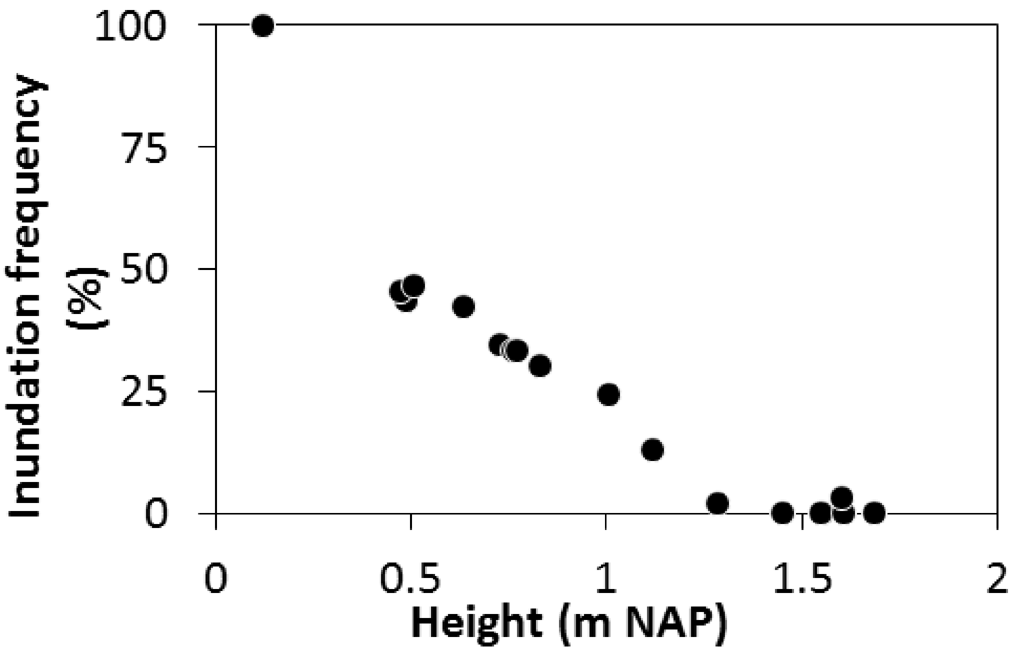


Figure 73. Pressure data processed into inundation period of height of all 18 vegetation points.

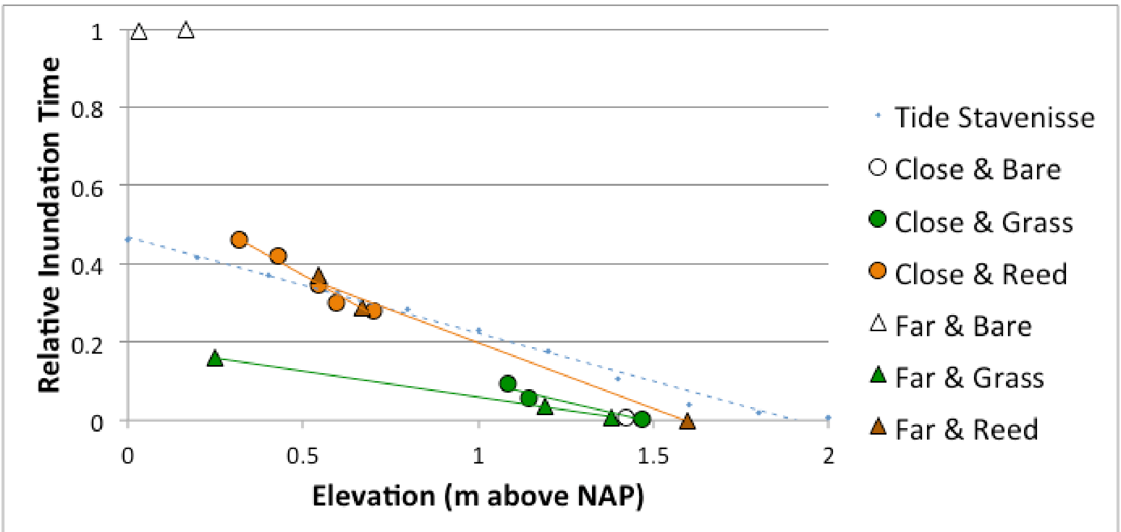


Figure 74. Analyses of the flooding data of Rammegors. Data are analysed based on location (i.e., far away or close to inlet) and vegetation type (i.e, tall reed, short grass and bare areas). This graph is based on MSc work by John Bastiaans & Miranka van Breugel (Rijks Universiteit Groningen).

Inundation frequencies are shown in Figure 75. Focused on the bare area in the northeast: sampling point 6 inundates once per week with just a few centimeters of water and sampling point 5 inundated just one time in the summer of 2017.

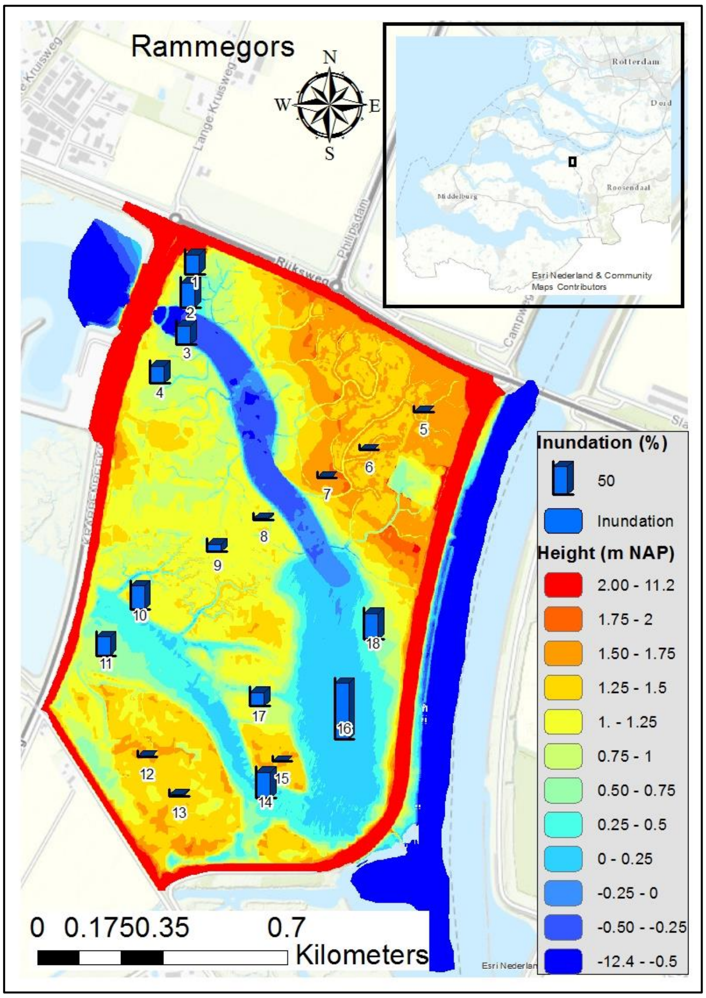


Figure 75. Inundated period (%) at 18 sampling points at Rammegors.

4.4.4 *SEDIMENT CHARACTERISTICS*

With a syringe from which the top has been removed, a sediment sample of the top 3 cm is taken. Because the cut-off syringe allows us to take a sediment sample with a fixed volume, we can determine the Bulk Density of the sediment by freeze drying the samples. Afterwards the grain size will be determined using the Malvern P2000 machine. Besides this the height is measured using a Leica dGPS.

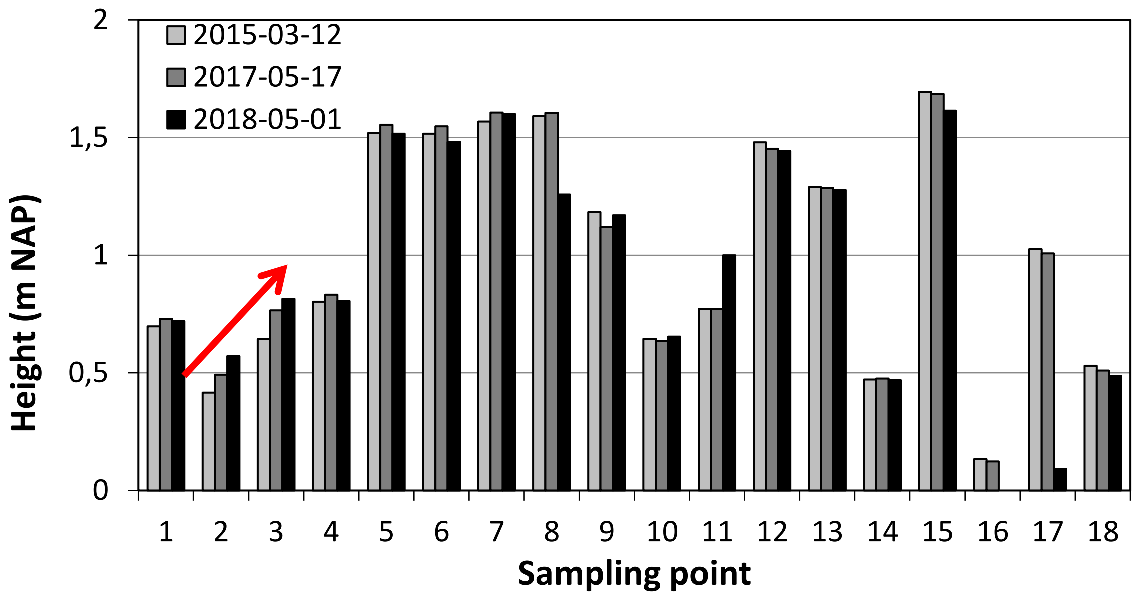


Figure 76. Results of height measurement using a dGPS (SE = 20 mm) at 18 vegetation points.

