Salt marsh pilot Marconi

Monitoring results

EcoShape

Colofon

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Management summary (EN)

The Project

Salt marshes were constructed along the coast of Delfzijl (the Netherlands) as part of the project Marconi Buitendijks. A part of the salt marshes serves as a pilot to develop knowledge on the development of man-made salt marshes.

The Marconi Buitendijks project was carried out to reconnect the city centre of Delfzijl to the Ems-Dollard nature reserve. The existing seawall was relocated and reinforced and now forms a connection between the city and the mudflats. In addition, a pioneer salt marsh was constructed along the coast, consisting of a pilot salt marsh of 15 hectares, a bird breeding island and a salt marsh park (city salt marsh) of 13 hectares.

The pilot salt marsh was carried out with three main goals:

- Create a natural land-water boundary to improve ecosystem quality;
- Develop knowledge on how to design and construct a pioneer salt marsh at a location that is not suitable yet for salt marsh development;
- Develop knowledge on the way in which the design and construction affect the development of a man-made salt marsh.

The pilot salt marsh consists of six compartments with three different percentages (5%, 20% and 50%) of mud (fraction <63 µm) in the upper meter of the subsurface. Some of the compartments were seeded with *Salicornia procumbens* (Long-spiked Glasswort). The development of the salt marsh was intensively monitored between November 2018 and September 2020. Additional monitoring was performed in the salt marsh park. In this report, we present and elaborate on the monitoring results of the pilot salt marsh and the salt marsh park.

Monitoring

The monitoring program focused on morphological and vegetation development. We measured sedimentation and erosion rates, development of tidal creeks, bed level, flooding frequency, vegetation cover and density at different, complementary temporal and spatial scales. Instruments that were used include a LiDAR drone, RTK-DGPS, CTDs, Sedimentation-Erosion Bars (SEB), and Acoustic Surface Elevation Dynamics (ASED) sensors.

Results and conclusions

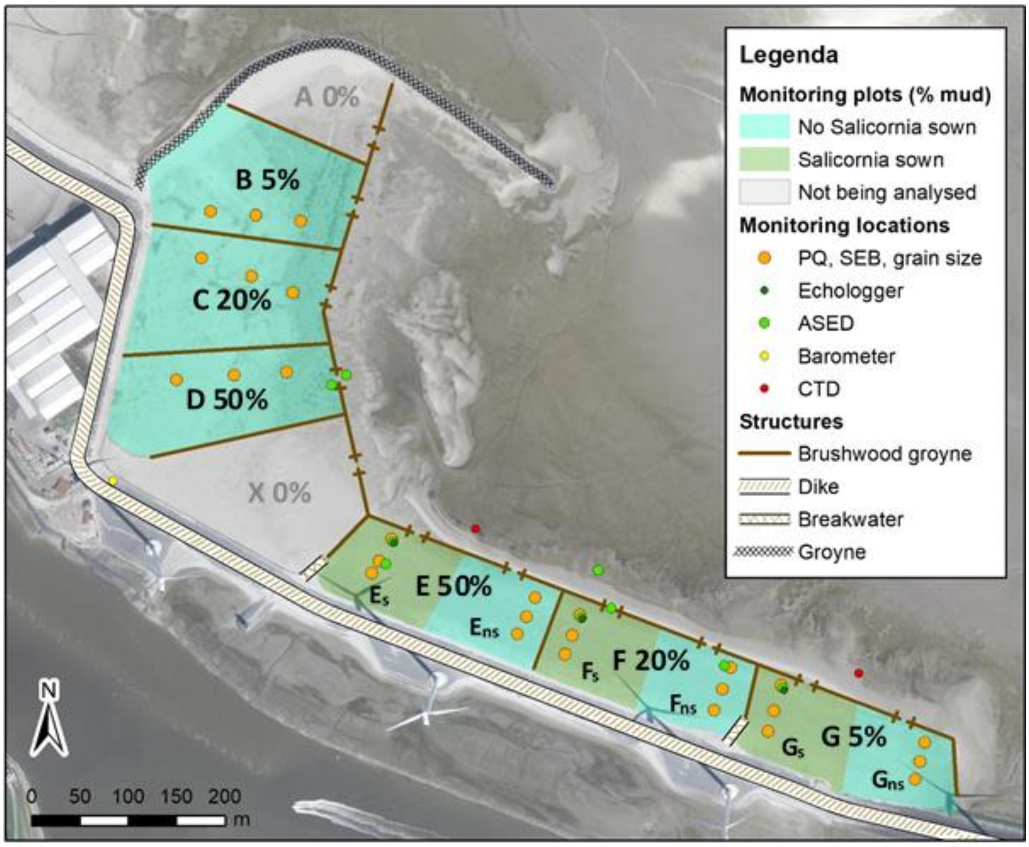
The measurements show that the presence of fine sediment in the soil is an important factor for vegetation development. The vegetation develops well with mud percentages of 20 and 50%, while the vegetation cover is significantly lower when only 5% of mud is present. The seeding of *Salicornia* had a significant effect on vegetation density in the first growing season, in the second year the effect was no longer significant.

The formation of tidal creeks is important for supply of sediment and nutrients and drainage of the salt marsh, which affects plant growth and succession. Also, creeks are valuable habitat, for example they serve as nursery for juvenile fish. Tidal creeks did form in most compartments below MHW, but not necessarily through the designed inlets between the brushwood groynes. Initial tidal creek formation already started before the brushwood groynes were constructed and water could flow relatively easily through these permeable groynes. Hence, the brushwood groynes had limited impact on tidal creek development and the location of creeks was mainly determined by the initial channels. Creek development is controlled by a combination of factors. The number, size and migration of tidal creeks seems to be larger for 1) a larger amount of water flowing through the tidal creek during each tidal cycle (the tidal prism; related to the elevation, area and shape of the tidal basin), 2) areas with mud in the shallow subsurface, and/or 3) sheltered compartments (e.g. high wave energy in more exposed compartments can result in sandbanks that block tidal creeks). The tidal creeks that did develop over a period of approximately two years were not as deep as in established marshes. The development of a tidal creek network with larger/deeper channels requires more time than was available in the pilot project. Furthermore, the relatively high elevation of the salt marsh, which was heightened to account for subsidence, probably slowed down creek development as it limited the volume of water flowing in and out of the salt marsh each tide.

No trend in the sedimentation rate was observed: the sedimentation rate falls within the uncertainty of the measurements. Longer term monitoring is required to draw conclusions about the growth of the salt marsh and its functioning as a mud trap.

All in all, the design and construction of the salt marsh successfully enabled pioneer vegetation establishment and growth. The extent of establishment and growth depended on environmental conditions including mud percentage and exposure. Further monitoring is recommended to learn more about the functioning of the salt marsh as mud trap, the development of creek networks, and their effect on salt marsh development, and vegetation succession. Both the practical lessons regarding design, construction and monitoring, and the developed knowledge on morphological and vegetation development of the salt marsh can be used worldwide to construct salt marshes and use the salt marshes' ecosystem services.

More information about the development of the project, the lessons learned from design and construction and the applicability of the acquired knowledge can be found in the report 'Kwelderontwikkeling als Nature-based Solution, Kennis en ervaring van de Proefkwelder Marconi' (Leuven et al., 2021) (in Dutch).



Design of the field experiment at the pilot salt marsh Marconi Delfzijl. Ns = not seeded, s = seeded. Background: aerial photograph of 2018 (beeldmateriaal.nl/Kadaster).

Managementsamenvatting (NL)

Het project

Kwelders zijn aangelegd langs de kust van Delfzijl als onderdeel van het project Marconi Buitendijks. Een gedeelte van het kweldergebied is ingericht als een proeftuin om kennis te ontwikkelen over de ontwikkeling van door mensen aangelegde kwelders.

Het Marconi Buitendijks project is uitgevoerd om het centrum van Delfzijl meer te verbinden met het Eems-Dollard natuurgebied. De zeedijk is verplaatst en versterkt en vormt nu een verbinding tussen de stad en het intergetijdengebied. Verder is een pionierkwelder aangelegd langs de kust bestaande uit een proefkwelder van 15 hectare, een vogelbroedeiland en een kwelderpark (stadskwelder) van 13 hectare.

De proefkwelder is aangelegd met drie hoofddoelen:

- De aanleg van een natuurlijke land-water overgang om de ecosysteemkwaliteit te verbeteren;
- Het ontwikkelen van kennis over hoe een pionierkwelder ontworpen en aangelegd moet worden op een locatie die nog niet geschikt is voor kwelderontwikkeling;
- Het ontwikkelen van kennis over de wijze waarop het ontwerp en de constructie de ontwikkeling van een door mensen aangelegde kwelder beïnvloeden.

De proefkwelder bestaat uit zes vakken met drie verschillende percentages (5, 20 en 50%) slib (fractie < 63 µm) in de toplaag van de bodem. Een aantal vakken is gedeeltelijk ingezaaid met *Salicornia procumbens* (Langarige zeekraal). Tussen november 2018 en september 2020 is de kwelderontwikkeling intensief gemonitord. Aanvullende monitoring heeft plaatsgevonden in het kwelderpak. Dit rapport beschrijft de resultaten van het monitoren van de proefkwelder en het kwelderpark.

De monitoring

Het monitoringsprogramma focust op ontwikkeling van de morfologie en biodiversiteit. Metingen zijn gedaan van sedimentatie- en erosiesnelheden, de ontwikkeling van kreken, de bodemhoogte, de overstromingsfrequentie en de vegetatiebedekking en -dichtheid. Instrumenten die hierbij zijn gebruikt zijn onder andere een LiDAR drone, RTK-DGPS, CTDs, Sedimentatie-erosiebalken (SEB) en Acoustic Surface Elevation Dynamics (ASED) sensoren.

Resultaten

De metingen tonen aan dat aanwezigheid van fijn sediment in de bodem een belangrijke factor is voor de vegetatieontwikkeling. De vegetatie ontwikkelt goed bij slibpercentages van 20 en 50 procent, terwijl de vegetatiebedekking significant lager is in de vakken met maar 5 procent slib. Het inzaaien van *Salicornia* had alleen in het eerste jaar een significant effect op de vegetatiedichtheid, in het tweede jaar was dit effect niet meer significant.

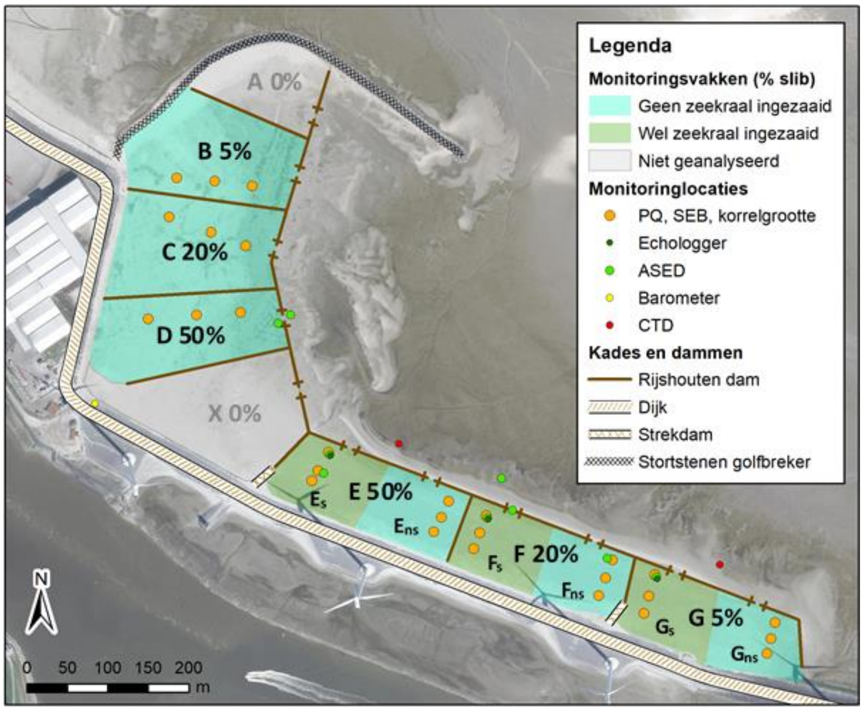
De ontwikkeling van getijdekreken is van belang voor aanvoer van sediment en nutriënten en afwatering van de kwelder, wat invloed heeft op de groei van kweldervegetatie en successie. Bovendien zijn kreken waardevol habitat, zo vervullen ze bijvoorbeeld een kraamkamerfunctie voor jonge vissen. Kreken vormden zich in de meeste proefvakken onder gemiddeld hoogwater, maar niet noodzakelijkerwijs in de ontworpen openingen tussen de rijshouten dammen. De eerste kreekvorming begon al voordat de rijshouten dammen werden aangelegd en water kon relatief makkelijk door deze permeabele dammen stromen. Daardoor hadden de rijshouten dammen beperkte invloed op de ontwikkeling van kreken en werd de locatie van de kreken met name bepaald door de initiële geulen.

De ontwikkeling van de kreken wordt bepaald door een combinatie van factoren. Het aantal, de omvang en de verplaatsing van de kwelderkreken lijkt groter te zijn 1) als er meer water door de kreek stroomt tijdens elk getij (het getijprisma dat wordt bepaald door de hoogte, de oppervlakte en de vorm van het drainagegebied), 2) bij gebieden met slib in de ondiepe ondergrond en/of 3) in afgeschermde vakken (bijvoorbeeld omdat hoge golfenergie bij minder afgeschermde vakken ertoe kan leiden dat zandbanken ontstaan die kreken gedeeltelijk kunnen afsluiten). De kreken die zich ontwikkelden over een periode van ongeveer twee jaar waren minder diep dan kreken in bestaande kwelders. De ontwikkeling van een krekennetwerk met grotere, diepere geulen heeft meer tijd nodig dan de tijd beschikbaar binnen het pilotproject. Daarbij leidde de relatief hoge ligging van de kwelder, zo aangelegd om rekening te houden met compactie en klink, waarschijnlijk tot tragere kreekontwikkeling omdat hierdoor bij elk getij een relatief klein volume water de kwelder in- en uitstroomt.

Er is geen duidelijke trend in de sedimentatiesnelheid in de kwelder: de sedimentatiesnelheid valt binnen de onzekerheidsmarges van de meetinstrumenten. Monitoring over een langere periode is nodig om conclusies te kunnen doen over de groei van de kwelder en de werking van de kwelder als slibinvang.

Het ontwerp en de aanleg van de kwelder heeft met succes vestiging en groei van pioniervegetatie mogelijk gemaakt. De mate van vestiging en groei was afhankelijk van verschillende omgevingsfactoren waaronder slibpercentage en blootstelling aan golven en stroming. Verdere monitoring wordt aangeraden om meer kennis op te doen over opslibbing op de kwelder, de ontwikkeling van kreeknetwerken, en het effect daarvan op de kwelderontwikkeling, en vegetatiesuccessie. Zowel de praktische lessen met betrekking tot ontwerp, aanleg en monitoring als de ontwikkelde kennis over morfologische- en vegetatieontwikkeling van de kwelder kunnen wereldwijd worden gebruikt om kwelders te construeren en de ecosysteemdiensten van kwelders te benutten.

Meer informatie over de totstandkoming van het project, de opgedane kennis over ontwerp en constructie en de toepasbaarheid van de ontwikkelde kennis staat in het rapport ‘Kwelderontwikkeling als Nature-based Solution, Kennis en ervaring van de Proefkwelder Marconi’ (Leuven et al., 2021) (in Dutch).



Ontwerp van de Marconi proefkwelder Delfzijl. Ns = niet gezaaid, s = gezaaid. Achtergrond: luchtfoto uit 2018 (beeldmateriaal.nl/Kadaster).

Content

1. Introduction

Salt marshes were constructed along the coast of Delfzijl (Netherlands) as part of the project Marconi Buitendijks. A part of the salt marsh area serves as a pilot area to develop knowledge about salt marsh growth. This report describes the results of two years of intensive monitoring of the development of the salt marshes.

Marconi Buitendijks: connecting the city with the sea

The city of Delfzijl is located along the edge of the Ems-Dollard estuary, a unique nature reserve that forms the transition from the river Ems to the Wadden Sea. Several important industrial areas directly border the Ems-Dollard estuary. The quality of life in the region is under pressure, partly because of earthquakes caused by gas extraction in Groningen. Sea level rise and subsidence pose additional challenges to guarantee coastal safety and combine all uses of the area. On top of these challenges, Delfzijl lacked possibilities for recreation and experiencing nature. The maritime character of the port city was lost as a result of large-scale industrialization in the second half of the last century. Several dike reinforcements led to an ever-greater separation between the city and the sea.

The Marconi Buitendijks project was carried out to reconnect the city centre of Delfzijl to the Ems-Dollard nature reserve. The existing seawall was relocated and reinforced and now forms a connection between the city and the mudflats. In addition, a pioneer salt marsh was constructed along the coast, consisting of a pilot salt marsh of 15 hectares, a bird breeding island and a salt marsh park (city salt marsh) of 13 hectares (Figure 1-1).

The pilot salt marsh

Salt marshes are important coastal habitats that provide nature-based protection against waves, sequestrate carbon, provide important habitats for birds and fish and facilitate growth with sea level rise. Improving the knowledge about salt marsh construction can be used worldwide to stimulate salt marsh growth and the use of the salt marshes' ecosystem services.