4.4.4.1 Bulk density

Samples with a fixed volume are taken from the top three cm, wet and dry weight are determined. Subsequently the bulk density is calculated. The suitable bulk density of the soil for vegetation establishment was determined to be above 0.6 g/cm^3 and below 0.9 g/cm^3. At densities below 0.6 g/cm^3 the soil is too loose for roots to stay attached. At densities above 0.9 g/cm3 the soil is too compact for roots to grow and prone to erosion (Faegin, 2009).

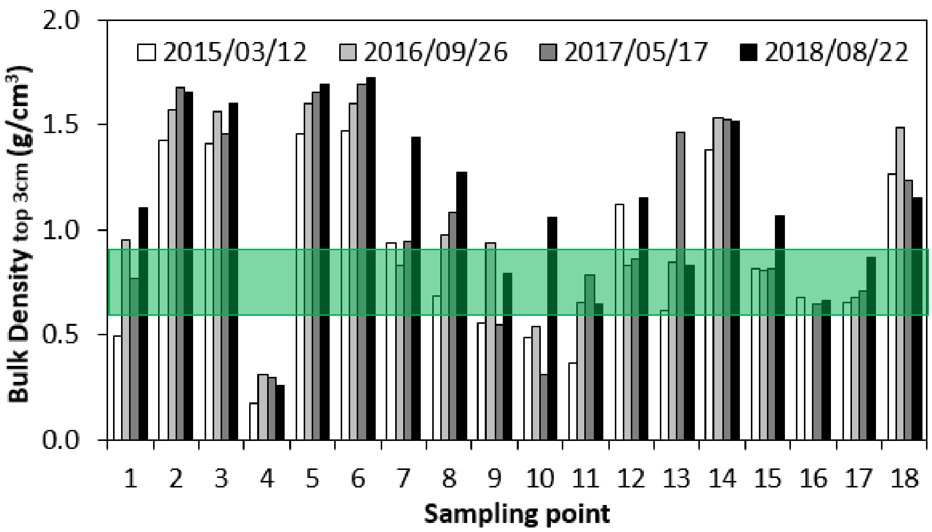


Figure 77. Results of bulk density (g/cm3) measurements. Green = most suitable for vegetation, according to Feagin (2009) between 0.6 and 0.9 g/cm3 .

4.4.4.2 *SOIL WATER CONTENT*

The suitable soil water content for vegetation establishment was determined to be between 24% and 60%. Between these soil water contents plants of the seeds in the pioneer and low salt marsh zone have been found to grow (Parlog, 2015).

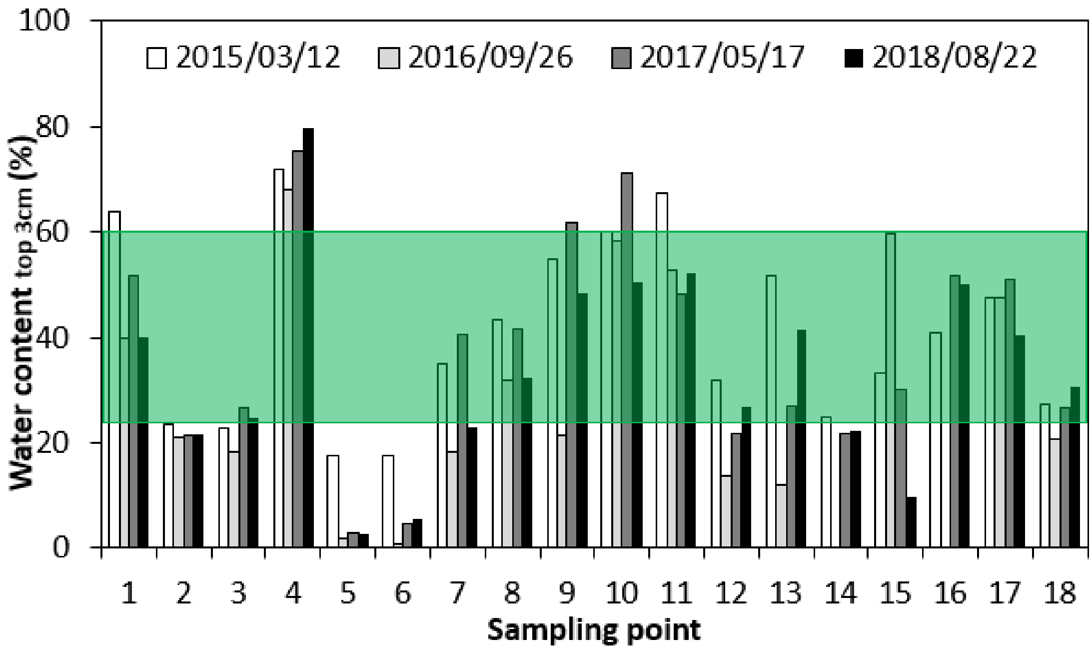


Figure 78. Results of soil water content with ideal (= green) circumstances for seedling establishment, between 24 and 60% (Parlog, 2015).

Correlation between water content (%) and bulk density (g/cm3) in top 3 cm over all 18 sampling points.

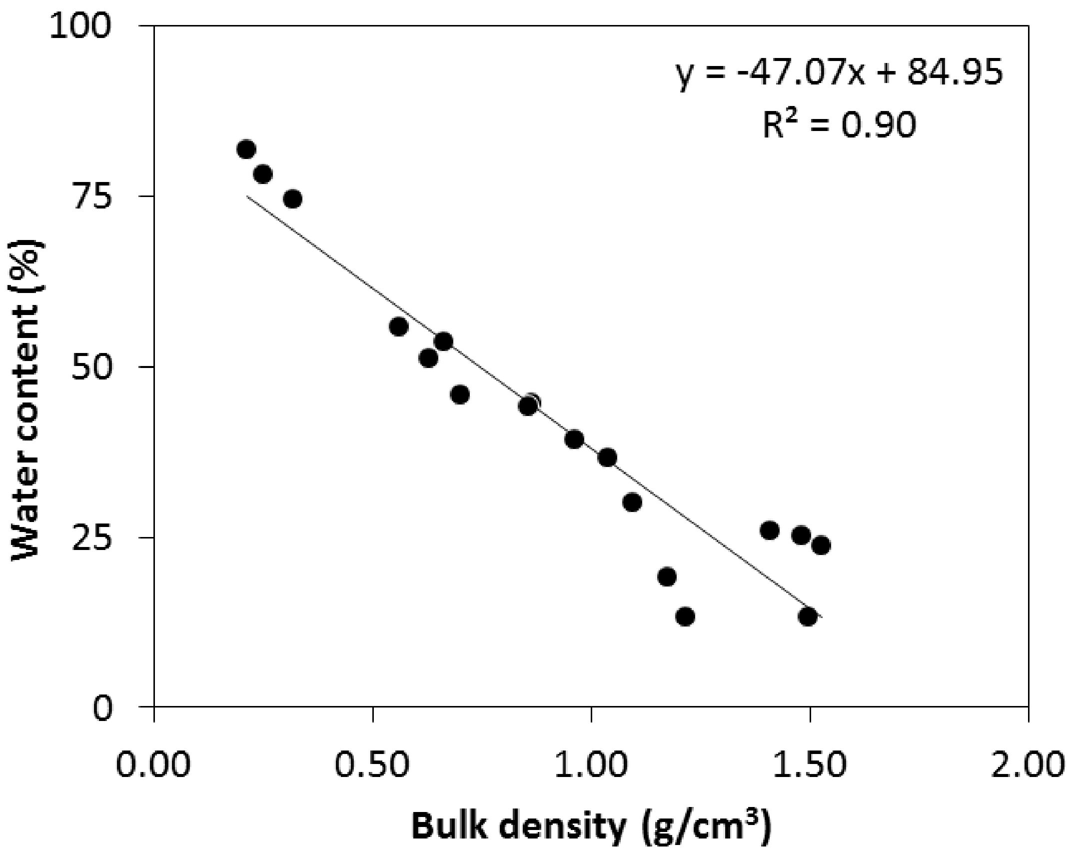


Figure 79. Relation in Bulk density (g/cm3) and water content (%).

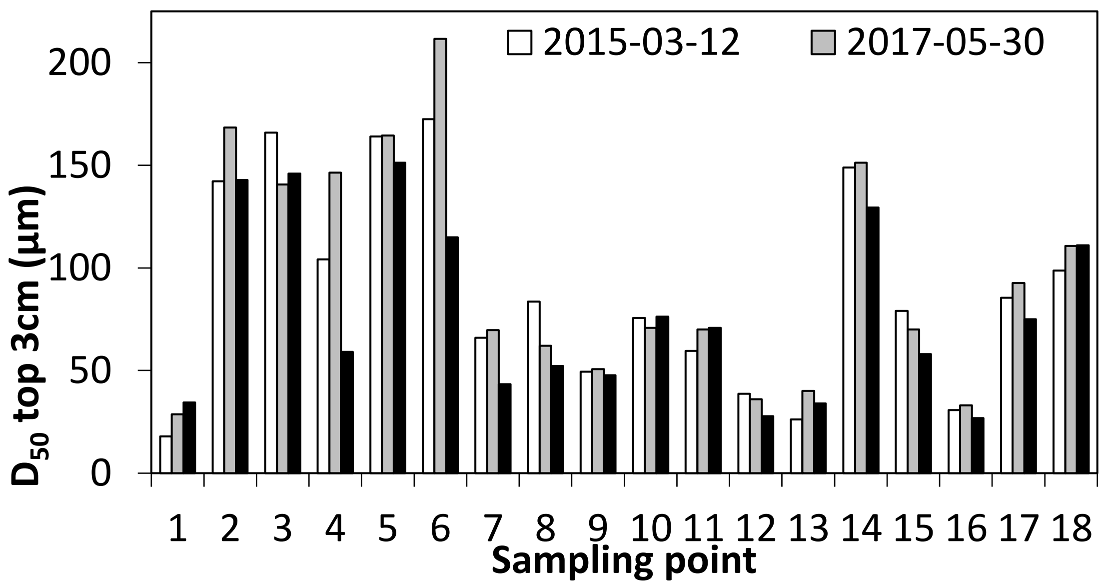


Figure 80. Grain size of top 3 cm at 18 sampling point in Rammegors expressed in d50 (µm), measured by Malvern P2000 machine.

4.4.4.3 *PENETROLOGGER / STIFFNESS*

The penetrologger is an instrument for in situ measurement of the resistance to penetration of the soil. The resistance to penetration is a means of determining the ground load-bearing capacity, and the ease with which roots can grow penetrating the ground. A cone is screwed on the probing rod, which is connected with a quick coupling to the force sensor on the penetrologger. The cone is pushed slowly and regularly into the soil. The depth reference plate, which is on the soil surface, reflects the signals of the ultrasonic sensor, which results in a very accurate depth measurement.

Figure 81. Use of the Eijkelkamp penetrologger.

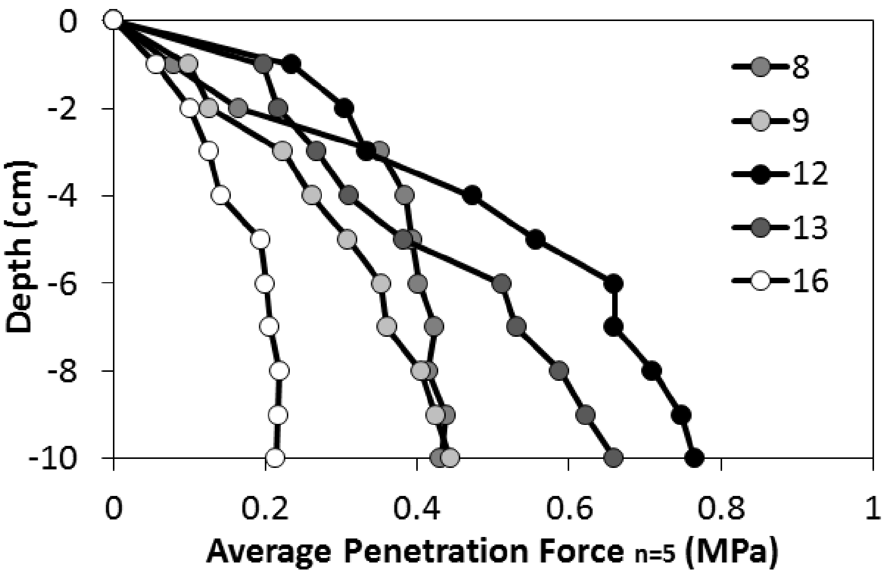


Figure 82. Results of penetrologger measurement expressed in megapascel per penetrated cm, average of 5 replicate measurements at points 8, 9, 12, 13 and 16.

4.4.4.4 *SHEAR STRESS / ERODEBALILITY*

Shear vane that measures bottom shear stress of top 5 mm.

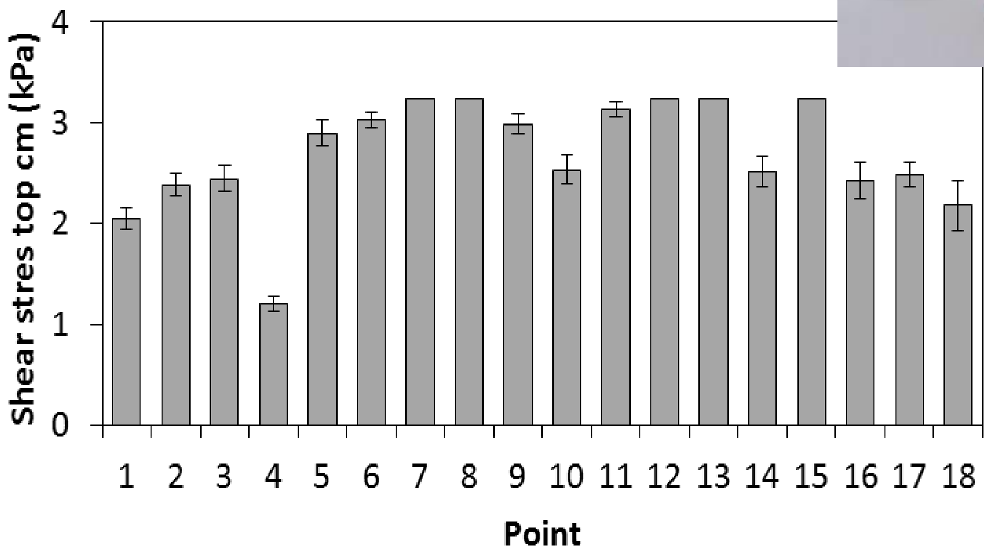


Figure 83. Shear vane measurements given in kPa (kN/m2).

4.4.4.5 *CORRELATIONS IN ABIOTIC FACTORS.*

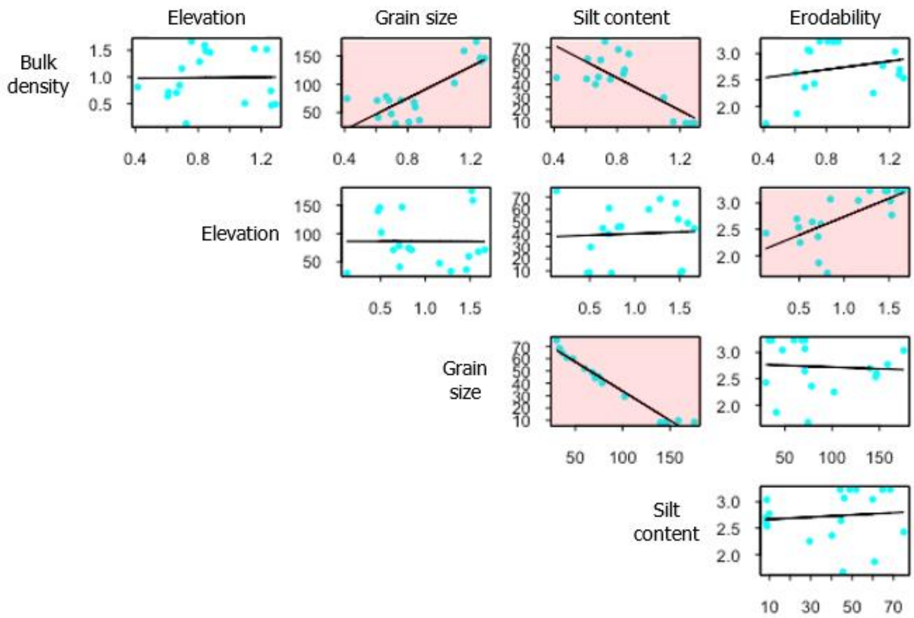
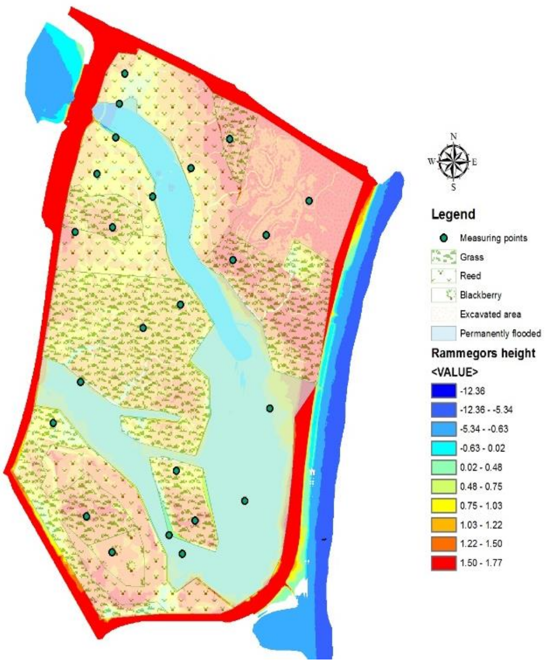


Figure 84. Correlations between the five sediment characteristics collected at Rammegors with a red background showing statistically significant correlations. The values have been averaged by point over all sampling periods.