In the Netherlands there is ample experience with methods that stimulate salt marsh development for land reclamation. These consist of drained sedimentation basins delineated by permeable brushwood groynes in places where accretion already occurred. However, in the Marconi project the aim was to construct salt marshes in a location that is too low for vegetation development and has too much wave exposure for accretion of mud.

Therefore, a pilot salt marsh was carried out with three main goals:

- Create a natural land-water boundary to improve ecosystem quality;
- Develop knowledge on how to design and construct a pioneer salt marsh at a location that is not suitable yet for salt marsh development;
- Develop knowledge on the way in which design and construction affect the development of a man-made salt marsh with a focus on the following research questions:
    - What is the effect of soil mud content on the morphological and biological salt marsh development?
    - What effect has seeding on the rate of vegetation development in constructed salt marsh?

The pilot salt marsh consists of six compartments with different percentages mud (fraction <63 µm, mixture of clay and silt) in the upper meter of the subsurface. Some of the compartments were seeded with *Salicornia procumbens* (Long-spiked Glasswort). After construction, the development of the salt marsh was intensively monitored between November 2018 and September 2020. Monitoring focused on bed level development and biodiversity.

Reading guide

This report describes the results of the monitoring of the development of the pilot salt marsh and additional monitoring of the salt marsh park. First, more information is given about the location and design of the pilot salt marsh (Chapter 2 and 3). After that, the monitoring methods and data analysis is explained (Chapter 4). We then present the results focusing on hydrodynamics, morphodynamics and vegetation development (Chapter 7). This is followed by a discussion of the results including conclusions and a summary of the lessons learned (Chapter 8).

More information about the development of the project, the lessons learned from design and construction and the applicability of the acquired knowledge can be found in the report ''Kwelderontwikkeling als Nature-based Solution, Kennis en ervaring van de Proefkwelder Marconi' (Leuven et al., 2021) (in Dutch).

Figure 1-1 Top view of the pilot salt marsh with behind it the salt marsh park (city salt marsh) and bird breeding island (July 2019, photo: Municipality of Delfzijl).

2. Study area

The salt marsh pilot is located near the town of Delfzijl, the Netherlands, on the west bank of the Ems estuary (Figure 2-1).

The Ems estuary is one of the major estuaries in the Wadden Sea and is located at the north-eastern part of The Netherlands and the north-western part of Germany. The estuary has a high ecological value. The estuary is heavily used by industry and shipping, and to a lesser extent, by fisheries and tourism. The major waterway of the Ems estuary forms an important navigation route and there are three ports for sea-going vessels including one at Delfzijl near the project location.

The estuarine environment near Delfzijl consists of sandflats and mudflats, but land-water boundaries are abrupt, and rock protected. The Mean High Water (MHW) level is 1.40 m above Dutch Ordnance Level (NAP). There is a mean semi-diurnal meso-tidal range of 3.06 m. At spring tide, the water levels are between approximately -1.9 and 1.5 m NAP and at neap tide they are between -1.1 and 1.2 m NAP (Dillingh, 2013). The estuary has a mean annual suspended sediment concentration of 90 mg/l.

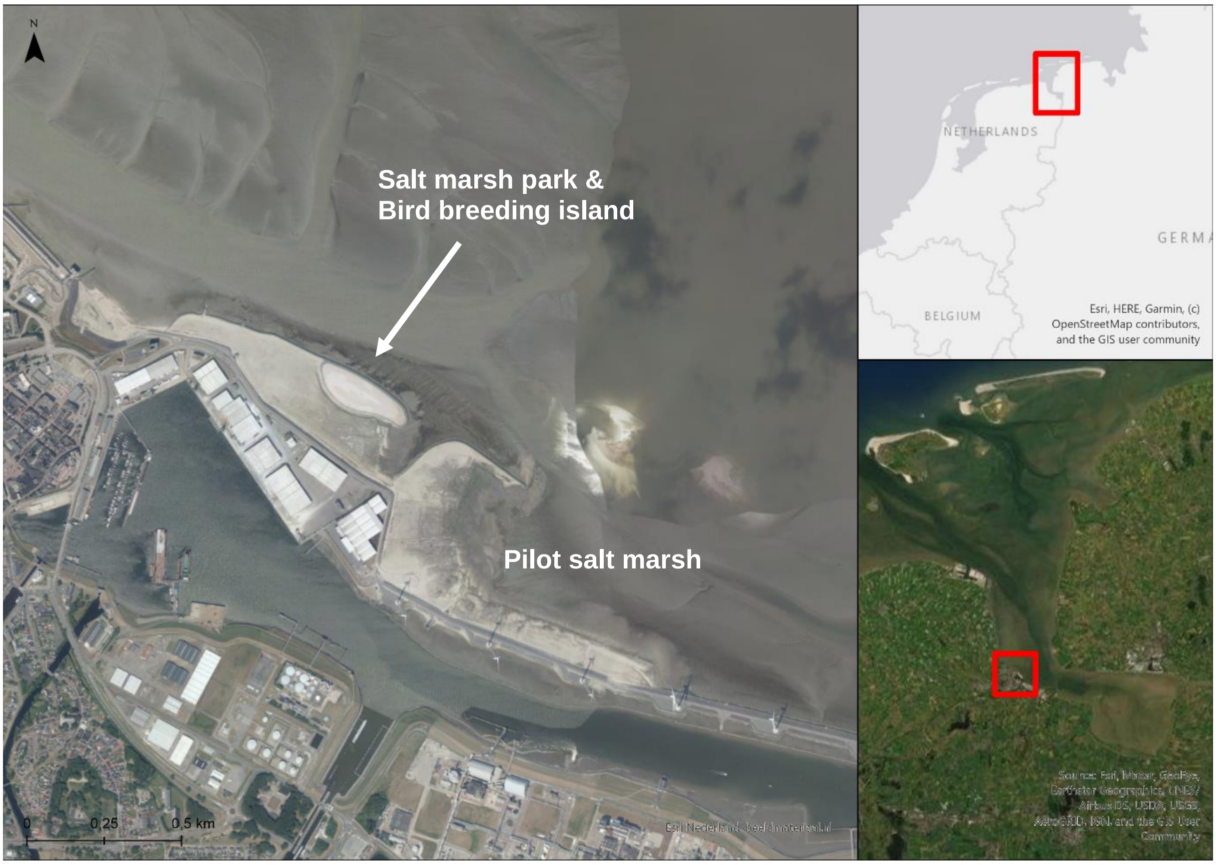


Figure 2-1 Location of the salt marsh pilot at the coast of Delfzijl in the Ems estuary in the Netherlands.

3. Design of the experiment

Design of the pilot salt marsh

The pilot salt marsh has a size of 15 ha and consists of six compartments delineated with permeable brushwood groynes (Figure 3-1). A riprap groyne was constructed west of the experimental site to provide extra protection against waves and currents.

The compartments B, C and D in the west differ in shape, but all have a surface area of 2.3 ha. They each have one opening in the permeable dams. The compartments E, F and G in the south have equal shapes, slopes and sizes according to the design. These compartments are 1.8 ha (216 x 85 m) in size and have two openings in the permeable brushwood groynes.

The base of the compartments consists of a sand fill. The bed level was designed to be between about 0.60 and 1.50 m +NAP (about equal to MSL), so that the salt marsh would be largely below mean high water (MHW) of 1.4 m +NAP. The construction height was higher, considering an assumed compaction and consolidation of about 30 centimetres.

To test the effect of mud enrichment on salt marsh development mud (silt and clay) was mixed in the top 1.0 m of the bed in three different percentages (5, 20 and 50) (Figure 3-1). A mixing depth of 1.0 m meter was chosen as one of the goals of the pilot was to study the effect of the percentage of mud in the soil on creek formation and one meter approximates the maximum depth of creeks at natural salt marshes. The mud was brought in from a land depot where dredged material was stored from a local port extension project. The dredged sediment had been consolidated to a rather firm clayey soil that was transported by trucks to the experimental site. The mixing of the soil through the top 1.0 m of the sandy bed was achieved with a deep spader (Imants 135SX265PL) pulled by a tractor. For the 5% compartments a layer of 8 cm of soil was placed on top of the sand and mixed through. For the 20% compartments a layer of 30 cm of sand was removed and replaced with soil and subsequently mixed through. For the 50% compartments a layer of 1 m of sand was removed, replaced with 80 cm of soil and covered with a bearing layer of 20 cm of sand for the heavy machines, and subsequently mixed through. In total 35,000 m^3 of clayey soil was applied. Mixing the sand and mud was ready in November 2018.

To test whether seeding with a pioneer species accelerates salt marsh development, we seeded with fragments of glasswort plants (*Salicornia procumbens*) in half of the southern compartments E, F and G (Figure 3-1). First. a total of 13,500 glasswort plants were manually collected in autumn 2017 from a nearby salt marsh. The plants were stored over winter for vernalization; the induction of a plant's flowering process by exposure to prolonged cold. One week before seeding, the plants were cut into about 100 pieces each by use of hand-driven antique straw cutting machine. The 1.35 million plant fragments were mixed with sawdust and put in freshwater for three days to start the germination process of the seeds. A set of experiments we carried out in climate chambers showed that the combination of vernalization and freshwater-induced germination gave the highest success rate. In May 2019 in each of the 9,000 m^2 test compartments the mixture of wetted plant fragments and sawdust was manually spread out in a density of 50 m^{-2}.

Design of the salt marsh park

The construction of the salt marsh park (Figure 1-1; Figure 2-1) finished around the same time as the construction of the pilot salt marsh (November 2018). It consists of an elongated area, which is shielded from tidal currents and waves by a riprap dam and has an inlet in the southeast. The bed level after construction varied from 1.45 m +NAP to 2.15 m +NAP. Contrary to the pilot salt marsh, channels were dug to stimulate development of tidal creeks. Furthermore, mud was supplemented on top of the sand bed and harrowed in in the top layer, so not mixed through in the top metre. The salt marsh park was not seeded.

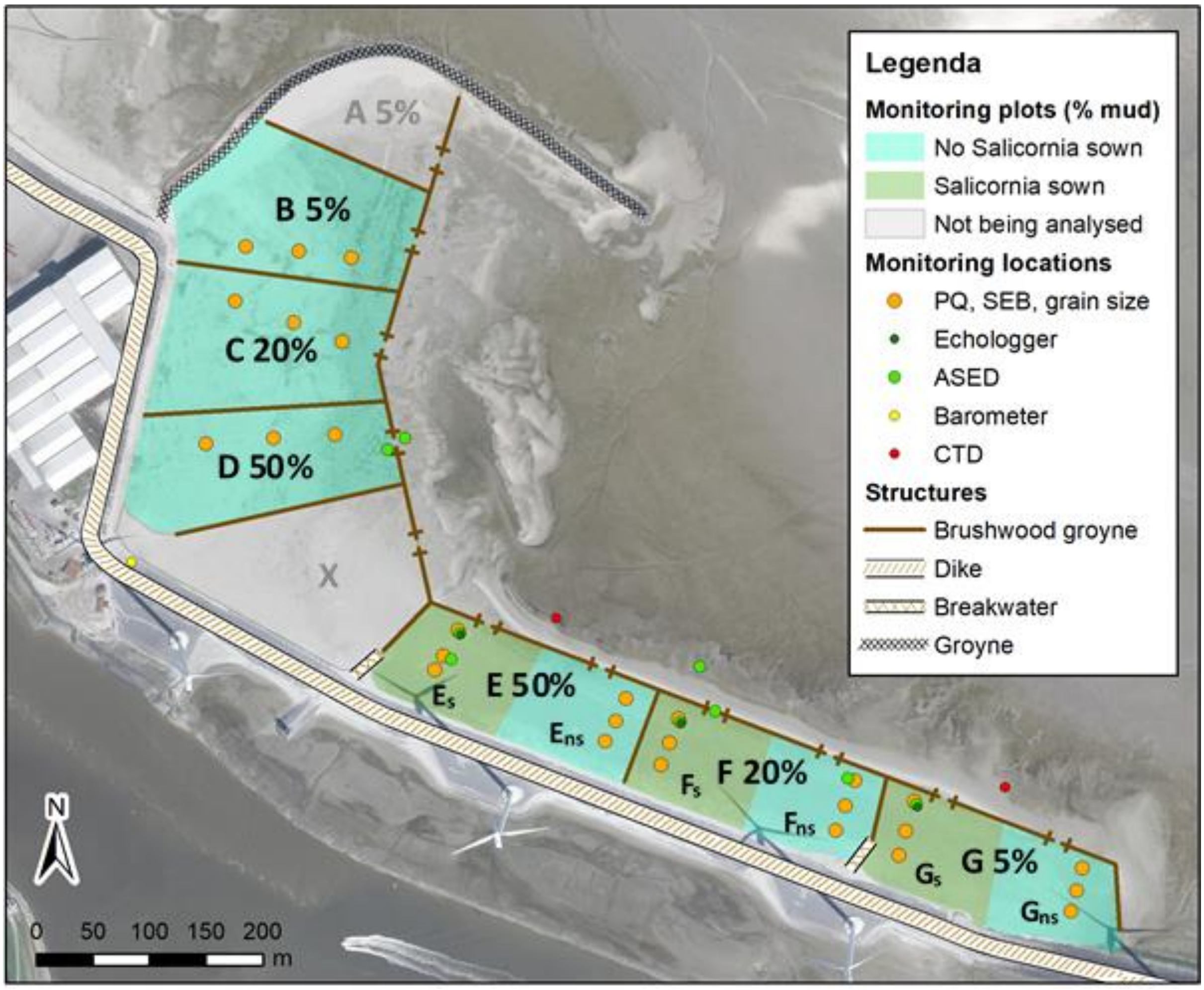


Figure 3-1 Design of the field experiment at the pilot salt marsh Marconi Delfzijl. Ns = not seeded, s = seeded. Background: aerial photograph of 2018 (beeldmateriaal.nl/Kadaster).

4. Monitoring program

The development of the morphology and biodiversity of the pilot salt marsh and salt marsh park were intensively monitored at different complementary spatial and temporal scales between November 2018 and September 2020 (Figure 3-1; Figure 4-1). The monitoring program was designed to determine sedimentation-erosion rates, development of tidal creeks, bed height, flooding frequency, vegetation cover and density and condition of the glasswort plants. We analysed the relation between biogeomorphological development of the salt marsh and elevation, slopes, mud percentages and vegetation cover. Measuring instruments that were used include LiDAR drone, RTK-DGPS, CTD's, Sedimentation-Erosion Bars (SEB), and Acoustic Surface Elevation Dynamics (ASED) sensors.

Repeated measurements (either 2 or 3 monthly, half yearly or yearly) were conducted in Permanent Quadrants (PQ's). In each of the compartments (B, C, D, E Seeded, E not Seeded, F Seeded, F Not seeded, G Seeded and G Not seeded), three PQ's' were defined: one seaward, one in the middle and one landward (Figure 3-1; Appendix 1).

Vegetation diversity and density, presence of microphytobenthos, the sediment composition and the bed level changes were periodically observed in and near all PQ's. RTK-DGPS measurements were performed to assess the development of the tidal creeks through the inlets in the brushwood groynes and the subsidence of the salt marsh. Continuous measurements were executed for a year or more to assess hydrodynamic exposure (water levels, inundation time and inundation frequency) and observe continuous bed level change, also at other locations than the PQ's. Finally, LiDAR and Orthophotos were taken each half year to obtain fully covering Digital Terrain Models and vegetation cover.

Vegetation characteristics were observed in the salt marsh park as well. In addition to the vegetation cover of the PQ's, vegetation diversity and density was determined for 40 (2019) or 35 (2020) plots, of which respectively 5 or 6 plots were in the salt marsh park. Moreover, after seeding *Salicornia procumbens*, the vegetation growth and biomass was measured in 120 additional plots in the pilot salt marsh.

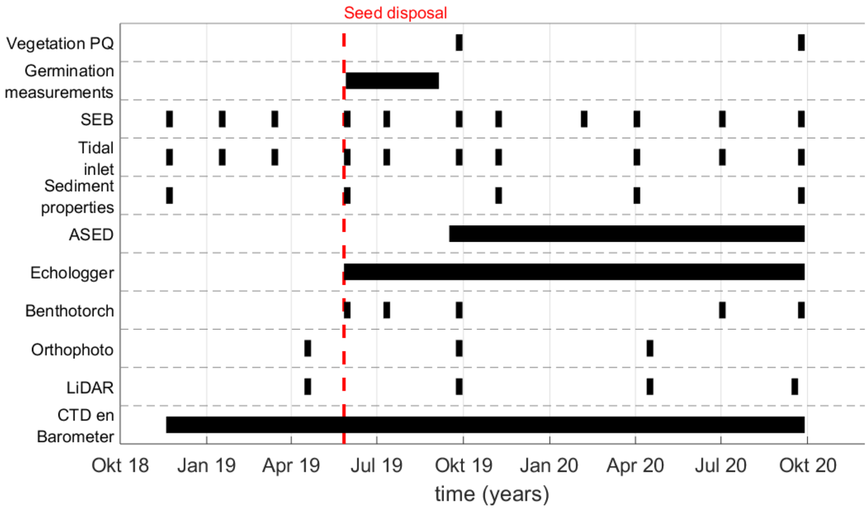


Figure 4-1 Overview of continuous and periodic observations at the Marconi salt marsh.

4.1. Monitoring and analysis of the water depth

The water depth was determined by averaging readings from two submersible dataloggers for conductivity, temperature and pressure (CTD-Diver from Van Essen instruments). Both loggers were placed at the seaward side of the brushwood groynes at compartments E and G (Figure 3-1), a few centimetres above bed level. The logger measured with an interval of 5 minutes. The water depth was calculated after correcting for atmospheric pressure, which was measured with a barometer placed on the dike (Figure 3-1).

In case only one of the instruments was active at a certain moment in time, the outcome of this instrument was used. There are also a few moments when no water level measurements are available for a longer period. We excluded periods in which there are no measurements for more than 12 hours from further calculations. These periods are:

- 28-11-2018 4:25u until 29-11-2018 2:00u (~ 1day);
- 15-12-18 6:25u until 17-12-2018 2:35u (~2 days);
- 20-08-19 17:40u until 28-08-19 19:15u (~8 days);
- 10-12-19 12:15u until 11-12-19 7:45u (~1 day).

We combined information about the bed and water level to calculate the total amount of time and the fraction of time that locations were flooded. We selected the maximum water levels for every high water to be able to determine the flood frequency of the entire salt marsh and specific locations.

4.2. Monitoring and analysis of the morphodynamics

4.2.1. Sediment composition

Sediment samples were taken within each PQ (see Figure 3-1). The initial measurement in November 2018 focused on the grain size distribution of the full mixed layer (top 1m of the substrate). One-meter-deep vertical cores were sampled each 20 cm to obtain a sediment composition profile. Subsequently, the top layer (top millimetre to centimetre) of the substrate was sampled two times per year to obtain the grain size characteristics of the deposited sediments. The initial and top layer sediment composition was determined for two sub-samples per sample.

The sediment samples were freeze-dried in the laboratory and sieved over a 1 mm sieve. The average grain size diameter (D50) and the contributions of different grain size classes (coarse sand, medium sand, fine sand, very fine sand, silt and clay) of the sediment were determined by laser diffraction using a Malvern laser particle sizer.

The samples of the cores at the start of the measurement period were used to determine whether the mixing of the fine sediment through the sand layer has been successful, and whether the desired sediment composition (mud percentage) has been reached. Hence, the average and standard error of the D50 and mud percentage per compartment were calculated and compared. In addition, the spatial variation in D50 and mud percentage within and between the compartments was compared. For all samples, the average of the two subsamples has been used for the analyses.

Changes in sediment composition of the top layer are related to the sediment dynamics. Spatial patterns in the average D50 and %mud per location were visualized in maps and the average sediment composition per compartment over time was calculated.

4.2.2. Digital terrain models (DTM’s) based on LiDAR

The elevation of the entire salt marsh was mapped two times a year using a LiDAR scanner mounted to a drone (Riegl VUX-SYS). Erroneous points were removed from the resulting point cloud. The absolute positioning of the point cloud was improved by applying georectification with ~24 ground control points (GCPs) in the salt marsh. Subsequently, the point cloud was converted to a raster with a grid cell size of 0.1 m x 0.1 m providing a digital terrain model (DTM).

The overall vertical accuracy of the DTM is in the order of a few centimetres. The accuracy of the DTM is determined by the accuracy of the LiDAR device (i.e. < 1 cm accuracy), the accuracy of the drone position (horizontally < 0.05 m, vertically < 0.1 m; IMU & GNSS system used) and the accuracy of translation from IMU to the data using PPK (< 2 cm). Generally, this results in a vertical accuracy of less than 5 cm, and a horizontal accuracy of about 10 cm. The absolute positioning (and hence accuracy) is improved during post-processing by georectification using the GCPs. The accuracy of the RTK-GPS (Trimble R6) used for measuring the GCPs is about 1 cm horizontally and 2 cm vertically. The vertical elevation difference between the final DTM's and the control points is generally 1-2 cm in both directions, with outliers up to 7 cm in the DTM for 24-09-2020.

Spatial patterns in the DTM's were visually discriminated and compared to the situation observed in the field to reveal the morphological units in the salt marsh and their evolution over time. Elevation differences were calculated by subtraction of subsequent DTM's to highlight changes over time. Furthermore, the average elevation of each compartment and a hypsometric curve per compartment are derived from each DTM. The borders of the compartment that are used for these calculations are indicated in the overview map (Figure 3-1) with the coloured patches: the dike and small breakwaters between compartment X and E and between F and G are excluded. At last, the DTM's are used to determine the elevation along transects through each set of three PQ's per compartment to get an overview of the relative position of these measurement locations.

4.2.3. Periodical bed elevation change

Bed level changes were measured multiple times a year at the 27 PQ's with Sedimentation-Erosion Bars (SEB's) (Figure 4-2, see also Nolte et al., 2013). This change includes sedimentation and erosion of the topsoil and compaction/consolidation that occurs in the upper 1.4 m of the subsurface in between two measurements.

The setup consists of two vertically aligned poles inserted 2 m apart into the ground until they reached a stable horizon. Two poles were placed at an approximate depth of 1.4 m at the 27 PQ's in November 2018. Every 2-3 months, a 2 m-long bar (oriented NW-SE) with 17 holes 10 cm apart is placed on top of the poles and a ruler is placed through each of these holes to measure the distance to the surface. The 17 measurements from each SEB are averaged, to collect a single estimate of bed level. The accuracy of the measurements is about 1.5 mm vertically. The bed level change rate has been determined by repeating these measurements over time.

Figure 4-2 Sedimentation-Erosion Bar (SEB).

The changes in the net sedimentation and erosion rate per month were statistically analysed with a linear mixed model with PQ as random effect to account for the repeated measures. Mud percentage, seed treatment, and inundation frequency were the explanatory variables in the model.

4.2.4. Subsidence

To measure the subsidence of the deeper layers, the height of the SEB poles and poles of the brushwood groynes relative to NAP was measured with RTK-DGPS.

To measure the subsidence of the deeper layers, the height of the SEB poles relative to NAP (~MSL) was measured every 2-3 months. The RTK-DGPS has a vertical accuracy of approximately 2 cm. The elevation difference between subsequent measurements represents the subsidence rate over the respective period below the foundation depth of the poles, which is 1.4 m below the surface.

During the construction of the salt marsh, deep subsidence poles were used to measure subsidence. However, these were removed before the monitoring started. As replacement, the height of the poles of the brushwood groynes at both sides of all inlets was measured to determine the subsidence rate. These poles were placed at a depth of approximately 3.0 m.

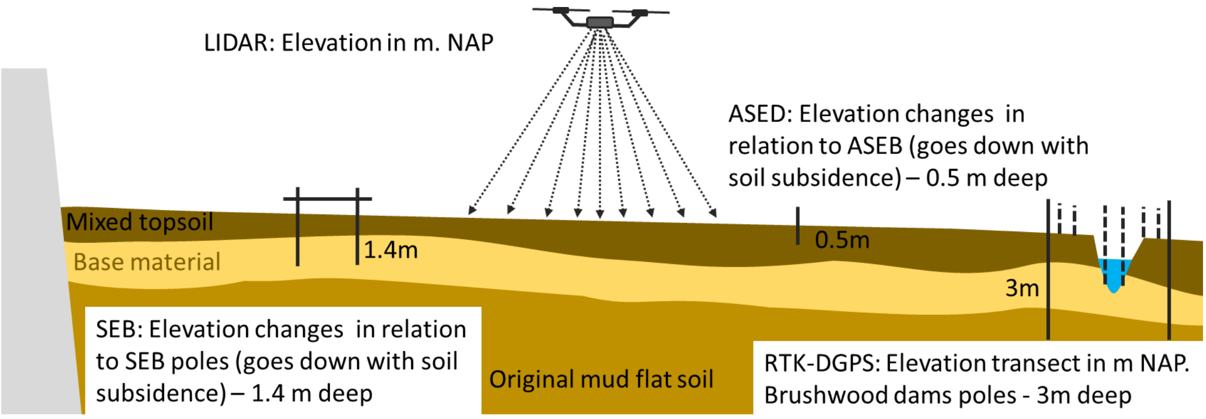


Figure 4-3 Different measurements on elevation and subsidence on Marconi.

4.2.5. Bed level change of the inlets

Tidal creek formation in the inlets was measured by measuring the bed elevation of the inlets of all compartments periodically (every 2-3 months). A cross-section of the bed elevation was measured using an RTK-DGPS between the two poles of the brushwood groynes adjacent to the inlet, with the datapoints spaced approximately every single meter.

The bed level evolution in the inlets and formation of tidal creeks were analysed by plotting the cross-sections for each time step per inlet. In addition, the cross-sectional area of the inlet between the brushwood poles below MHW (1.4 m +NAP) was calculated for each timestep.

4.2.6. Continuous sediment elevation dynamics

The bed level change was continuously measured at nine locations (Figure 3-1; Figure 4-1; measurement locations with name in Appendix 1) for a single year (September 2019 – September 2020) with ASED (acoustic surface elevation dynamics) sensors. The instruments were installed downward looking, with the measuring head aimed vertically at the bottom. ASED sensors can collect measurements once the measuring head is fully inundated. A burst of eight measurements was stored every 5 to 15 minutes. The sensors were installed to be able to:

1. observe tidal creek development (2 instruments in compartment D);
2. observe the continuous bed level development of a tidal creek through an inlet (1 instrument in compartment F Seeded);

3. observe bed level change seaward from the brushwood groynes (1 instrument seaward from compartment F);
4. compare bed level change in compartments with different sand / mud mixtures (3 instruments in compartments E, F and G seeded);
5. compare compartments with and without seeds (2 instruments in compartments F Seeded and F Not seeded);
6. compare bed level change in the front of a compartment and in in the middle of a compartment (2 instruments in compartment E Seeded).

Note that some instruments are used for multiple comparisons and analyses.
The raw signal of every burst was converted to a distance between the bed and the head of the instrument and the eight measurements of every burst were averaged using a Python post-processing script. Since the ASED sensors were used for the first time, the instrument and post-processing script were validated using manual measurements of the height of the head of the instrument above the bed every time the instruments were installed and removed.

The standard deviation of every timeseries was calculated to determine the elevation dynamics. Additionally, the total bed level change and standard deviation of the bed level change of the growing season (April – September) and outside the growing season (October – March) were determined. Moreover, measurements in the tidal creek and tidal inlets were compared with LiDAR and RTK-DGPS measurements respectively. Finally, open weather data from the KNMI (Royal Netherlands Meteorological Institute) was used to explain observed dynamics.

4.3. Monitoring and analysis of vegetation development

4.3.1. Seedbank analysis

The mud used to build the marsh has been analysed for the presence and type of seeds to determine the natural establishment of salt marsh vegetation on the pilot salt marsh. In September 2019 soil samples were collected of the top 4 cm and the deeper soil layer (40 cm depth) at each of the 27 PQ's. The samples were transported to the lab and sieved over a 500 µm sieve. All harvested seeds were germinated in the climate chamber according to the germination protocol of Ter Heerdt (Ter Heerdt et al. 1996). The climate chamber was kept at a constant temperature of 25ºC with a day/night cycle of 7.30 till 20.00 of daylight (Spectrabox pro 5, 360 W). Seeds were put on top of saline sediment collected in the pioneer zone at the salt marsh of Westhoek. Fresh water was applied every week. Germination of seeds was recorded, and the seedlings were identified to species level.

4.3.2. Vegetation diversity and density

The vegetation diversity and density were measured repeatedly to study vegetation development and compare this between the different compartments. In situ measurements of vegetation diversity and density were performed at the 27 PQ's each year in September (Figure 4-1; Figure 3-1). Additional measurements were performed at random plots of 2x2m at the salt marsh park and the pilot salt marsh. In 2019 and 2020 respectively 40 and 35 random plots were measured. For each plot, total vegetation cover was estimated. Furthermore, the plant species cover was estimated using a decimal scale (Londo, 1976). The species names and identification were based on Van der Meijden (2005).

Vegetation development was analysed with several statistical models. We analysed all vegetation plots (27 permanent plots and 75 random plots) with a linear model including mud percentage, seed treatment, year and surface elevation as explanatory variables. Secondly, the vegetation of only the permanent plots was analysed with a linear model including mud percentage, seed treatment, year, inundation frequency and sediment dynamics as explanatory variables. For the effect of sediment dynamics on vegetation cover the sedimentation rate between November 2018 – September 2019 and September 2019 – September 2020 was calculated for each PQ. A separate model was analysed where instead of using the intended mud percentage the measured grain size was used. The measured grainsize was the fraction of mud which was measured at a depth up to 20 cm in November 2018.

The species richness of all vegetation plots was analysed with a general linear model with mud section, seed treatment, year and surface elevation as explanatory values. Finally, the cover of the two *Salicornia* species in all the vegetation plots was analysed with a linear model, including mud percentage, seed treatment, year, surface elevation and species as explanatory variables. The total vegetation cover was transformed with a square root, and the vegetation cover of the *Salicornia* species with a log transformation, to ensure the data had a normal distribution. For the statistical difference between the different mud percentages a Tukey HSD post hoc test was performed.

4.3.3. Vegetation classification from orthophotos

At the same day that the LiDAR data was collected, a separate drone (DJI Phantom 3) flew over Marconi and took overlapping photos. From these photos an orthophoto was developed encompassing the whole area. The resolution of the orthophoto is 2 cm.

From this orthophoto the vegetation and algae cover were classified. The classification of the different vegetation types was done automatically by creating a Random Forest model on a pixel basis. Training data was created from the orthophoto by creating polygons which consist of only vegetation or only bare ground, the training data was used to create the Random Forest model.

We calculated the classification error with the additional random vegetation plots. In 2019, the vegetation classification cover was generally lower than estimated in the field (33 of the plots were estimated lower out of the 40 plots in total). The average error was 13.4 ± 2.0% and especially the small seeded *Salicornia procumbens* were underestimated by the classification. In 2020, the pattern was reversed, and the vegetation classification was an overestimation of the cover in the field (20 of the plots were estimated to be higher out of the 35 plots in total). The average error was higher than in 2019 at 25.7 ± 3.91%, areas with high vegetation cover were classified as having a 100% vegetation cover, whereas the cover was slightly lower (around 80%). Furthermore, different light conditions during the drone flight and shadows of windmills also resulted in a higher error.

4.3.4. *Salicornia sp.* growth and biomass

Salicornia sp. growth and biomass were measured at 120 additional plots of 1 m^2 during the growing season of 2019 to have a better spatial coverage of the growth of *Salicornia procumbens*. In the seeded part of compartments E, F and G, 25 plots (aligned in 5 transects perpendicular to the dam with each 5 plots) were established (Figure 4-4). In the non-seeded part of compartments E, F and G 15 plots (3 transects perpendicular to the dike with 5 plots) were established as a control.

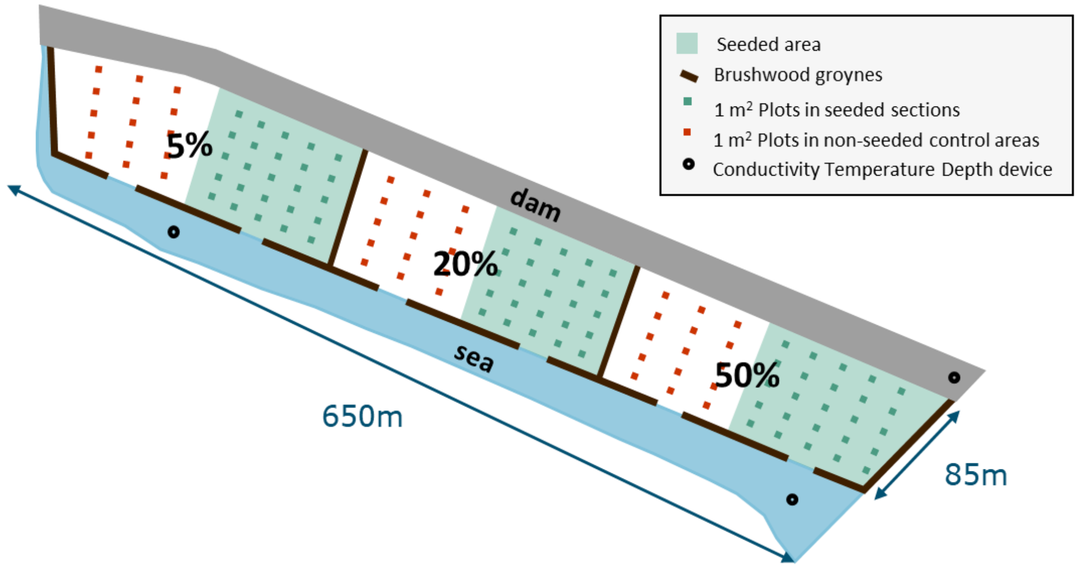


Figure 4-4 Overview of the location of additional plots that measured the growth and biomass of Salicornia. The compartments shown are from left to right G (5% mud), F (20% mud) and E (50% mud) (note that the north is in the downward direction).

For each of the 120 additional plots the number of *Salicornia sp.* plants were counted every two weeks between May 29 and Aug 26. Since it is not possible to distinguish the two different *Salicornia* species (*S. europaea* and *S. procumbens*) in the field in the beginning of the growing season, no further distinction was made.