The map shows the locations of the fifteen points. Mud content is derived from median grain size and bulk density is derived from water content.

4.4.5 *MAPPING VEGETATION*

In 2015 the *Phragmites* patches, Grass, bare sediment and permanent water are mapped by walking the contours by a hand-held GPS. These referenced 'routes' are converted into a map, including a long-term vegetation prediction (based on the current height). At all vegetation points (Figure 70) above and below ground biomass is determined. Coverage of the above ground biomass is defined by cutting a m^2 (J. Goud en A. Schaafsma, 2015). This mapping shows major similarities with the WMR/NIOZ mapping shown in the report: *Getijherstel in het Rammegors* (K. Elschot 2016). The present vegetation is determined, shoot density is counted, divided in 3 height classes (<10, 10-30 and > 30 cm) and dried. Below ground biomass is determined by taking cores (Ø 10cm) of the top 10 cm, subsequently cleaned and dried.



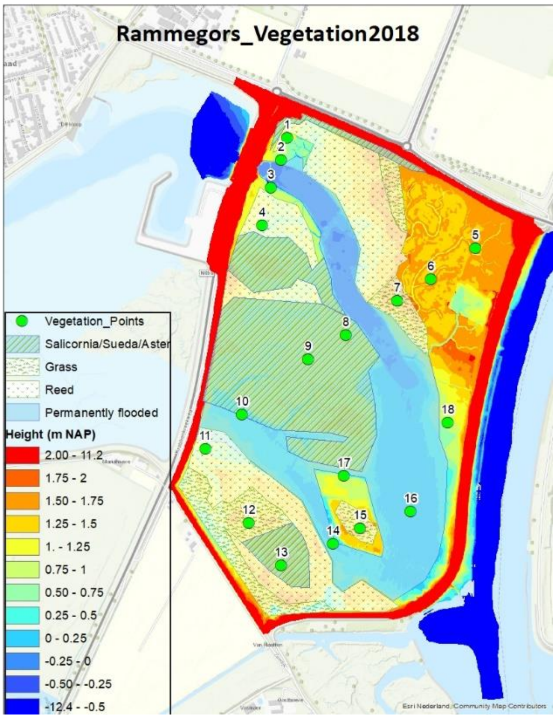


Figure 85. Vegetation coverage in 2015 and 2018 at Rammegors.

Vegetation is monitored at all 18 points at three moments, before opening in May 2015, in June 2017 (after 6 months of the real opening) an in November 2018 (two years after opening. Figure 86 shows a clear transition in vegetation, changing from fresh water species into marine species. After opening there is a huge die-off of fresh water species which are replaced by salt water species by the end of 2018. Only the higher, not inundated areas and highly abundant Phragmites (Reed, which has thick rhizomes that will not easily die because of salt-water inundation) still have some fresh water vegetation.

Figure 86

Figure 86. Estimated marsh coverage of different species in Rammegors at the 18 points, shown as corresponding elevation, based on the field survey on May 2015, June 2017 and November 2018. Elevation and so inundation time is the most important factor in the occurrence of vegetation species, clear transition of fresh to salt water species is visible in the lower points.

The Northeast area, represented as monitoring point 5 and 6, is still relative bare and has a lack of salt water vegetation. This area is sandy (Figure 80), dry (Figure 78) and seed availability is very limited because of the minimum inundation time (Figure 75).

Besides this contact is made with Piet van de Reest, who makes yearly vegetation recordings in 50 PQ's (fixed area of ø 3m) in the Rammegors area. Results of this work and comparison with this will be shown in the follow-up report.

4.4.6 *SEEDLING SURVIVAL EXPERIMENT I*

EXPERIMENTAL DESIGN: To understand the role of soil properties on *i)* the survival of seedlings and *ii)* development of vegetation tussocks, we performed a manipulative field experiment. This experiment was initially scheduled to take place in the Rammegors area at differing substrates (i.e., different levels of decaying organic matter and soil penetration resistance). However, the breakdown of the dam and the stagnant water levels thereafter prevented us from setting up the experiment within Rammegors area. In order not to waste all the seedlings that were germinated and cultivated for the Rammegors field experiment, we decided to use them for an alternative substitute experiment, with similar objectives.

In the substitute experiment, we determined the effect of *i)* sediment compaction and *ii)* soil chemistry (anoxia) on seedling survival, as this answers important question related to the restoration of tidal basins (managed realignment / mars restoration). Therefore, we picked four other locations in the Eastern Scheldt (Rattekaai East & Rattekaai West) and in the Western Scheldt (Rilland & Groot Buitenschoor), using both seedlings (*Spartina*, *Scirpus*, *Aster*, *Phragmitus*) and small tussocks (*Spartina*); see Figure 87. These replacement sites differ in soil properties, salinity, but also benthic fauna assemblage. The Eastern Scheldt sites Rattekaai East and Rattekaai West differ from the Western Scheldt sites Rilland and Groot Buitenschoor in salinity: 32 ppt vs. 6 ppt respectively. Furthermore, these sites differ in sediment composition and - associated with this - in soil chemistry and geomechanical properties. For example the Rattekaai East site is rich in organic matter. Soil penetration resistance is much higher at Rilland and Rattekaai West in comparison to the other two sites. An overview of site characteristics and the experimental layout is summarised in Table 9.

MATERIALS & METHODS: At all the sites seedlings and tussocks were transplanted at two elevations (inundation levels). We used *Spartina anglica* (English cordgrass) and *Scirpus maritimus* (Bulrush) seedlings in the Eastern and Western Scheldt field sites, and added as extra *Phragmitus* (Reed) and *Aster tripolium* (Sea aster) seedling to the sites in the Western Scheldt. All seedlings we grown from seeds collected the year prior to the experiments in the Western Scheldt. Per plot we planted eight seedlings per species. At each plot we also transplanted a tussock of Spartina (~15x15 cm), which was collected near the plots. Seedling survival plots and tussocks were replicated five times at every site and elevation (n=40). Seedling survival and tussock development/density was monitored biweekly. In October the lateral outgrowth of the tussocks was measured. Furthermore, of every plot a full analysis of the soil properties was done, and also sampling of the benthic fauna was performed.

Table 9. Concise overview of the field site characteristics and the species planted in the experiment.

Location	*salinity*	*Organic rich*	*Bulk density*	*Seedlings used*	*Tussocks used*
	(ppt)		*(g cm^{-3})*		
Rattekaai West	*32*	*No*	*1.32 - 1.40*	Spartina, Scirpus	*Spartina*
Rattekaai Oost	*32*	*Yes*	*0.73 - 1.11*	Spartina, Scirpus	*Spartina*
Rilland	*6*	*No*	*1.32 – 1.42*	Spartina, Scirpus, Aster, Phragmitus	*Spartina*
Groot Buitenschoor	*6*	*No*	*0.56 - 0.61*	Spartina, Scirpus, Aster, Phragmitus	*Spartina*

RESULTS

There are clear species-specific differences in survival. Yet, as not all results from the benthos sampling are available, no full analysis of the explanatory variable was possible. Benthos samples still have to be sorted and analysed. However, there are some clear general and species-specific general trends notable:

1. The difference in seedling survival between the exposed location of Rilland and the more sheltered location of Groot Buitenschoor cannot be explained by the level of wave exposure, as a higher mortality would be expected at the most wave exposed location. We speculate that this result may be explained by the presence of different benthic communities at both sites, and more specifically we expect differences in ragworm (*Hediste diversicolor*) densities. From personal observations in the field, and while sieving benthos samples, the ragworm density appears to be

much higher at Groot Buitenschoor than Rilland. Previous research by the NIOZ-Yerseke at Paardenschor, suggests that ragworms can play a dominant top-down control on seedling establishment. Yet the actual ragworm numbers still need to be quantified in the samples to arrive at more definite conclusions.