In August, near the end of the growing season, the anchoring strength of 90 *Salicornia sp.* plants (ranging from 2.8 to 12.5 cm in length) in the three seeded sections was measured. These *Salicornia sp.* plants were randomly chosen outside the previously measured plots. The anchoring strength was measured with a spring scale and the corresponding plant and root strength recorded. At the beginning of September, the *Salicornia sp.* plants of all plots were harvested, shoot biomass was dried for 48h at 70°C and subsequently weighted.

The number of *Salicornia sp.* plants of each plot over time were analysed with a generalized linear mixed model with a poison distribution. The explanatory variables were compartment and seed treatment. We accounted for the repeated measures by adding plot ID as a random effect. The binominal presence/absence data of Salicornia in the plots was tested with a Chi^2 test and a binominal linear model. The biomass was not statistically tested, because there were too many zeros in the dataset.

4.3.5. Microphytobenthos density

Microphytobenthos density was measured using a benthotorch (bbe moldaenke), which measures the chlorophyll-a/cm^2 for green algae, cyano bacteria and diatoms. Due to technical issues the benthotorch could only be used in May, July and September in 2019 and June and September in 2020. Because there is a high spatial variability in the chlorophyll-a density we measured and averaged five points within a permanent plot (PQ).

Microphytobenthos was analysed with a linear mixed model, with PQ as random effect to account for repeated measures. Mud percentage and surface elevation were included in the model as explanatory variables. A separate model was analysed where instead of using the intended mud percentage the measured grain size was used. The measured grain size was the mud percentage of the top layer. If the grain size was not measured for a certain date the previous grain size measurement was used. The microphytobenthos data had to be normalized with a log transformation.

5. Results

5.1. Large-scale morphology

5.1.1. Salt marsh elevation

The elevation of the salt marsh (Figure 5-1 and Appendix 2) is higher than intended, because the subsidence rate (compaction/consolidation) shortly after construction was lower than expected (see also Section 5.3.5 and Chapter 6). A large part of the salt marsh is located above mean high water (MHW: 1.4 m +NAP, blue line in Figure 5-1). The seaward side of all compartments is below MHW, but still above MLW. The average elevation of all compartments is above MHW. Therefore, most days only the seaward side of the compartments is flooded. The area landward of the brushwood groynes generally is up to 10-20 cm higher than at the seaward side: sediment seems to be trapped behind the brushwood groynes, even though the groynes are permeable to water.

The location and elevation of the main morphological features - sandbars, tidal creeks and some artificial features - are shown in Figure 5-1. These are described in more detail respectively at the end of this section, in Section 5.3.4 and in Section 5.1.3.

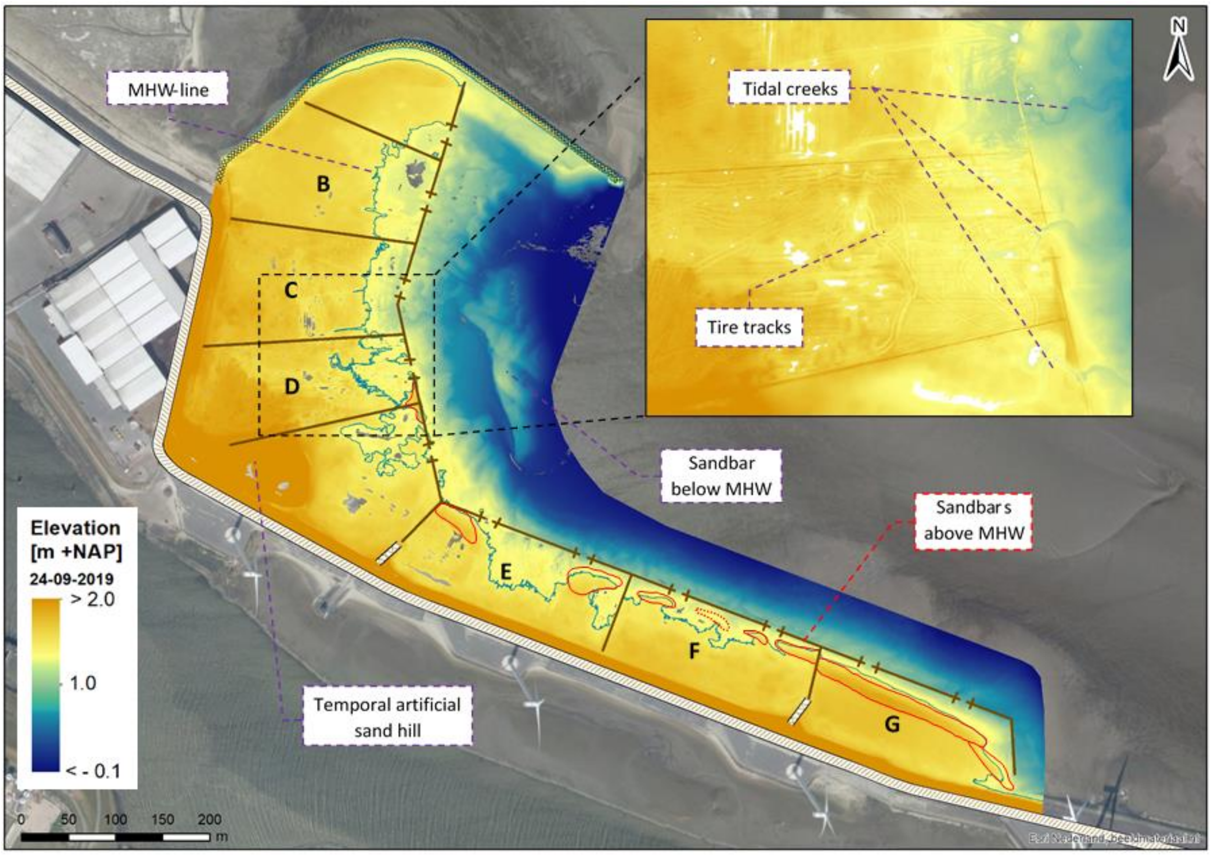


Figure 5-1 Digital terrain model of Marconi based on LiDAR measurements at 24-09-2019. MHW = mean high water (1.4 m +NAP). Background: aerial photograph of the Netherlands 2019 (beeldmateriaal.nl/Kadaster).

Bed level distribution

The bed level distribution is shown in the hypsometric curves in Figure 5-2. The area below MHW, which is frequently flooded, ranges from 13% (compartment G_s and D) to 42% (compartment E_{ns}). Hence, the largest area of the compartments is only flooded during for example storms. The difference in the elevation between the seeded and not seeded sections in compartment E and F is small, but rather large in compartment G. Hence, differences in for example vegetation development between the seeded and not seeded sections in compartment E and F cannot be related to elevation differences, while this could be the case in compartment G.

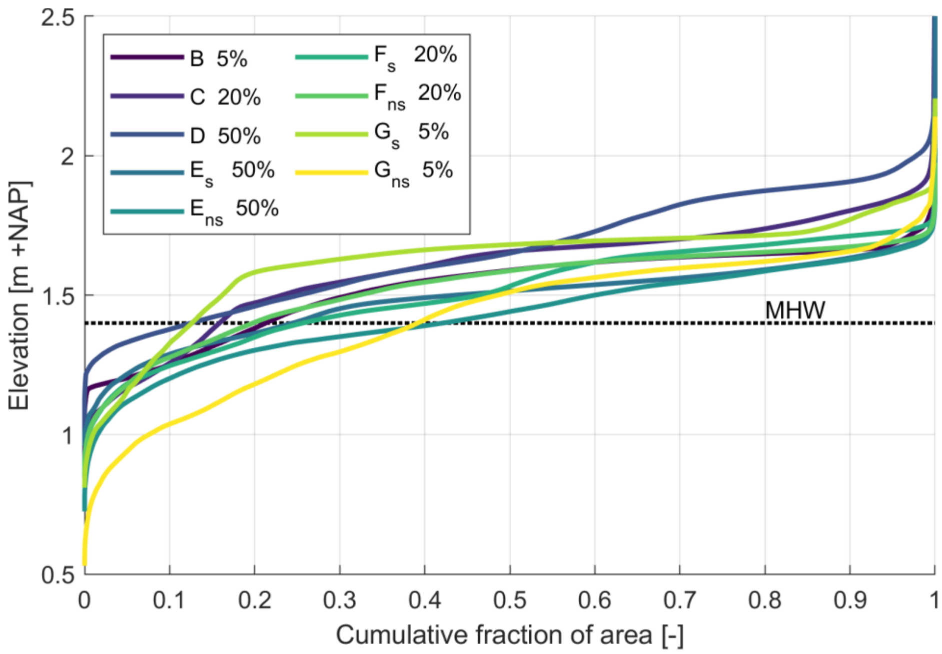


Figure 5-2 Hypsometric curve of the compartments (the coloured patches in Figure 3-1) based on the DEM of 24-09-2019. S = seeded, ns = not seeded, MHW = mean high water (approx. 1.4 m +NAP).

Elevation along the PQ transects

The transects through the PQ's show clear differences in the elevation, slope, shape and distance from the dike to the sea between the compartments (Figure 5-3). The transects show local elevation changes due to the presence of sandbars and tire tracks. Therefore, the landward PQ is not always higher than the middle PQ, and the middle PQ is not always higher than the seaward PQ.

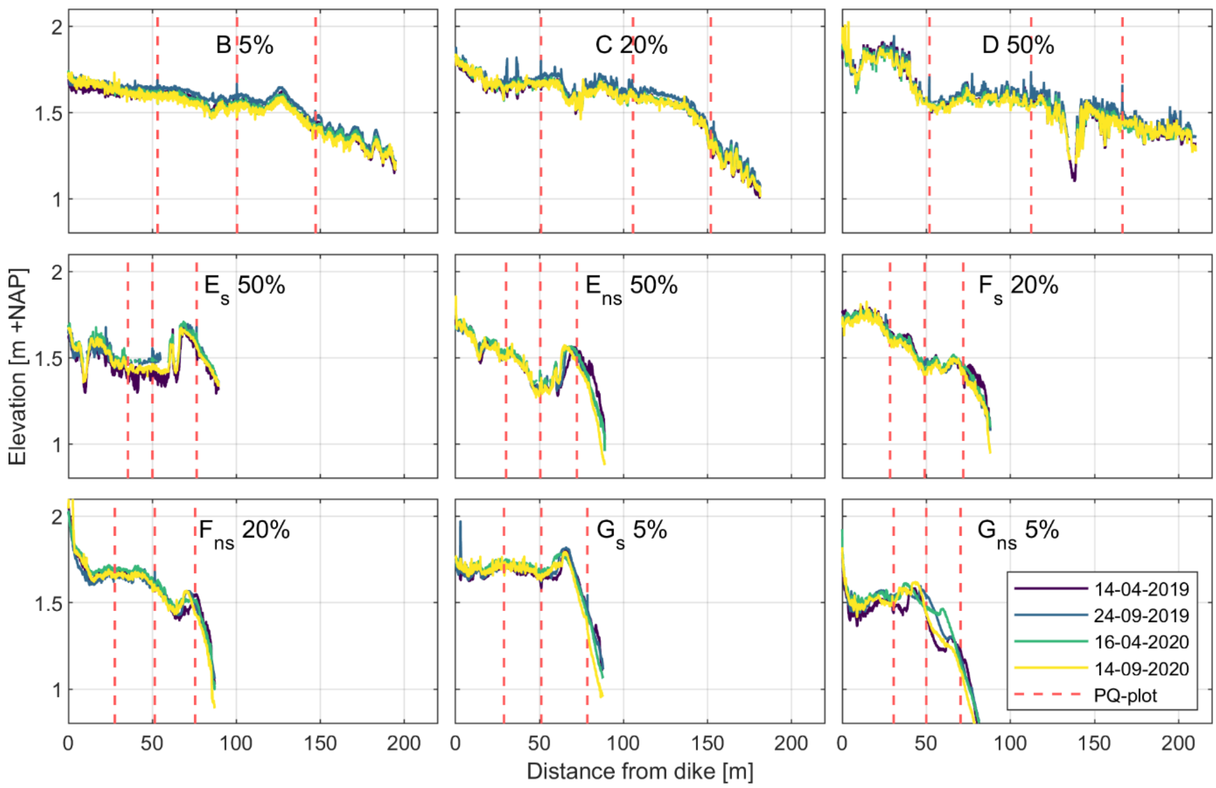


Figure 5-3 Elevation along transects through each set of PQ's per area from the dike to the brushwood groyne based on the DTM of 14-04-19, 24-09-20, 16-04-20 and 16-04-20. Location of the PQ's in Figure 31.

Sandbars

In the southern compartments (E, F and G), sandbars formed shortly after construction of the salt marsh (Figure 5-4). They are located just above the MHW-line (crest elevation up to about 1.8 m +NAP), in the high water swash zone. Compartment G has a main, continuous sandbar that is oriented ENE-WSW, and a smaller sandbar aligned with the eastern tip of the salt marsh 'behind' the main sandbar. The sandbar in compartment F is interrupted and in compartment E, two lobes of sand are present in the corners. Also, some small bars with crests at about 1.3 to 1.4 m +NAP are present in the shallower corner in front of compartment X and Ens (Figure 5-5, left).

All sandbars or lobes generally are about 10-20 cm higher than the surrounding bed level and have a steep landward edge and gentle slope towards the brushwood groynes. In the field, lobes of freshly deposited sand are observed on top of some of the sandbars directly behind the brushwood groynes (see right-side of Figure 5-5, right).

In contrast to compartment E, F and G, no distinct sandbars were present in B and C, and only small lobes of sand directly behind the brushwood groynes were present in D. However, there are some small sandbars seaward of compartment B and there is a large sandbar complex seaward of compartment C, D and X. These sandbars, together with the riprap groyne, provide shelter to compartments B, C, D and X from waves.

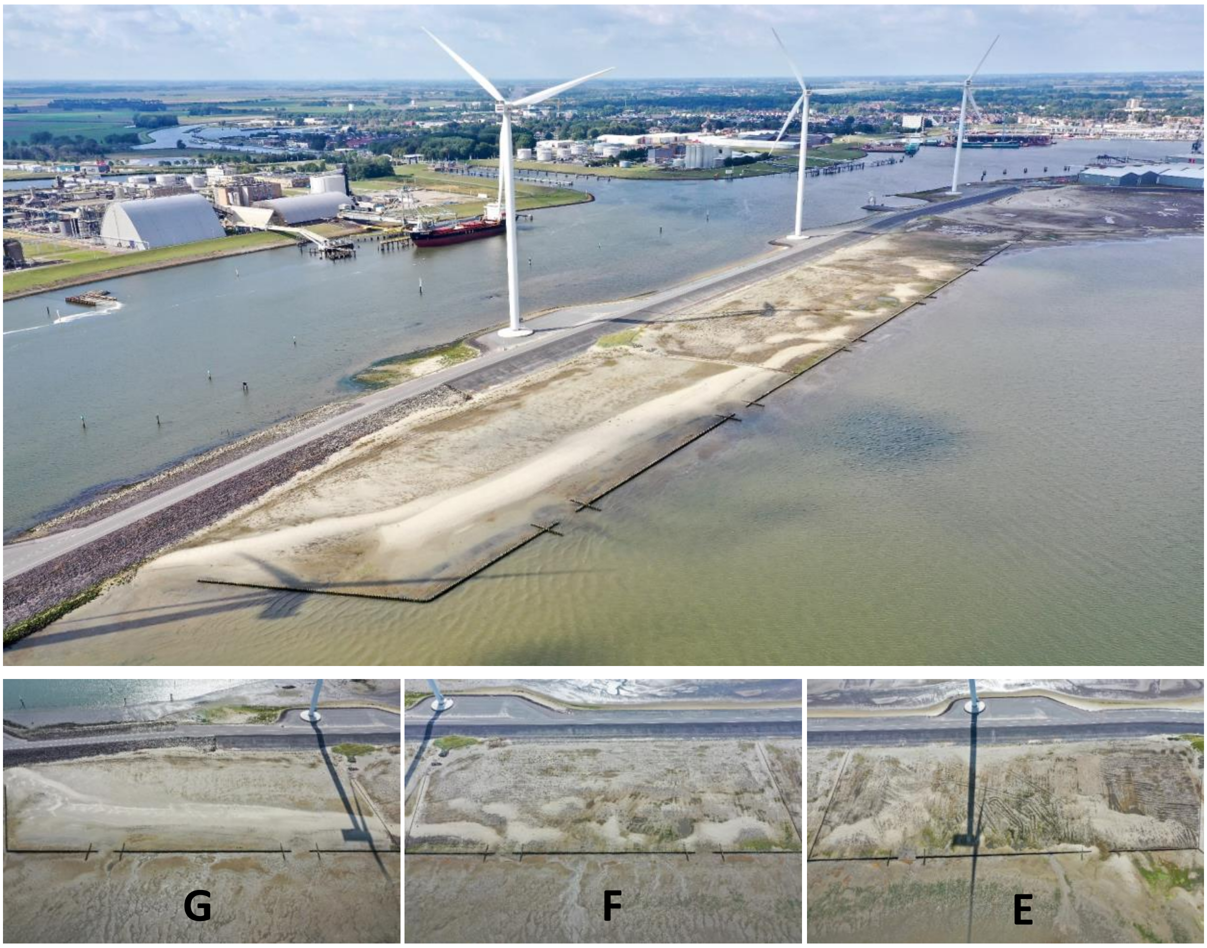


Figure 5-4 Sandbars in compartment E, F and G as seen from the air at 10-09-2019.

Figure 5-5 Left: Sandbars in and in front of compartment X and E (not seeded) in the DTM of 16-04-2020. Right: Sandbar at the seaward side of compartment F (top), G (bottom left) and E (bottom right).

5.1.2.Initial sediment composition of the subsurface

The mud (grain diameter < 63 µm) is well mixed into the upper meter of the salt marsh during construction according to the average sediment composition per compartment (Figure 5-6; Figure 5-7). The average percentages of fine sediment approximate the intended percentages of 5, 20 and 50% (Table 5-1). This indicates that construction with this respect was successful and that comparison between the compartments based on the intended percentages of fine sediment (5, 20 and 50% respectively) is appropriate.

The average mud percentages for the compartments with the highest intended percentage of 50% are closest to the intended value, with deviations of -2 and -3 ‰ (Table 5-1). The fine sediment percentage for the other compartments deviated a little more from the intended percentages of 20 and 5% with respectively +5 ‰ and +2 to +4 ‰. Hence, the total amount of mud mixed through the sandy base layer per compartment was appropriate.

On the other hand, the variation in the mud percentage as well as the D50 (based on the standard errors) is smaller in the compartments with ≈5% mud than the compartments with ≈20% and ≈50% mud. This can be related to the limitations in thoroughly and evenly mixing relatively large volumes of mud through the sandy base layer. The resulting local variation in initial sediment composition is visible in the individual core samples (Figure 5-6 and Figure 5-7) and confirmed by field observations: some clumps of mud were observed in the sediment cores and on the surface in multiple compartments.

Table 5-1 Initial median grain size (D50) and percentage of fine sediment (grain diameter < 63 µm) in the upper 1 meter of the subsurface, averaged over each compartment. The averages and the standard error (SE) are based on the average values (over 2 samples) per depth-interval of 0.2 m of all cores within the compartment.

Compartment	**Intended % mud**	**Average % mud based on corings**	**SE* % mud**	**Average D50 [µm] based on corings**	**SE* D50 [µm]**
B	5 %	9 %	6	219	30
C	20 %	25 %	14	169	51
D	50 %	47 %	11	86	48
E	50 %	48 %	12	86	39
F	20 %	25 %	14	145	41
G	5 %	7 %	8	186	20

The sediment mixing was least good in the lower part of the upper meter of the bed (Figure 5-6). The sediment seems slightly coarser at larger depths. Also, the mud percentages between -0.8 and -1.0 m seem to be lowest (Figure 5-7), probably because thoroughly mixing the mud at larger depths was harder.

The sediment composition does slightly differ for different distances from the sea but does not show a clear pattern, as intended (Figure 5-6 and Figure 5-7).

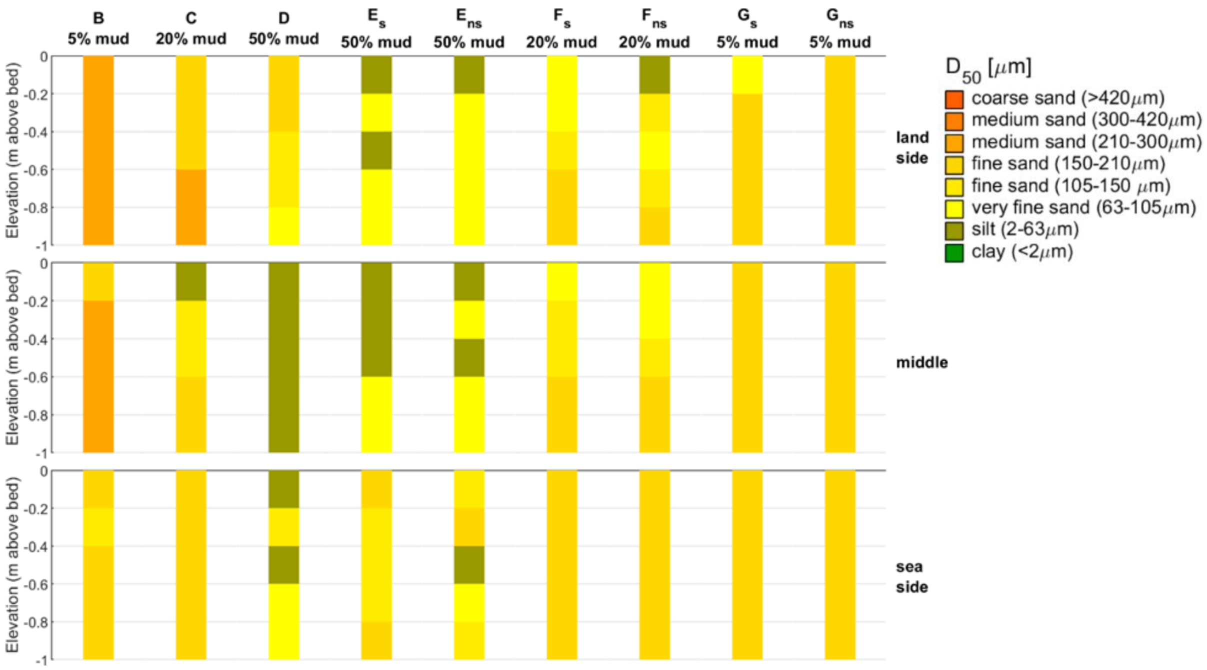


Figure 5-6 Initial median grain size (D50) in the upper meter of the subsurface. Each column represents a core near each PQ at 19 or 20 November 2018; each value is the average D50 of two samples per depth interval of 0.2 m.

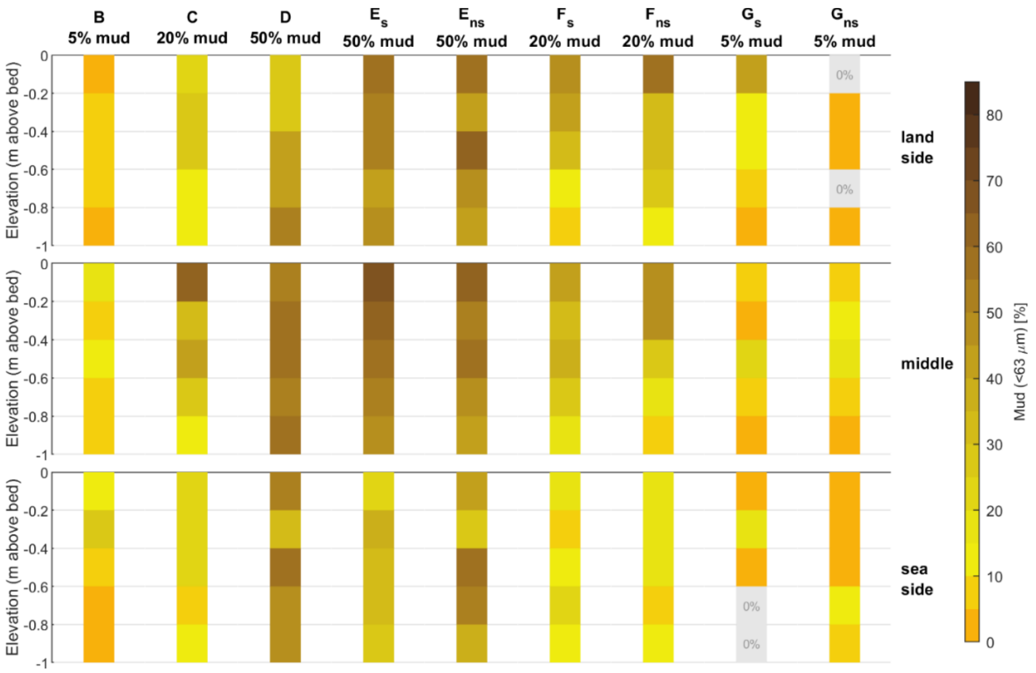


Figure 5-7 Initial percentage of fine sediment (grain diameter < 63 μm) in the upper meter of the subsurface. Each column represents a core near each PQ at 19 or 20 November 2018; each value is the average of two samples per depth interval of 0.2 m.

5.1.3. Artificial features

In August and September 2018, trucks, bulldozers and excavators brought fine sediments on top of the sandy base layer. A deep spader pulled by a tractor mixed fine sediment through the sand on site. A wide track-laying vehicle was applied to flatten the surface. However, one year later the tire tracks of the heavy machines are still visible in the field and in the DTMs, showing local elevation differences ranging from several centimetres to more than 20 cm (Figure 5-8; Figure 5-9). The tire tracks are most evident in the compartments with 50% mud (D and E), and almost absent in the compartments with 5% mud (B and G).

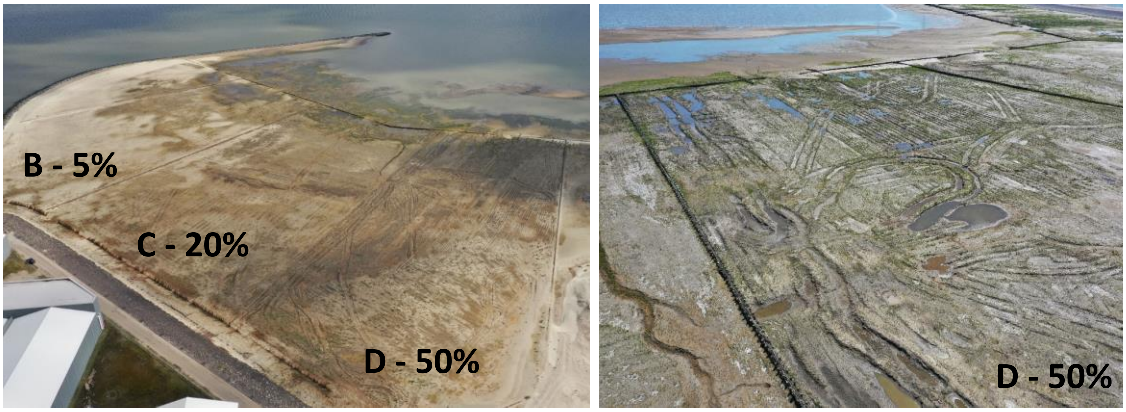


Figure 5-8 Tire tracks formed during the mixing of the mud through the sandy base layer (drone photograph of 10-09-2019 (left) and 25-06-2020 (right)). The higher the mud content of the compartment, the more tracks are left behind.

Figure 5-9 Photograph of the traces of the tire tracks in compartment E at 24-09-2020 (left) and in compartment E t 29-08-2019 (right) during low tide.

In the central compartment X – which was not monitored – a pile of sand is present in the DTM of September 2019 (Figure 5-10, left). This is an artificial hill of sand that was left over after the construction of the salt marsh. Between September 2019 and February 2020, the hill has been removed and a pond was formed in its place (Figure 5-10, right).

Figure 5-10 Photograph of the sand pile in compartment X in September 2019 (right side of left picture, view from compartment D) and the pond in September 2020 after removal of the pile (right picture, view from the dike).

5.2. Hydrodynamics

5.2.1. Water depth

The measured water level at high tide in front of the salt marsh generally varies between approximately 1.0 and 1.5 m +NAP (Figure 5-11). Storms caused an increase in the water level up to 3.7 m +NAP.

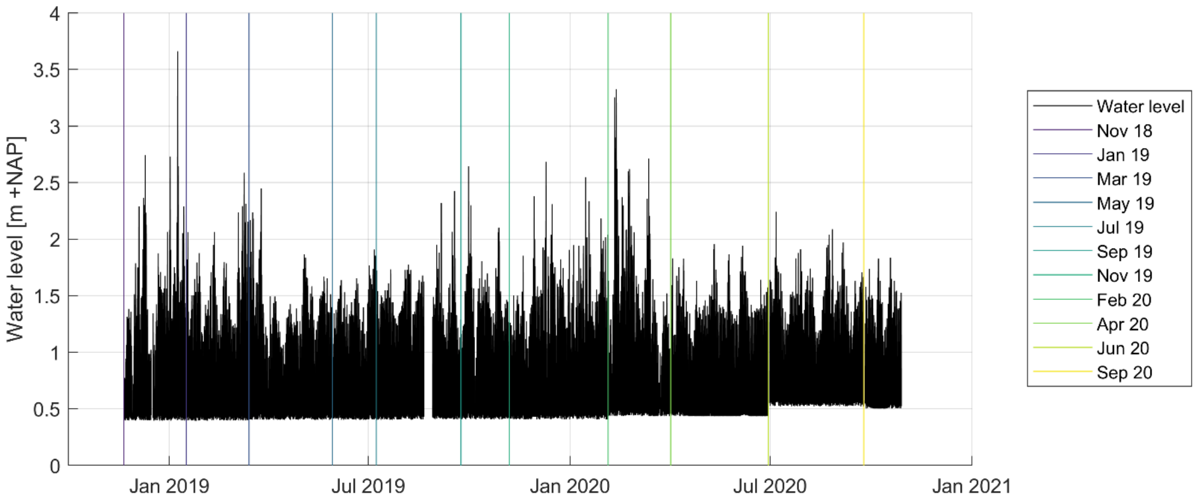


Figure 5-11 Water level over time including fieldwork dates. This water level is the average of the water level measured with CTD1 and CTD2.

Between November 2018 and September 2020 the entire salt marsh, of which the highest parts are located just below 2 m +NAP, is flooded approximately 73 times (Figure 5-12). The water level rarely exceeds 3 m +NAP. Complete flooding of the salt marsh occurs most often in winter and early spring (Figure 5-13). In the summer period complete flooding occurs much less often.

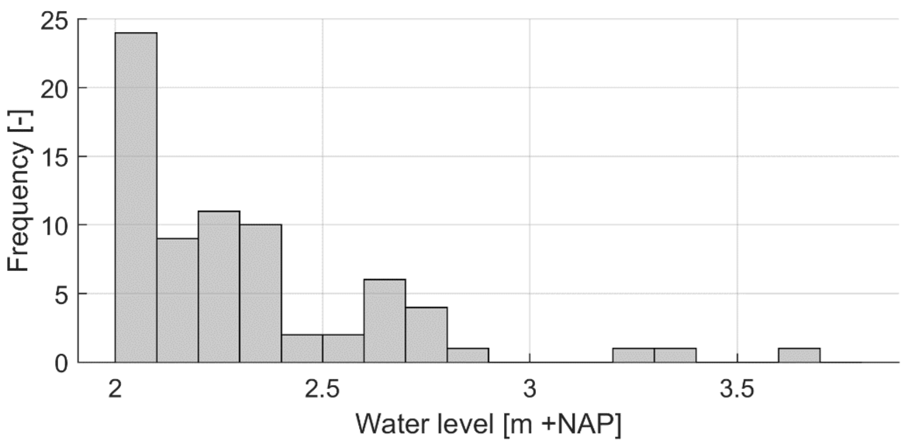


Figure 5-12 Occurrence of high water levels between November 2018 and September 2020. At water levels above 2m +NAP the entire salt marsh is flooded.

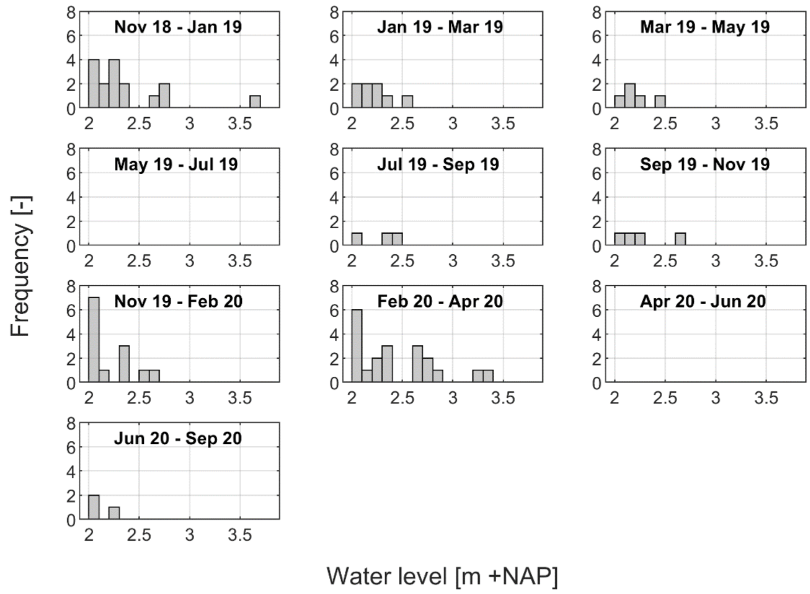


Figure 5-13 Occurrence of high water levels in the different measurement periods. At water levels above 2m +NAP the entire salt marsh is flooded.

On average the PQ's are flooded about once per day to once every 4 days (Figure 5-14). The average frequency of flooding differs strongly between measurement periods Some plots are only flooded once every 10 days in summer while these locations are flooded up to twice a day in winter/early spring.