2. In general, Spartina and Aster seedlings are lost more quickly at Groot Buitenschoor, followed by the site of Rilland (both Western Scheldt locations with low salinity) than at both locations at Rattekaai (Easternscheldt). This is surprising, as salinity is the highest in the Easternscheldt, and a higher salinity tends to limit seedling growth. We speculate that this difference may also be related to different ragworm (*Hediste diversicolor*) densities, as ragworm tends to be less present in more saline environments. Yet the actual ragworm numbers still need to be quantified in the samples to arrive at more definite conclusions.
3. Survival of seedlings can be ranked as: *Spartina* > *Scirpus* > *Aster* > *Phragmitus.* This trend may partly be salinity driven, but may also be related to the mechanical properties. *Spartina* and *Scirpus* appear to be much more robust than *Aster* and *Phragmitus* seedlings, meaning that the mechanical properties of the first two species may be more tolerant to pioneering conditions.

Spartina anglica:

The seedlings perform best at intermediate elevation. At the lowest elevations (level 1 & 2 of Rilland & Groot Buitenschoor) the seedlings are lost more quickly than at the higher elevations at Rattekaai (level 1). But at the higher elevations (level 2) at Rattekaai the seedlings suffer from drought stress and are lost at higher rates as a result.

Scirpus maritimus:

The seedlings perform best at the higher elevation (level 2 of Rilland & Groot Buitenschoor). Seedlings are more quickly lost from Groot Buitenschoor.

Phragmitus australis:

Phragmitus is not a good pioneer and is lost quickly from the pioneer zones of Rilland and Groot Buitenschoor. There is no significant difference between elevations in the loss rate.

Aster tripolium:

Like *Phragmitus*, *Aster* does not do well in the pioneerzones of Rilland and Groot Buitenschoor and is lost quickly from the experimental plots. There is no significant difference between elevations in the loss rate.

Figure 87. Overview of the locations for the seedling survival experiment carried out in 2015 within the Rammegors project.

Table 10. Overview of seedling loss rates at the experimental locations shown in Figure 87.

Location	Species	Level	Loss rate (day^{-1})	SE
Rattekaai East	Spartina	1	0.001	0.0004
		2	0.011	0.0017
	Aster	1	0.035	0.0045
		2	0.036	0.0047
Rattekaai West	Spartina	1	0.024	0.0030
		2	0.019	0.0025
	Aster	1	0.044	0.0057
		2	0.021	0.0027
Rilland	Spartina	1	0.012	0.0015
		2	0.005	0.0009
	Scirpus	1	0.017	0.0021
		2	0.012	0.0017
	Phragmitus	1	0.095	0.0123
		2	0.076	0.0098
	Aster	1	0.074	0.0097

		2	0.051	0.0066
Groot Buitenschoor	Spartina	1	0.022	0.0027
		2	0.011	0.0014
	Scirpus	1	0.044	0.0055
		2	0.030	0.0038
	Phragmitus	1	0.115	0.0149
		2	0.131	0.0170
	Aster	1	0.083	0.0108
		2	0.096	0.0125

4.4.7 *WINDOW OF OPPORTUNITY FOR SPARTINA SEEDLING ESTABLISHMENT*

EXPERIMENTAL DESIGN: To understand the effects of drainage and sediment type on the required length of window of opportunity (measured as critical erosion depth) for *Spartina* seedling establishment in restoration sites Rammegors and Perkpolder (Figure 88).

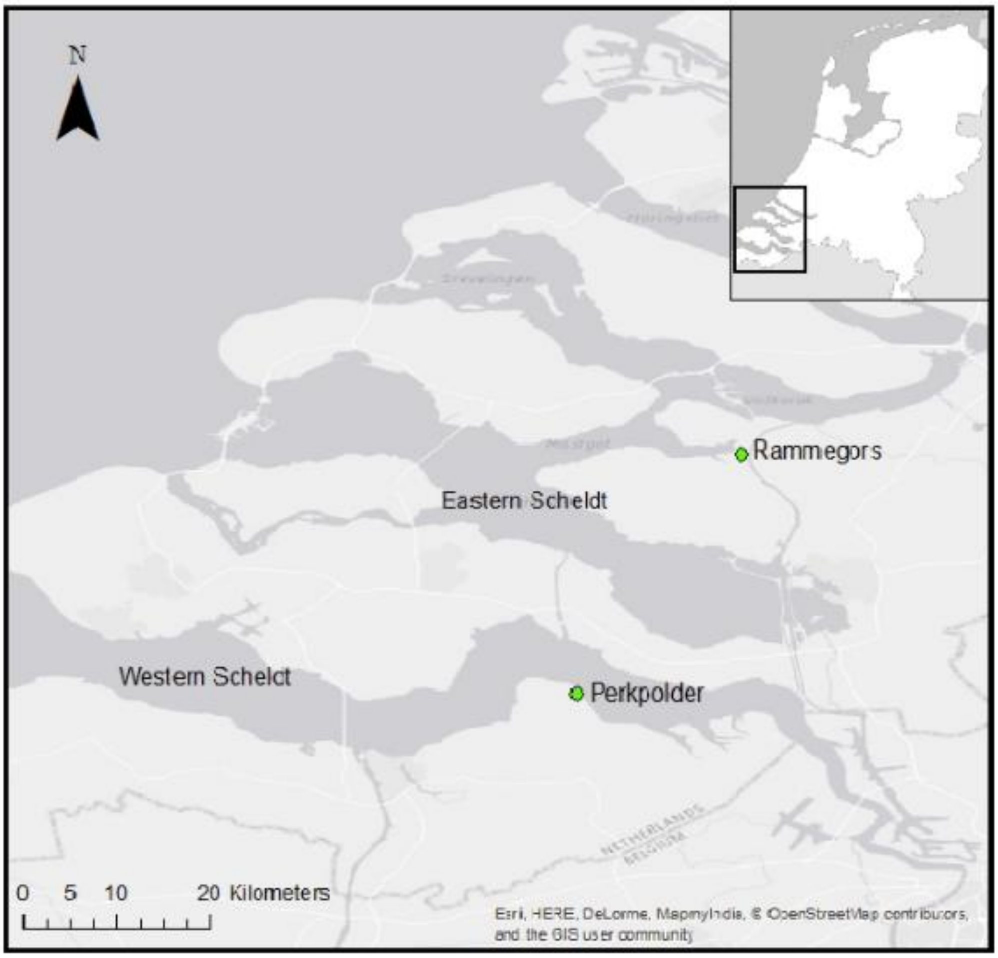


Figure 88. Rammegors is located in the Eastern Scheldt estuary whereas Perkpolder is located in the Western Scheldt estuary.

MATERIALS & METHODS:

This experiment was conducted in tidal mesocosms with controllable salinity and inundation conditions (Figure 89). Spartina seedlings were grown in PVC pots (Figure 89c). Because Rammegors is a highly heterogeneous area, two types of sediment are collected in Rammegors: sediment on which mainly reed was growing and sediment on which mainly grass was growing. As Perkpolder is a highly homogenous area, only one type of sediment exists in this area. In total, there were three sediment types (Perkpolder, Rammegors reed, Rammegors grass), two salinities (16 and 28 ppt), two types of drainage (poor and well drained), and two inundation periods (3 hrs/12 hrs and 6 hrs/12 hrs). The drainage treatment was created by either making 10 small holes in the plastic bag that was surrounding the sediment in the pot (i.e. PVC pipe) resulting in the well-drained treatment or by making no holes at all in two bags surrounding the sediment in a pot resulting in the poor drained treatment. After 20 days, seedling survival, critical erosion depth (CED) and shoot/root-length were measured. For the three sediment types and two drainage treatments, grain size distribution, organic C, sediment penetration resistance, water content, dry bulk density, and critical shear strength were determined.

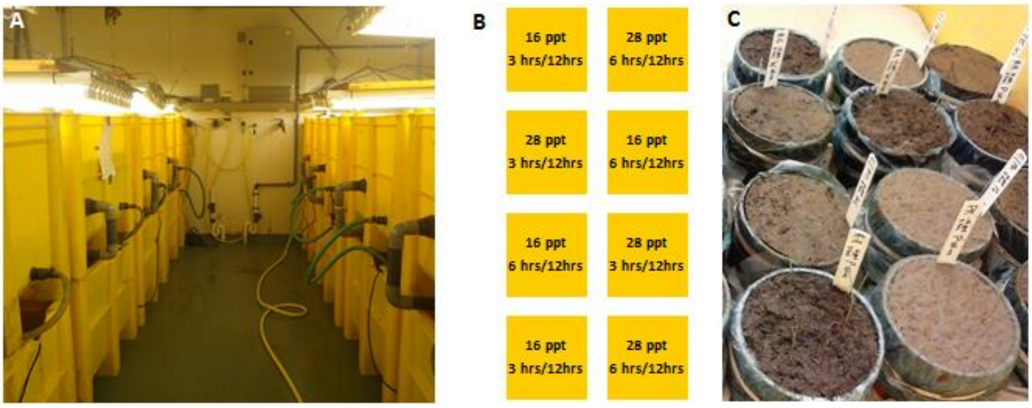


Figure 89. A The set-up of the tanks in the mesocosm. B The tanks consisted of two different salinities being 16 and 28 ppt, and two different inundations being 3hrs/12hrs and 6hrs/12hrs. C Each tank consisted of 8 pots from each sediment type (i.e. 24 pots in total) out of which half was well drained and half was poor drained and therefrom half was filled with three seedlings per pot and half was just the sediment.