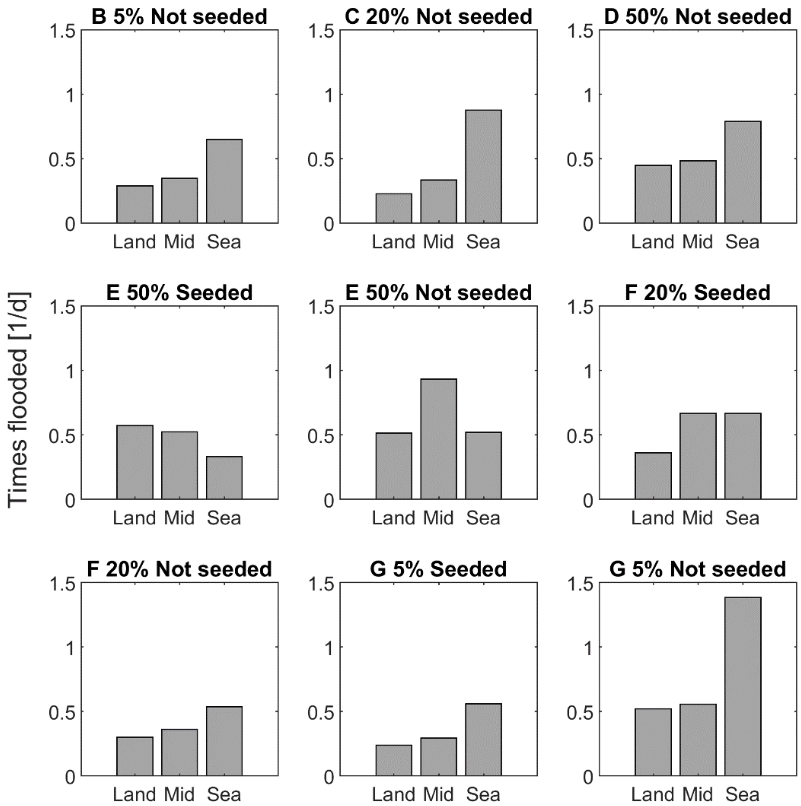


Figure 5-14 Average times per day a PQ is flooded between November 2018 and September 2020. Letters correspond to the compartments. The percentages indicate the percentage of mud in the top layer of the soil. Soil subsidence is not considered, but inclusion of soil subsidence has only little effect on the outcomes and does not affect the overall pattern as presented in this figure.

Flooding of the inlets

The inlets in the brushwood groynes of the compartments are flooded between once and twice per day on average. The higher located ‘D’ and ‘Es’ are flooded less often, while ‘Ens’ up until ‘Gns’ are flooded more often.

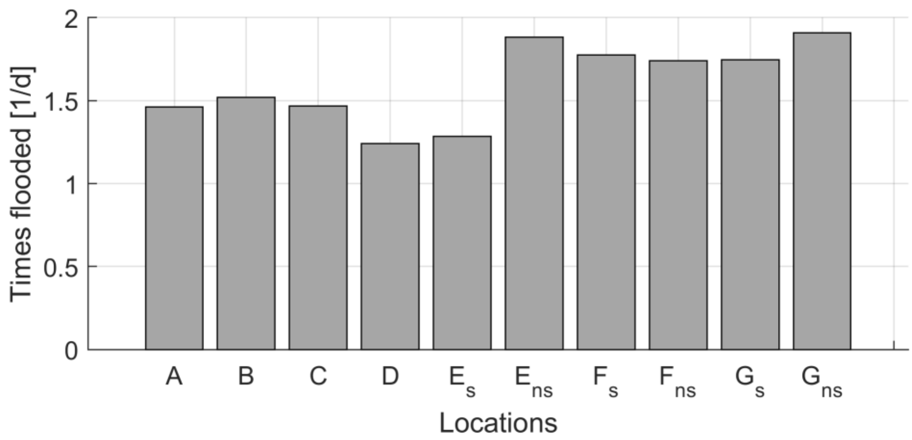


Figure 5-15 Average time per day the inlets are flooded between November 2018 and September 2020. Letters correspond to the compartments. The letters s and ns in the subscript refer to seeded and not seeded parts of the compartments.

5.2.2. In- and outflow

The area and shape of the compartments affect the water volumes that flow in and out of the compartment during each tide. Compartment B, C and D have a larger total surface area than compartment E, F and G (about 23,000 m^2 versus about 20,000 m^2), but a smaller compartment width at the lower, seaward side. Therefore, the water volumes for these compartments are comparable (Table 5-2). Compartment D has the smallest water volumes- due to its shape (relatively small seaward front) and its overall high elevation (see Figure 5-1; Figure 5-2). During mean high water, most water flows in and out of compartment G due to its low elevation at the seaward side and at the south eastern edge of the salt marsh, while during total submersion most water is stored in compartment B and E due to their lowest mean elevation.

Table 5-2 Water volume in each compartment during MHW (1.4 m +NAP; tidal prism) and during total submersion (2.0 m +NAP) based on the DTM of September 2019, April 2020 and September 2020. Note that these volumes do not exactly equal the water volume flowing in and out as some exchange of water between the compartments is possible through the brushwood groynes.

Compart-ment	Tidal prism [m^3] (below MHW: 1.4 m +NAP)				Water volume during total submersion [m^3] (water up to 2.0 m +NAP)			
	19-04-19	24-09-19	16-04-20	14-09-20	19-04-19	24-09-19	16-04-20	14-09-20
B	930	641	799	936	11,775	10,742	11,477	11,986
C	804	668	824	884	10,153	9,386	10,308	10,464
D	397	173	313	361	7,898	7,255	7,876	8,080
E	961	849	719	958	11,749	11,122	10,698	11,507
F	600	630	573	786	8,929	9,254	8,807	9,437
G	1,274	1,213	1,213	1,579	9,846	9,497	9,353	10,065

5.3. Elevation change

5.3.1. Large-scale elevation changes

The largest elevation changes occurred outside the compartments: the sandbar in front of compartments C, D and X changed slightly in shape, and some sedimentation took place seaward of mainly compartment E and F (Figure 5-16). Also, directly seawards of the brushwood groynes the sediment bed eroded.

Inside the compartments, the growth and migration of the sandbars is visible in compartment E, F and G (Figure 5-16). In compartment E and F, a rise in bed level was observed mainly at the landward side of the sandbars: the sandbars migrated or grew landward. In compartment G, the landward migration of the elongated sandbars was even more distinct with a clear pattern of sedimentation and erosion.

Tidal creeks developed over time (see Section 5.3.4 and Figure 5-16).

The 'scattered' erosion and sedimentation pattern especially at the western side of compartment E corresponds to the gradual flattening of the tire tracks: the lower parts are filled with sediment, while the higher parts are eroded.

The above-described trends and patterns in bed level change are observed during the entire monitoring period. Maps of all DTM's and the changes in elevation between each two subsequent DTM's are shown in respectively Appendix 2 and 3.

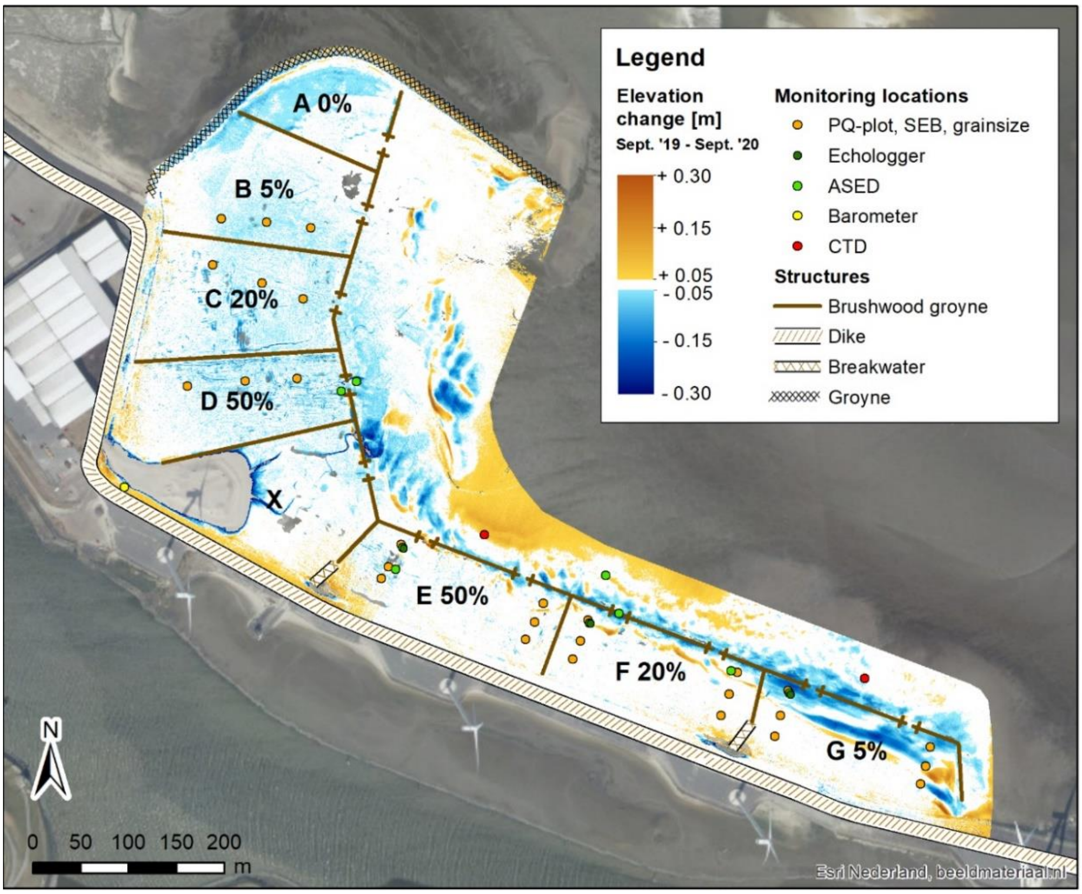


Figure 5-16 Elevation difference between 24-09-2019 and 24-09-2020 based on the DTM's. Yellow-orange colours = bed level increase (net sedimentation), bluish colours = bed level decrease (net erosion/compaction). The vertical accuracy of both DTM's is in the order of a few centimetres, hence elevation changes smaller than 5 cm are within the error margin and are not shown in the figure (white). Source aerial photograph: beeldmateriaal.nl/Kadaster.

5.3.2. Elevation change measured with the SEB's

The net bed level changes (combination of erosion, sedimentation and compaction/consolidation of the top 1.4 m of the bed) at the PQ's in compartment B – D t were small, most likely because the area is more sheltered (Figure 5-17). Large bed level changes occur in compartment Es, F and G – especially at the seaside - due to the migration of the sandbar (Figure 5-17; Figure 5-18). There was no effect of mud percentage on bed level change ($F_{2,24}$ = 1.33, p = 0.28). Furthermore, there was also no significant effect of flooding frequency on sedimentation ($F_{1,240}$ = 0.15, p = 0.70).

In contrast to other salt marshes (Allison et al. 1995), there seems to be no seasonal pattern of sedimentation in winter and compaction in summer. This could be because either the sandbar migration and/or subsidence masked the smaller bed level changes or that sedimentation in winter was low due to low vegetation density.

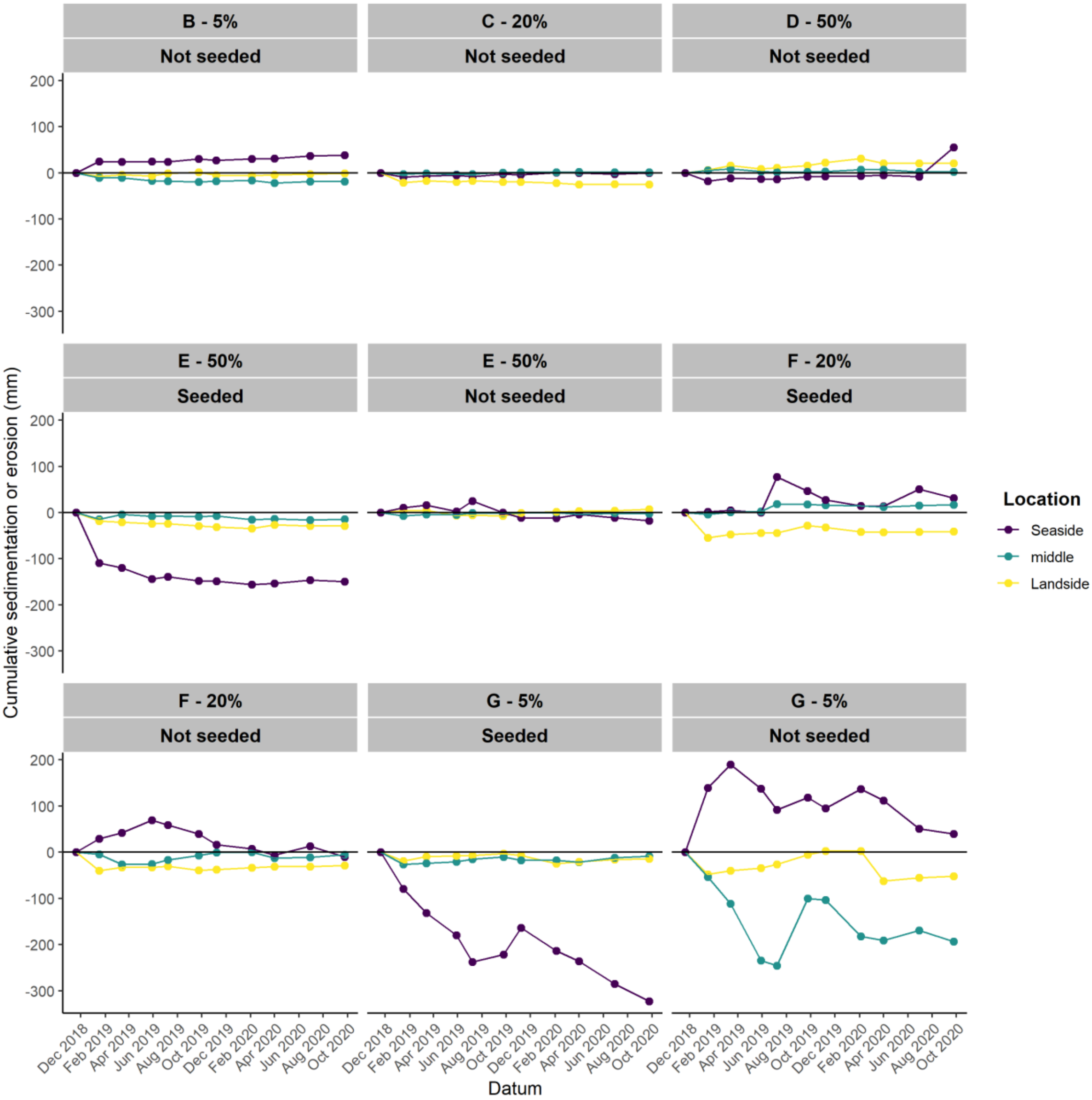


Figure 5-17 Net bed level changes in mm over the 2-years measurement period at the different PQ's. The bed level change includes sedimentation, erosion and compaction/consolidation of the top 1.4m of the bed.

Figure 5-18 The seaward SEB in compartment Es is located on a dynamic sandbar in contrast to the more landward SEB's. Drone photograph of 25-06-2020.

5.3.3. Elevation dynamics measured by the ASED-sensors

The ASED measurements (specific locations in Appendix 1) show elevation changes to be in the order of centimetres to a maximum of 15 cm (Figure 5-19). The largest changes occurred at the locations below MHW (in compartment D Not seeded, F Seeded Outside and F Seeded Inlet), while changes at the locations above MHW were in the range of centimetres only. The elevation changes landward from the brushwood groynes and outside tidal creeks were small.

The observed changes are larger at locations with longer inundation periods (Figure 5-14; Figure 5-15): the standard deviation of the full timeseries is large at locations below MHW and small at locations above MHW. Vegetation was not observed at these locations with high bed level dynamics (c.f. Willemsen et al., 2018).

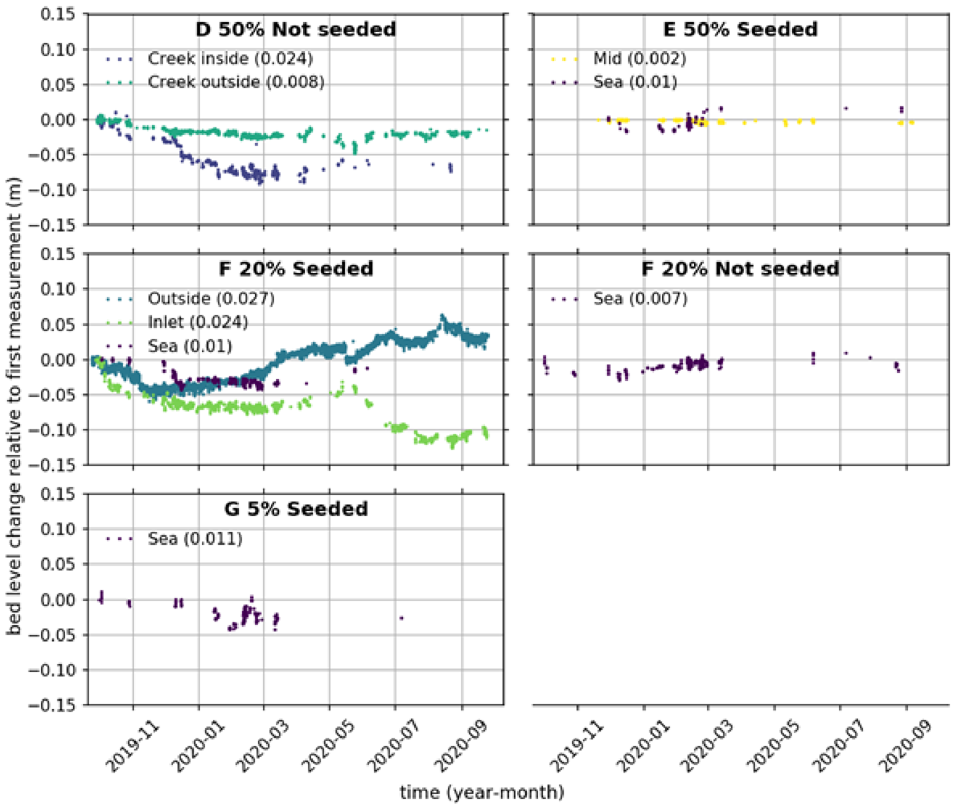


Figure 5-19 Bed level change relative to the first measurement, measured at nine locations with the ASED sensors. The values between brackets in the legend of all panels indicate the standard deviation (in meters) of the full time series. The exact locations of the different observation points are highlighted in Appendix 1.

Bed level dynamics in front of the salt marsh

Seaward from compartment F Seeded, two ASED sensors were installed: one at the tidal flat in front of the compartment and one at the inlet of the compartment in between the brushwood groynes.

Bed level changes at the tidal flat (Figure 5-20) first showed erosion of approximately 5 cm in the fall of 2019, followed by sedimentation (+/- 7 cm) in the first months of 2020. From May till October 2020 a repeating bi-monthly pattern of erosion and sedimentation occurred. Both in September and October 2019 and May and June 2020 erosion (+/- 5 cm to 10 cm) was observed at the tidal inlet (Figure 5-19 F Seeded 20% Inlet; Figure 5-20). These periods of erosion were followed by periods of sedimentation. Nevertheless, sedimentation was not able to balance erosion.

Figure 5-20 Sensor outside compartment F seeded (left; 01-04-2020) and at the inlet of compartment F Seeded (middle and right; 04-02-2020).

Effect of seeding on bed level dynamics

Both in the Seeded and Not seeded F compartment (20% mud), bed level change was observed at the seaward side of the compartment (Figure 5-21). The not seeded compartment showed initially erosion of approximately 2 cm, whereas approximately 4 cm erosion of the compartment that was seeded was observed no earlier than December 2019 (Figure 5-21). The erosion in the compartment that was not seeded was quickly counteracted with sedimentation up till February 2020, whereas the bed level in the seeded area varied around the bed level reached after erosion and recovery was observed in the summer of 2020. These patterns might have been the result of the sandbar moving landwards and exactly passing the measurement locations, thereby affecting the local bed level dynamics (Figure 5-22). The observed differences (point measurements) and the almost equal standard deviation of the bed level change in both compartments show no evidence of a more stable bed in the compartment where seeds were distributed, and vegetation was better able to establish in the first year. The general similarities in bed level change at both measurement locations can be explained by approximately equal hydrodynamic exposure (Figure 5-14).

Effect of mud percentage on bed level dynamics

To compare bed level dynamics at the compartments with a different sand / mud mixture, sensors were installed in compartments E Seeded (50% mud), F Seeded (20% mud) and G Seeded (5% mud) (Figure 5-21, bottom panel). The standard deviation of the bed level change in all compartments was almost equal (0.01 m). Nevertheless, differences in bed level change were observed. Erosion was observed in December 2019 in compartment E (approximately 2 cm) and F (approximately 4 cm), followed by sedimentation in February (compartment E) and March (compartment F). More landwards, in the centre of compartment E (Figure 5-19, E 50% Seeded - Mid), the bed level was stable and hardly any change was observed, although this location was flooded more often (Figure 5-14). Nevertheless, exposure to waves might have been slightly lower at this location, due to the higher elevated grounds more seaward. Moreover, more cohesive sediment was observed at this location, suppressing bed level change (Figure 5-6; Figure 5-7). Continuous erosion was observed in compartment G and the range in which measurements appear in compartment G in the first months of

2020 was rather large (large variability in short period), exceeding the range in compartment E and F, despite a lower elevation (Figure 5-14). This might have been caused by the sandier substrate (Figure 5-6; Figure 5-7). Nevertheless, the dynamics of the sandbar might have influenced these results as well.

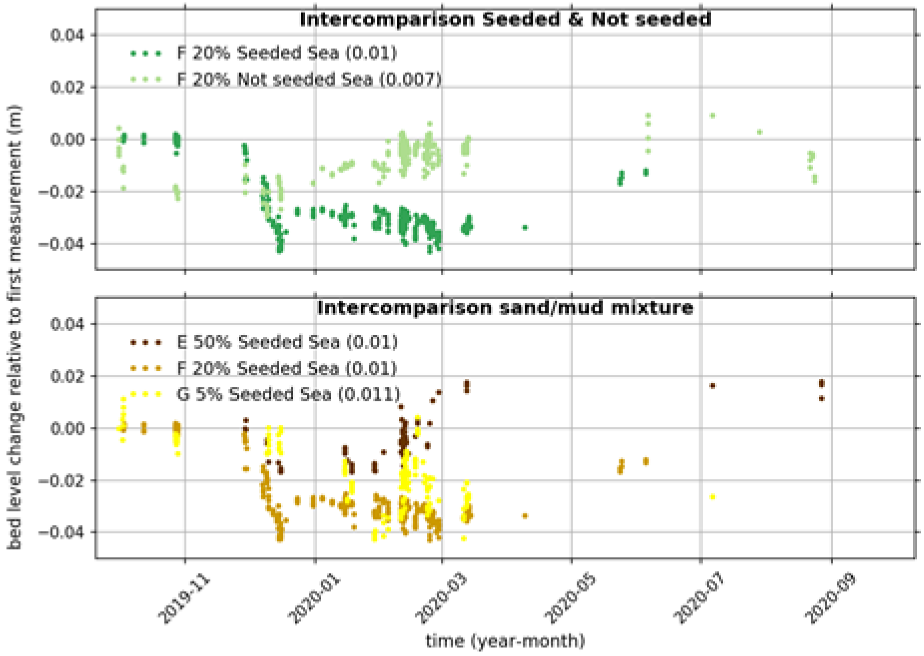


Figure 5-21 Comparison of the continuous bed level change for a seeded versus not seeded area (top panel) and different sand/mud mixtures (bottom panel). The values between brackets in the legends of both panels indicate the standard deviation (in meters) of the full time series.

Figure 5-22 ASED sensor at the sandbar in compartment F not seeded.

Seasonal changes in bed level dynamics

Bed level change in the growing season of *Salicornia procumbens* (April - September), was generally positive (sedimentation), whereas only erosion was observed outside the growing season (October – March) (Figure 5-23). Only at the tidal inlet of compartment F seeded, clear erosion was observed in the growing season. The erosion outside the growing season was observed to be much larger than the sedimentation during the growing season. Nevertheless, the dynamics inside the different compartments (dynamics in tidal creeks excluded) remained limited, not hindering the growth of vegetation (c.f. Hu et al., 2015b). Notable exception was location F Seeded (Sea), where the moving sandbar might have influenced seasonal bed level change (Appendix 3). Elevation change due to the landward moving sandbar might have resulted in the burial of established vegetation (Figure 5-24).

The seasonal observations were linked to wind data collected by KNMI near Lauwersoog, northwest from Marconi (Appendix 4) and Nieuw Beerta, southeast from Marconi (Appendix 4). Wind speed is generally larger in the non-growing season, and smaller in the growing season. More onshore directed winds, with a larger wind speed, were observed during the growing season. This might increase the amount of sediments arriving at the different compartments. Erosion during the non-growing season and sedimentation during the growing season was also observed more pronounced seaward from the different compartments (F 20% Seeded Outside), although the tidal inlet at F seeded (F 20% Seeded Inlet) remained erosive during the growing season, perhaps due to the flow concentrating through the inlet and the onshore directed winds, resulting in more onshore directed waves (Appendix 4).

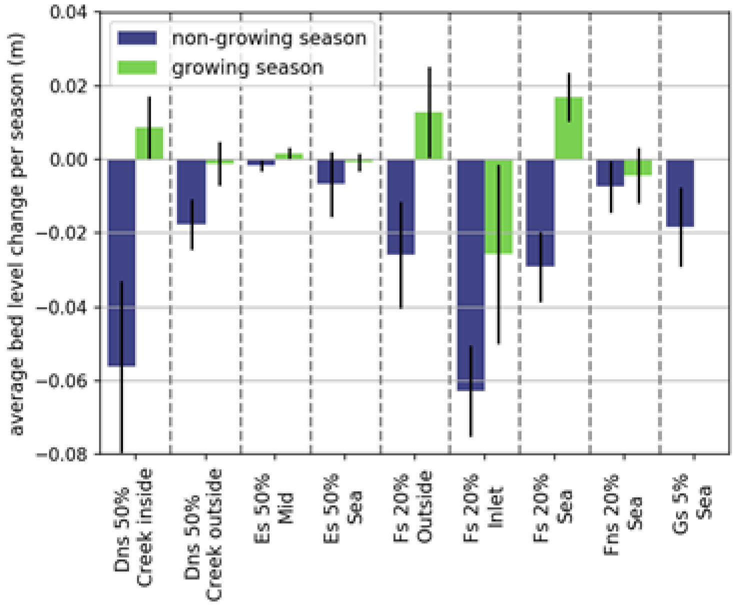


Figure 5-23 Average bed level change per half-yearly season: October- March and April – September (growing season). The black lines indicate the standard deviation of the bed level change per half yearly season.

Figure 5-24 Burial of established Salicornia vegetation due to the landward progressing sandbar in compartment F Not seeded (20% mud).

Validation of the ASED sensors

The state-of-the-art ASED sensors and developed post-processing script were validated. The manually measured height above the bottom of the sensor and the height above the bottom measured by the sensor itself were compared (Figure 5-25). In general, the manually measured value was 3 cm to 4 cm lower than the height measured by the ASED sensor and post-processed using the script. This resulted in a mechanistic offset. Nevertheless, the fitted line through all points of comparison has a slope of 1.0001, almost equal to exactly one. Moreover, the r^2 of this line is 0.99, which indicates an almost perfect match of the fitted line with the observation points. For the current analysis, the offset is not relevant, neither affecting the results, since all ASED observations were related to the initial measurement. However, for future studies, where other analysis will be applied, the offset can be added as a calibration factor in the post-processing script.

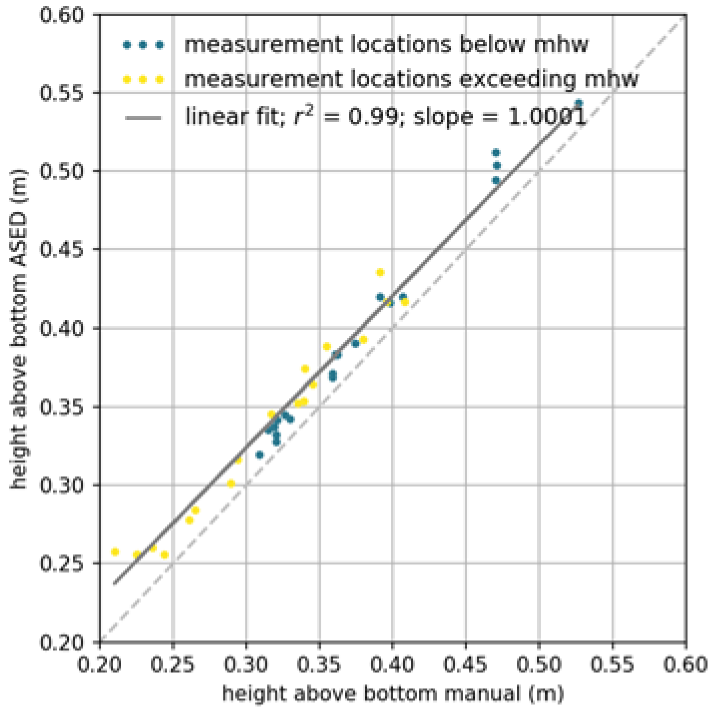


Figure 5-25 Comparison of manually measured height above bottom of the measurement head of the ASED and height above the bottom autonomous obtained by the ASED every time the ASED is installed and retrieved from the field.

5.3.4. Tidal creek formation

Tidal creeks developed at both the landward and seaward side of the brushwood groynes at the salt marsh, mainly below mean high water level (Figure 5-1; Figure 5-28 and photographs in Appendix 5). The intention was that tidal water flow would concentrate in the inlets in the brushwood groynes and form a tidal creek there. However, most active tidal creeks are now located outside the inlets. These tidal creeks started developing before the construction of the brushwood groynes and remained active. Only compartment B and D have a tidal creek through the inlet (Figure 5-26). Compartment G is the only compartment in which no tidal creek formed up until the last field visit in September 2020.

Development of the bed level in the inlets

Although tidal creeks only developed through the inlets of compartments B and D, most inlets show a gradual deepening due to a combination of subsurface compaction and erosion by flowing water (Figure 5-26;Figure 5-27). The only exception is compartment E_s, where the bed level increases due to the formation of a sandbar at the eastern side of the inlet. The bed level in the inlets stabilized after about a year (Figure 5-26).

The strongest lowering is observed in the inlets of the south-eastern compartments E_{ns}, F and G (Figure 5-26; Figure 5-27). These inlets are more exposed to waves due to their orientation and more exposed to (tidal) currents due to their lower (initial) elevation (Figure 5-1; Figure 5-26). The (initial) grain size of the applied sediment layer does not seem to play a differentiating role between the surface elevation of the inlets, although sediment samples were not collected exactly at the tidal inlet itself.

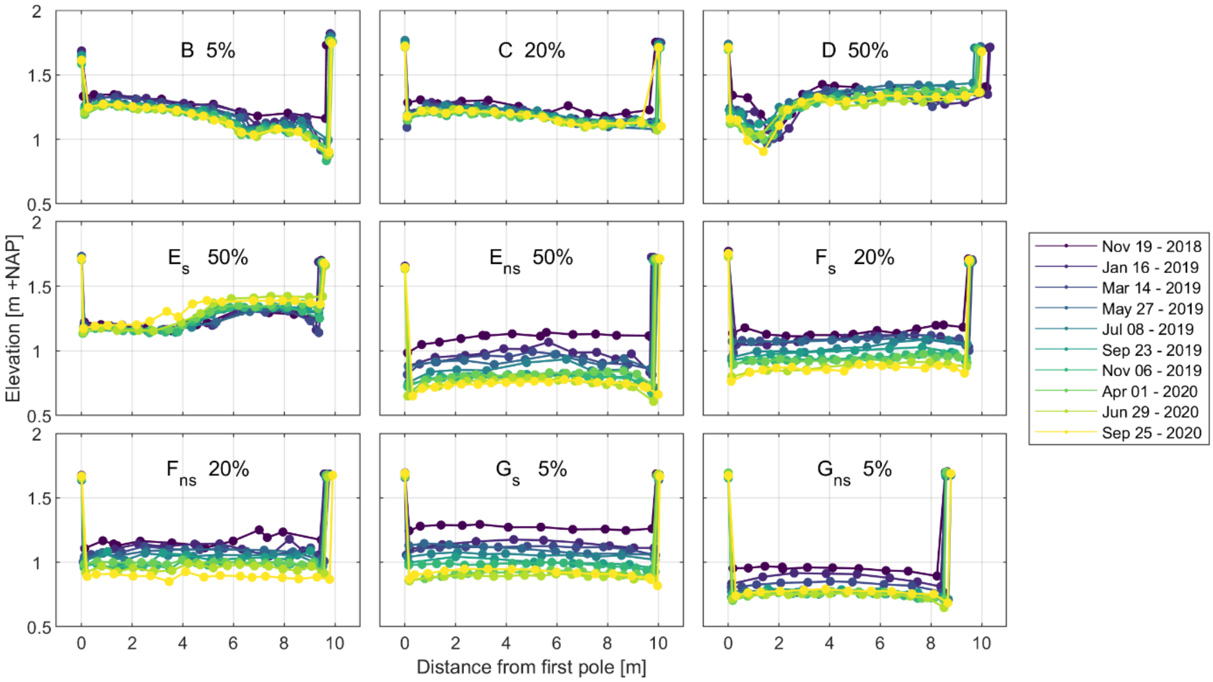


Figure 5-26 Cross-sections of the inlets of all compartments over time. The first and last point are measured on top of the bordering poles of the brushwood groynes.