MAIN RESULTS:

The results showed that critical erosion depth is overall positively correlated with root length ($P<0.01$, Figure 90B). The CED indicates the vertical sediment erosion that needs to be exceeded before the seedlings would dislodge or topple over when exposed to wave energy. There were many interaction effects, but always in the same direction in which high salinity and inundation negatively affected the CED (Figure 90A).

The CED of the seedlings was influenced by salinity and inundation via their influence on the root length of the seedlings (Figure 91). The root length was overall negatively influenced by high inundation, which was most apparent for seedlings grown in the Rammegors reed sediment (P<0.0001). High salinity also negatively affected the root length (P=0.0011). High salinity reduced the growth of roots, implying that a longer WoO is needed to reach the seedling stability needed to withstand hydrodynamic forces.

Although sediment type only slightly impacted root growth, the required length for seedling establishment can still be greatly affected by sediment types that differ in erodibility. The easiness with which the sediment can erode is captured in the critical shear strength (CSS). The lower the CSS, the higher the erodibility, i.e. the easier the sediment will erode. The CSS was lowest in the Perkpolder sediment (P<0.0001), hence this sediment is most likely to erode when exposed to hydrodynamic forces (Figure 91). For the Rammegors reed sediment, the CSS was highly influenced by drainage, when the sediment was poor drained and thus contained high amounts of water, the sediment erodes more easily than when it was well drained (P<0.0001) (Figure 92).

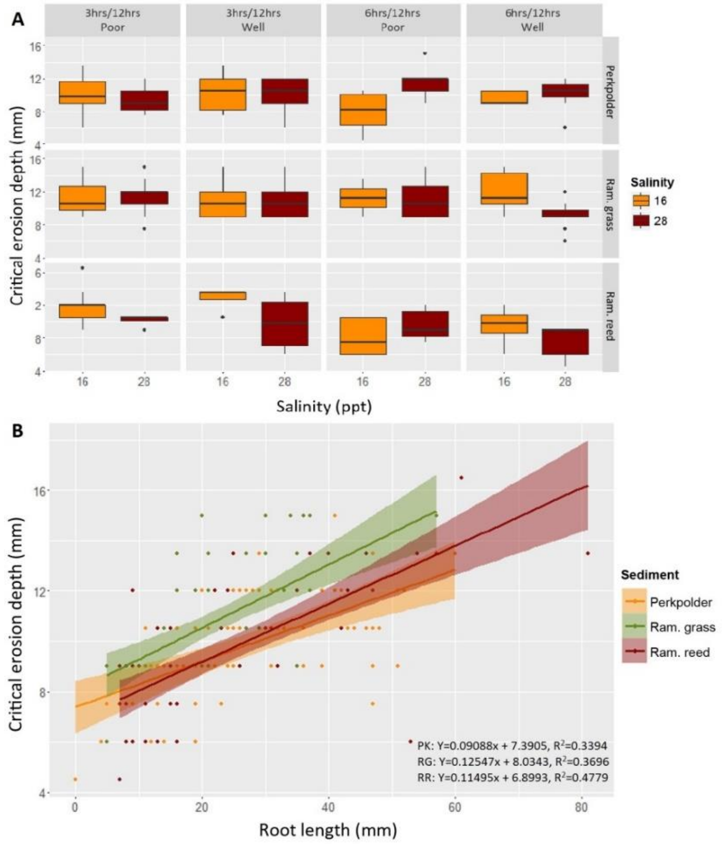


Figure 90. The effect of inundation, drainage, salinity and sediment type on the critical erosion depth (mm) of the seedlings that needed to be exceeded before the seedlings would dislodge. A. The critical erosion depth (mm) of the seedlings in all 24 treatments. The relation between the critical erosion depth (mm) and the root length (mm) of the seedlings for all 3 sediment types. N varied depending on survival within the treatment.

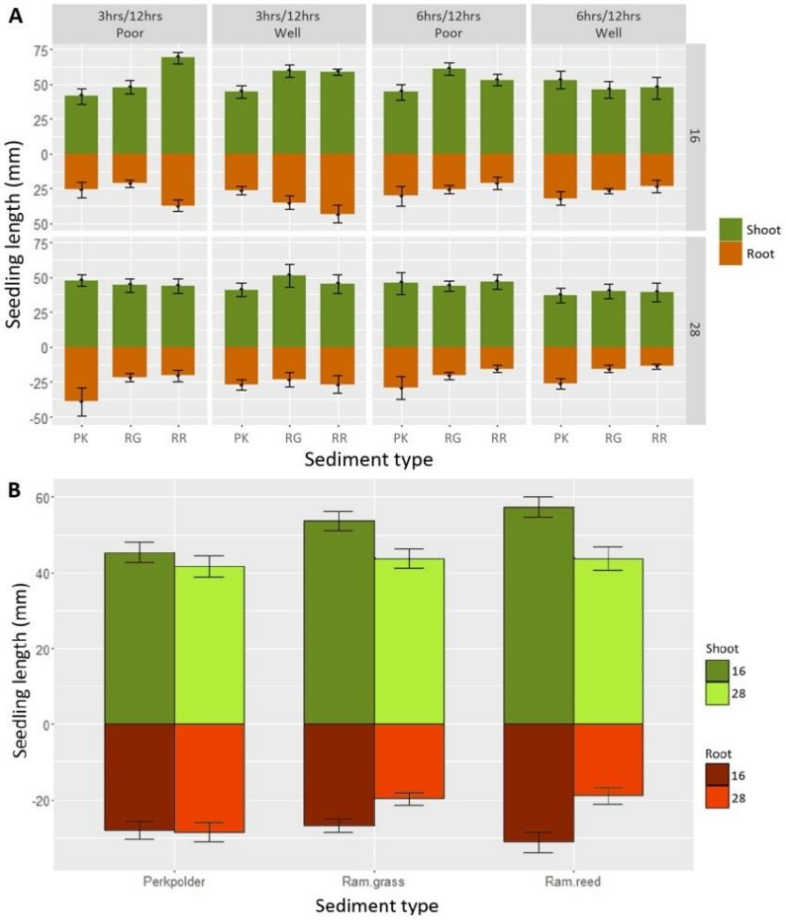


Figure 91. Spartina seedling length. A The average shoot (green) and root (orange) length (mm) of all 24 treatments. The three sediment types are depicted by PK for Perkpolder, RG, for Rammegores grass, and RR for Rammegors reed. Salinity is presented on the left y-axis. B The average shoot (green) and root (red) length (mm) of the seedlings under the two types of salinity (16ppt and 28ppt) and 3 types of sediment. N varied depending on survival within the treatment.

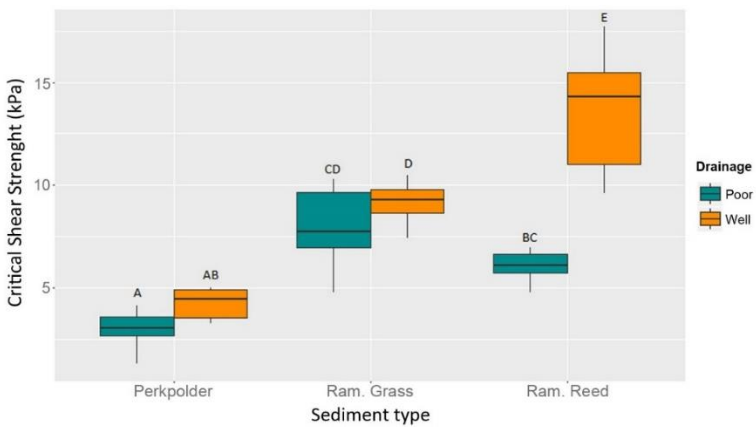


Figure 92. The critical shear strength (kPa) for all sediment types and the poor drained and well drained treatments N=6.

4.4.8 *SEEDLING EXPERIMENT II*

Seedlings of *Aster tripolium*, *Limonium vulgare*, *Puccinelia maritima* and *Spartina anglica* were planted (n=5) at the 18 vegetation points to monitor the survival and grow. Given high abundance of Salicornia in this intertidal area, species is not taken in count.

Germination and first grow phase (12 weeks) is executed in the greenhouse of NIOZ-Yerseke. Then on 2017-06-26 seedlings were planted in a randomized boxplot design. Due to die-off in greenhouse, Limonium was planted at less points. No plants were transplanted to point 16, as this location is permanently inundated.

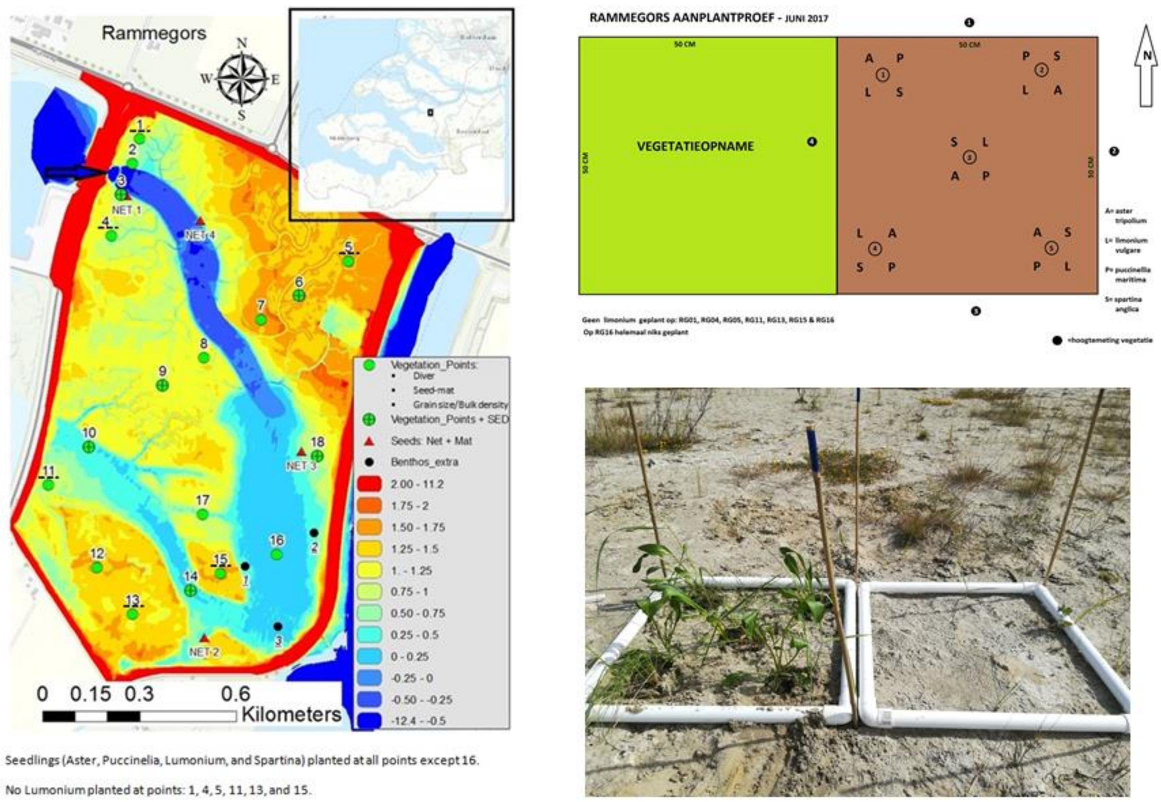


Figure 93. Seedlings planted in randomized block-design at indicated points.

RESULTS

A multiple regression analyses with the combination of sediment parameters mentioned in 4.5.3 and the inundation period reveals that points 8, 9, 11 and 17 most suitable for seedling survival. These are the actual results after 131 days of planting:

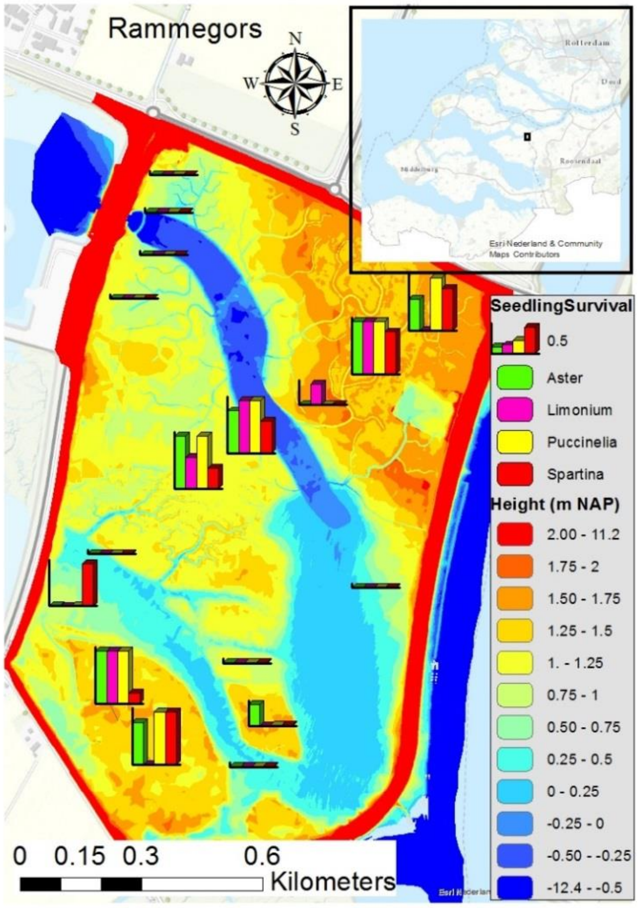


Figure 94. Average (n=5) seedling survival per sampling point at Rammegors.

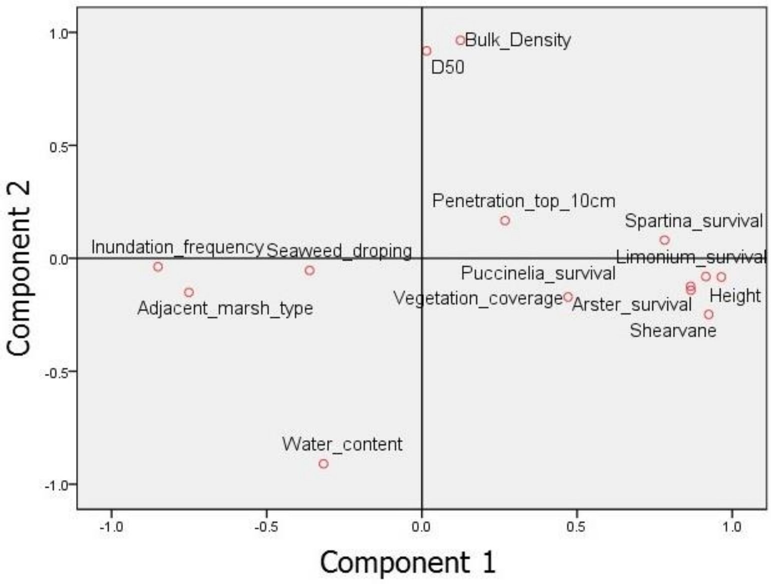


Figure 95. Principal Component Analysis (PCA) for the correlation of seedling survival with all environmental traits.

The component 1 axis of the PCA shows that seedling survival was mostly positively correlated with elevation and negatively correlated with inundation frequency, which can be expected as these parameters are complementary (Figure 95). The component 2 axis was positively correlated to bulk density and grain size (D50), and negatively correlated to water content (Figure 95). No significant trend occurred along the component 2 axis.

Therefore, our results suggest that the elevation, and the related inundation frequency, is the critical factor that influence marsh establishment in Rammegors. Specifically, the seedling survival of different species at different elevation (i.e. inundation frequency) is shown in Figure 96 and Figure 97.

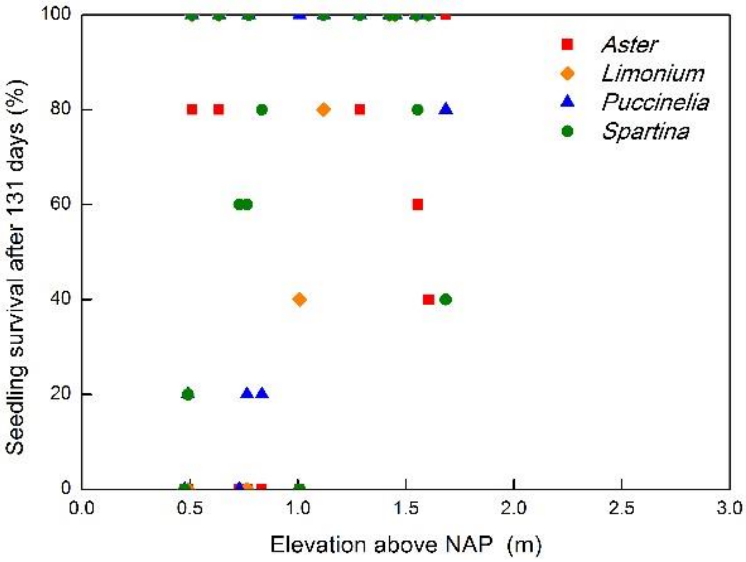


Figure 96. Seedling survival of different species at different elevation height.

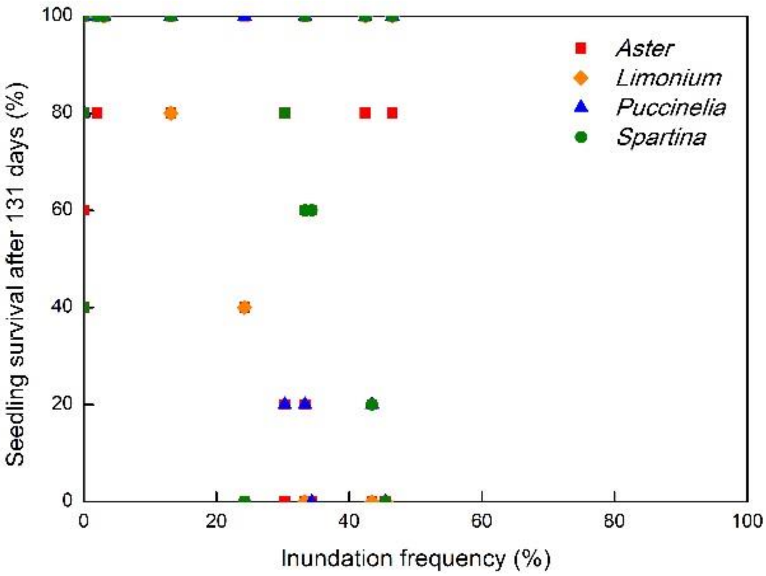


Figure 97. Seedling survival of different species at different inundation frequency.

4.5 CONCLUSIONS

Fresh water vegetation is retreating and being replaced by the intertidal vegetation.

There is a substantial die-off of fresh-water vegetation such as reed and grass in the inundated areas. The vegetation is replaced by salt-water species as Salicornia and Aster. The species are highly abundant and expand naturally in high quantities, there seems to be no influence of dead organic material on the colonization of the salt-marsh pioneer vegetation. The higher elevated areas, without the arrival of salt water, still have a high abundance of fresh water species.

There is no seed limitation.

In the last two years, Rammegors changed rapidly into an intertidal area and saltmarsh. Results of floating nets and seed traps show a huge availability in vital seeds of Aster, Salicornia and Reed. However, there is hardly no Spartina anglica observed. This is unexpected given the nearby presence of this species in the adjacent intertidal area of the Eastern Scheldt.

There are no relevant sediment changes observed since the opening of the area and the introducing of the tide.

Elevation does not change in most parts of Rammegors. The incoming water is clear without any suspended material. This can explain why no significant sedimentation is observed. There is a small sandy area in the northern part of Rammegors, which experiences some bed level change probably due to wind-drifted sand. Overall, the composition of the sediment is approximately stable as the grain size and bulk density results are practically constant over time. Similarly, the compaction of the mature soil did not change in the last three monitoring years due to the new inundation regime. Dead organic material has no noticeable influence on the redox and sulfide concentration in the pore water of the top 10cm in sediment. Hence, the die off of the fresh-water vegetation probability didn’t impact the establishment of salt-marsh vegetation in any relevant way.

Experiments

The mesocosm experiment shows that poor drainage has a negative effect on seedling survival. As well as the negative effect of high salinity values on the root development.

Besides this, the most important factor coming out of the seedling survival experiment in-situ is the height and its corresponding inundation time. Optimum seems to be between 50 and 95% dry time.

For seedling survival in case of erosion, the critical depth is positively correlated with the root development and length.

5. EDUCATION

- Demonstration of field measurements techniques for HZ UAS students on 14th of March 2016 by Perry de Louw and Pieter Pauw (Deltares).
- Lecture about coastal groundwater systems and measurements techniques on 7th of March 2016. by Perry de Louw (Deltares).
- Presentation of the groundwater monitoring results in and around Rammegors for farmers around Rammegors. 6 March 2017 in St. Philipsland by Perry de Louw (Deltares).
- Demonstration of groundwater measurement techniques for HZ UAS students (small groups) in summer and autumn of 2018 by Nicola Stanic (HZ UAS).
- Excursion to Rammegors area as part of Eco-Engineering module for 2nd year HZ UAS students. Focus on vegetation development, benthic colonization and groundwater measurements.
- BSc thesis of HZ UAS student Jens Schouwenaar (2018). Effect of tides on the salinity of the soil and groundwater in Rammegors.
- Master thesis of WUR-student Ilja America (2018). Modelling the salinization process in nature area the Rammegors (WUR).
- BSc thesis of HZ UAS student Marie Wahl (2019). Exploring relationships between groundwater trends and benthos communities in Rammegors.
- 2015-present, Haobing Cao, MSc and PhD, Tjeerd Bouma
- 2015-2018, Zhengchang Zhu, PhD and Postdoc, Tjeerd Bouma
- 2015-present, Jim van Belzen, PhD and Postdoc, Tjeerd Bouma
- 2015, Vegetation development, Jeroen Goud en Amber Schaafsma, 2, 3, minor, Carla Pesch en Tjeerd Bouma.
- 2016, Increasing the succes of saltmarsh restoration, Annick van der Laan, 1, 2, MSc Thesis, Zhengchang Zhu.
- 2016, Factors limiting the settlement of pioneer vegetation on a reconstructed salt marsh , Marinka van Breugel en John Bastiaansen, 2, 2, BSc internship, Jim van Belzen
- 2016, Factors governing stem breakage of salt marsh vegetation , Li Ma, MSc internship (Radboud), Zhengchang Zhu and Haobing Cao

6. OUTREACH AND EXPOSURE

- Poster presentation at 25^{th} Salt Water Intrusion Meeting in Gdansk (Poland), June 2018. "Influence of tides, bathymetry, lithology and regional flows on the salinization process in nature area the Rammegors"
- Publication in conference-proceedings: America, I., De Louw, P.G.B., Bier, G. Van der Zee, S.E.A.T.M. (2018). Influence of tides, bathymetry, lithology and regional flows on the salinization process in nature area the Rammegors. E3S Web Conf. Volume 54, 2018. 25th Salt Water Intrusion Meeting (SWIM 2018) https://doi.org/10.1051/e3sconf/20185400001.
- Publication in conference-proceedings: Stanic, N. and De Louw, P.G.B., (2018). Monitoring of Vadose Zone Salinity Change and Dynamics of the Ecosystem in Response to Depoldering of Rammegors, SDHI and SDH conferentie, Nis, Serbia
- Oral and poster presentations from HZ and WMR during the 2018 Scheldesymposium in Antwerp.
- Presentation at IVN nature education in Roosendaal about tidal recovery in Rammegors.
- A newsletter article will be published on the "Zuidwestelijke Delta" website (https://www.zwdelta.nl/ in June 2019 about the results of project to date as reported in this document.

Project results have been presented by Tjeerd Bouma, listed below. In addition, project results have been presented by PhD students, from which we did not keep a detailed track record.

- Sustaining intertidal ecosystems under climate change for coastal protection. Invited key-note lecture – 12^{th} Netherlands Annual Ecology Meeting (NAEM) – Lunteren, 12 & 13 February 2019, Netherlands
- Towards wetland restoration by understanding establishment thresholds. Invited lecture – 2^{nd} annual Symposium on Coastal Resources and Environment (CORE 2018). Themed on: Wetland Restoration . Hohai University, October 19-23, Nanjing, China
- Intertidal ecosystems & global change: linking fundamental science with application. Invited key-note lecture – 6^{th} International Conference on Estuaries and Coasts (ICEC) – Caen, 20-23 August 2018, France
- Small-scale process as driver of large-scale dynamics in coastal vegetation - An ecologist view on Bio-Geo-Morphology. Invited key-note lecture - River, Coastal and Estuarine Morphodynamics (RCEM) – Padova, 18-21 September 2017, Italy

- Small-scale process as driver of large-scale dynamics in coastal vegetation - An ecologist view on Bio-Geo-Morphology. Invited lecture *school of marine engineering and technology – Sun Yat-sen University (SYSU)* 2017
- Small-scale process as driver of large-scale dynamics in coastal vegetation - An ecological view on Bio-Geo-Morphology. Invited key-note lecture - Where Land Meets Ocean: The Vulnerable Interface" ECSA-meeting 2017, Shanghai, China
- Small-scale Processes as Driver of Large-Scale Dynamics in Coastal Vegetation – Dutch part of the Christiaan Brunings Lecture. 10 January 2017 (invited key-note lecture).
- Ecologische uitdagingen Westerschelde. – Bouwen aan een veerkrachtige Schelde Delta – Werkconferentie op 1 en 2 juni, Hotel Westduin in Vlissingen; HZ Delta Academy en Rijkswaterstaat (invited lecture).
- Publiekssymposium "*waterveiligheid en welvaart door natuur*"; lezing door T.J. Bouma: "Schelde natuur: grote zorg *of/en* gouden kans". - Publieksbijeenkomst 8 juni 2017, UCR 2017
- The role of fundamental & interdisciplinary science in implementing flood risk mitigation measures NAEM conference 9 Feb. 2016 (invited speaker)
- Nature based solutions – incorporating ecosystem restoration in the design of harbours and waterfronts. Tjeerd J. Bouma– Developing ecosystem-based solutions for resilient European harbor and coastal waterfronts (ECORES) – EuroMarine and World Harbour project joint workshop 4-6 May 2016, Univ. Bologna. Ravenna Italy. (invited keynote speaker)

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