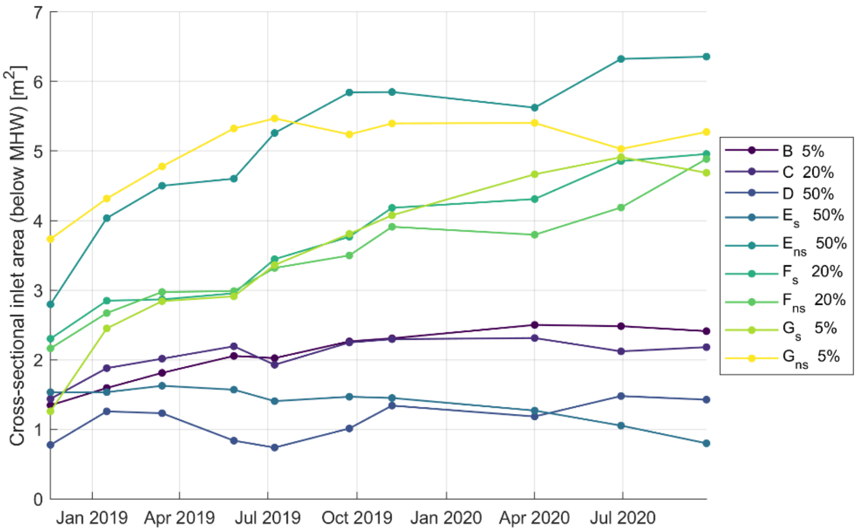


Figure 5-27 Evolution of cross-sectional area for each inlet over time. The cross-sectional area is defined as the area below mean high-water (1.4 m +NAP).

Development of the tidal creeks in and in front of the compartments

The tidal creeks in compartment X, D and some tidal creeks in compartment B and C show a bed level lowering: they widened and/or deepened between at least September 2019 and September 2020 (Figure 5-16). This is also observed with the ASED sensors (Figure 5-19). Lateral migration of the tidal creeks inside and directly in front of the compartments is limited based on the DTM's, except for the larger tidal creek in compartment D and X.

In general, distinct tidal creeks developed in the sheltered compartments (C, D and X), mostly with a mud contribution between 20% and 50%. Smaller tidal creeks were observed in sheltered compartment B consisting of 5% mud and in the more exposed compartments E and F with a mud contribution of 20% to 50%. No tidal creeks formed in the exposed compartment G with 5% mud. The volume of water flowing in and out of the compartment relative to the compartment width is larger for compartments B, C and D than for compartments E, F and G (Table 5-2). Moreover, the sandbars in compartment E, F and especially G might have blocked and buried tidal creeks. This suggests that tidal creek formation depends on a balance between hydrodynamic exposure and the presence of fine sediment. Mixing sand with fine sediment results in more cohesive sediment: some fine sediment (i.e. > 5%) seems to be needed to form tidal creeks.

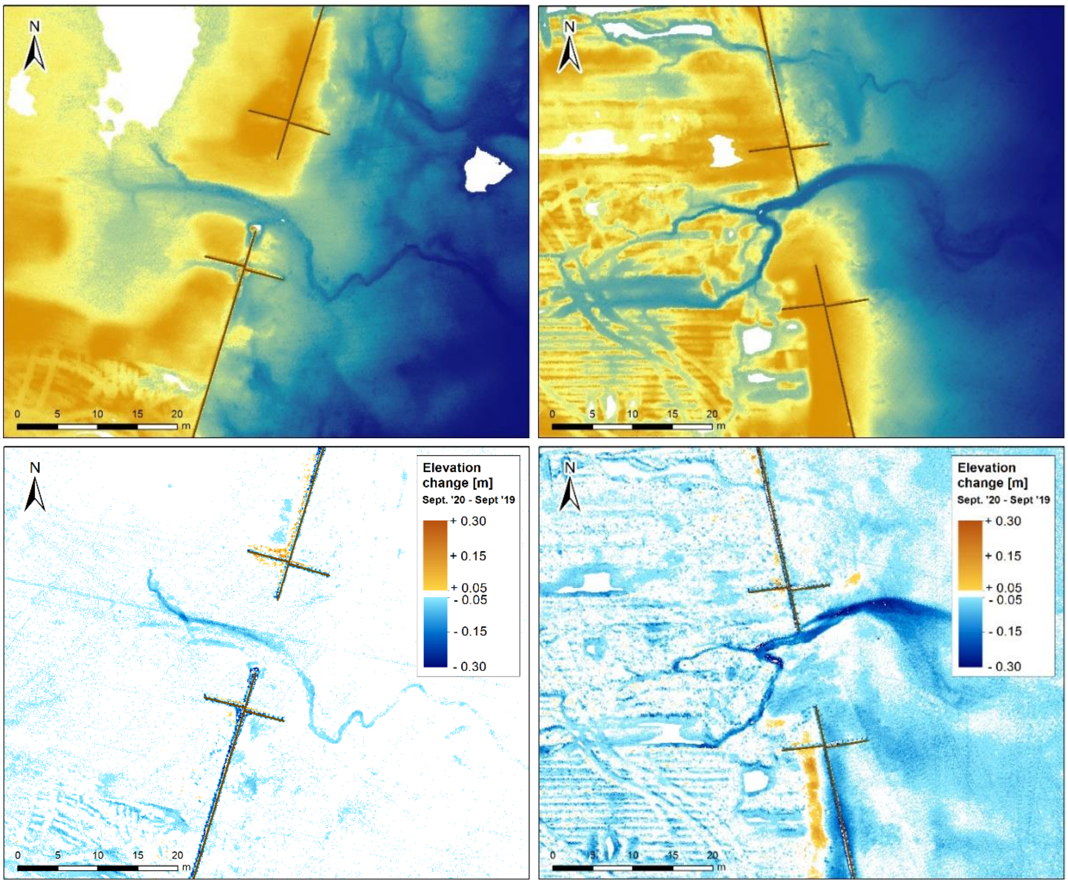


Figure 5-28 Tidal creeks in and around the inlet of compartment B (left) and D (right) in the DTM of 16-04-2020 (local histogram equalize stretch) (top) and in the elevation difference between 24-09-2019 and 14-09-2020.

Tidal creek in compartment D (50% mud)

The tidal creek through the inlet of compartment D – a compartment with 50% mud – is one of the deepest and most actively changing tidal creeks at the salt marsh (Figure 5-28). It has a width of approximately 2-3 m and a maximum depth of about 0.3 m (Figure 5-26). The tidal creek deepened and migrated north during the monitoring period. Especially the seaward side of the tidal creek showed strong lateral migration. The strong meander at the landward side has been rather stable in terms of lateral migration. This may be related to the fine sediment concentration and hence high cohesiveness that is higher within the compartment than outside the compartment.

Continuous measurements of the bed level with ASED sensors in the tidal creek inside compartment D (50% mud, not seeded) show that the bed level of the part of the tidal creek decreased over the fall and winter of 2019/2020 and remained stable over the following spring and summer period (Figure 5-19; Figure 5-29). This may be either due to seasonal forcing or reaching an equilibrium depth. Outside the compartment, the measurements of the sensor recorded the development of the inner bend rather than the deepening of the tidal creek due to the lateral migration of the tidal creek (Figure

5-30). The bed of the inner bend of in front of the compartment slightly decreased in the fall and winter of 2019/2020 and remained rather stable afterwards.

Figure 5-29 Tidal creek inside compartment D at 27-05-2019, 30-06-2020, and 20-08-2020 (from left to right).

Figure 5-30 Tidal creek outside compartment D at 14-03-2019, 27-05-2019, 18-09-2019, 04-02-2020, and 20-08-2020 (from top left to bottom).

Tidal creek in compartment B (5% mud, not seeded)

The tidal creek through inlet B consists of two parts: one directly in front of the southern end of the brushwood groyne (combination of a small tidal creek into the compartment and an erosion pit surrounding the brushwood groyne tip) and one that extends deeper into the compartment (Figure 5-28; Appendix 5). Both sections eroded relatively fast between the first measurement in November 2018 and March 2019 and 'stabilized' afterwards. The tidal creek is a few meters wide and up to 0.3 m deep in the inlet (Figure 5-26). Lateral migration of the tidal creek is limited based on the DTM's.

Tidal creek in compartment X

In 2020, the widest tidal creek at the salt marsh is one that crosses a brushwood groyne in compartment X (see DTM's in Appendix 2 and photographs in Appendix 5). The growth of the tidal creek in compartment X is probably due to the removal of the sand pile that resulted in a large pond connected to the sea through the tidal creek. This increased- the tidal prism of the compartment and allowed the tidal creek to erode. Moreover, the tidal creek in compartment X showed strongest lateral migration inside and outside the compartment in the DTM's, with a pattern of sedimentation and erosion at opposing sides of the channel.

5.3.5. Subsidence

The subsidence (compaction, consolidation and possibly other subsidence effects) of the subsurface after applying more than a metre of sand on top of a soft sediment mudflat was estimated based on the measurements of the height of poles at both sides of the inlets and the SEB-poles at each PQ.

The measurements of the SEB-poles indicate increasing subsidence over time, but the data does not show a consistent trend over time as the uncertainty of the dGPS measurements is larger than the subsidence (Figure 5-31). The subsidence is about 2 cm/yr between November 2018 and September 2020. The SEB-poles have a length of 1.80 m of which 40 cm protrudes above the ground. The 2 cm/yr is hence a measure of subsidence about ~1.4 m below the ground surface.

The subsidence is largest in section B and C of the salt marsh (Figure 5-31). There is no clear relation between the subsidence rate and the distance from land or the percentage of mud in the upper meter of the subsurface.

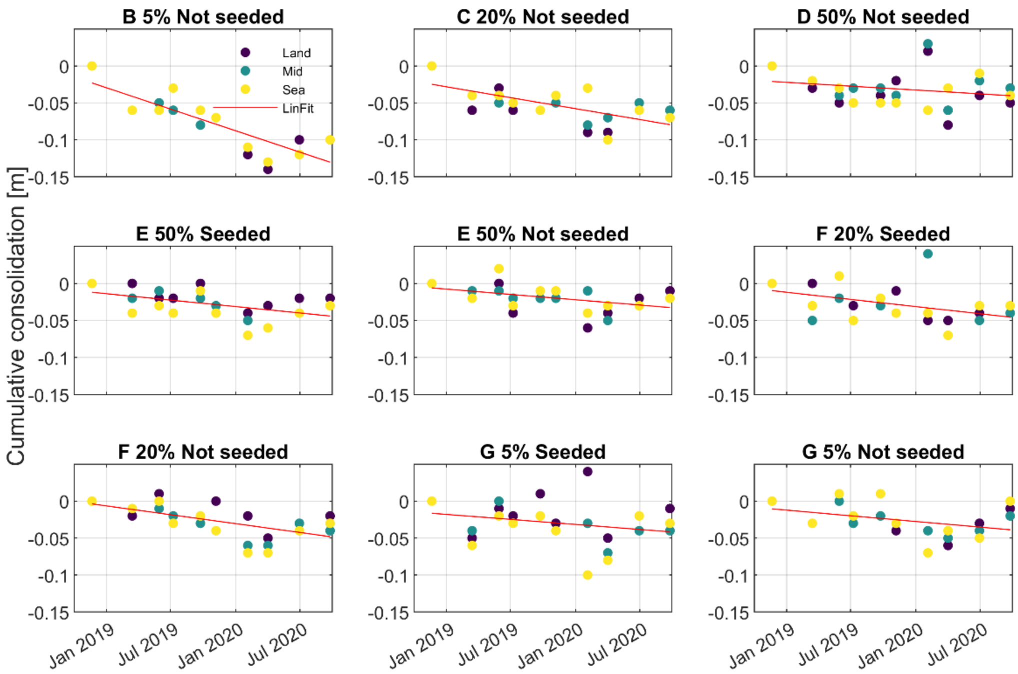


Figure 5-31 Cumulative subsidence over time observed based on measurements of SEB-poles at each PQ.

The elevation of the top of the poles bordering the inlets shows a small decline (on average -1.4 cm/yr), but, like the measurements of the SEB-poles, does not show a consistent decline (Figure 5-32). This is probably related to measurement inaccuracies of the dGPS and possibly also to differences in foundation beneath the poles. The bottom of the poles is located about 3 meters below the surface hence the measured subsidence is largely consolidation of sediment that was already present before construction of the salt marsh.

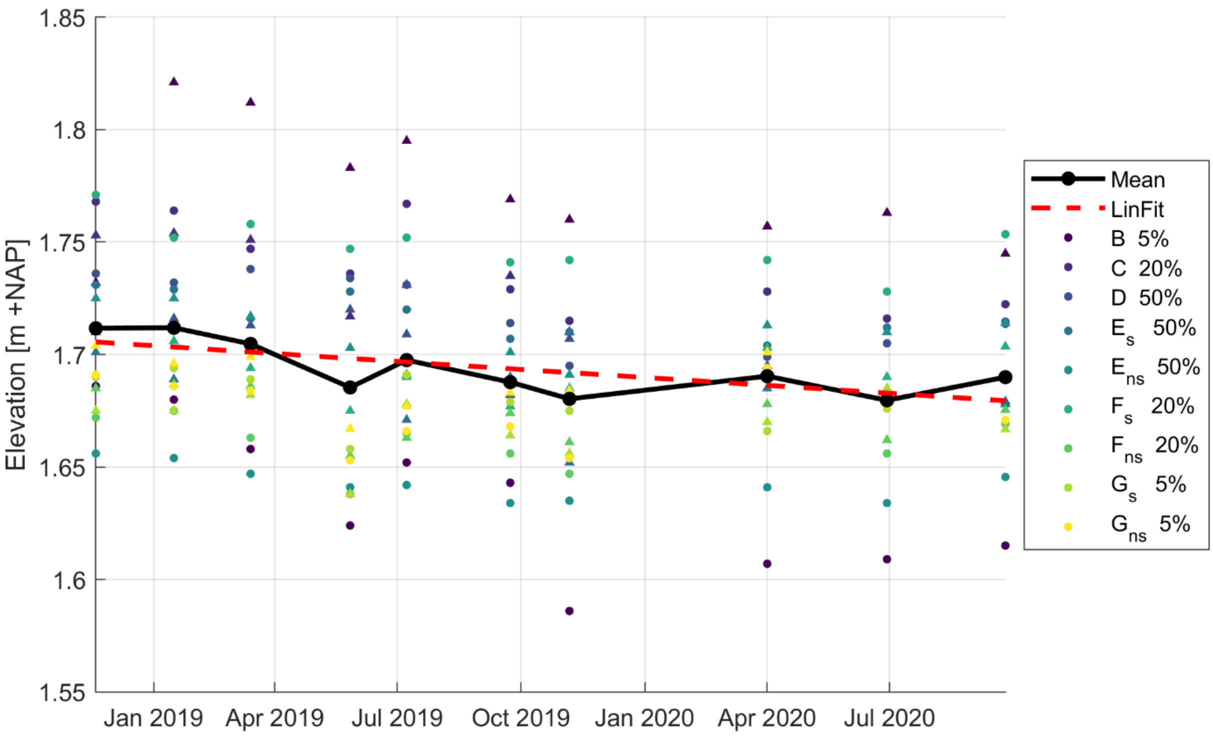


Figure 5-32 Elevation change of the top of the poles bordering the inlets of the compartments. The poles have a length of 3.5 m and are founded at on average 3 m below initial surface level. In the figure, triangles instead of dots are used when multiple poles of the same inlet were measured.

5.4. Changes in top layer sediment composition

The sediment in the top layer of the compartments B, C and D (5, 20 and 50% mud, not seeded) located west becomes finer between May '19 and April '20, followed by a slight coarsening between April and Sept. '20 (Table 5-3, Table 5-4). Overall, the sediment is finer at the end of the monitoring period than at the beginning in compartment B, C and D. No clear trend in average sediment composition over time is observed in compartment E (50 % mud). In compartment F and G (20 and 5% mud), the average mud percentage in the top layer remains low despite a small increase between Nov. '19 and Sept. '20. The trend in (increasing) average mud percentage does not always match a (decreasing) trend in the average D50.

The average sediment composition in compartment E, F and G is strongly influenced by sandbar dynamics in these compartments, as is visible in the spatial variation in the sediment composition over time (Appendix 6). The sediment at the measurement plots landward of the sandbars did become finer between the first and last measurement.

Compartment B, C and D located west all have a similar orientation and geometry and are sheltered from waves, which may have resulted in more sedimentation of fine sediment compared to other compartments. In the field it also seemed that in these compartments there was a fine sediment layer on top of the bed which supports this hypothesis.

The D50 and mud percentage in the top layer in the different compartments is partly related to the initial sediment composition. However, compartment E, F and G have a higher average D50 and lower percentage of mud in the top layer than compartment D, C and B with respectively the same initial mud percentage. This can be partly explained with the sandbar in compartment E, F and G.

Table 5-3 Mean and standard error (SE) of the median grain size (D50) of the top layer (< 1 cm deep) over time. The colours (orange-yellow-green) scale with the grain size. All values are based on all samples per compartment (duplet samples at the same location have not been averaged first).

Compart-ment	May '19		November '19		April '20		September '20	
	Mean D50 [µm]	*SE**	*Mean D50 [µm]*	*SE**	*Mean D50 [µm]*	*SE**	*Mean D50 [µm]*	*SE**
B - 5%	212	34	179	67	172	43	175	12
C - 20%	138	90	101	80	84	70	98	72
D - 50%	54	39	51	56	31	8	39	10
E - 50%	151	77	112	NaN	134	79	111	79
F - 20%	176	30	181	29	188	28	164	42
G - 5%	198	24	208	29	213	35	189	37

Table 5-4 Mean and standard error (SE) of the percentage of fine sediment (grain diameter < 63 µm) in the top layer (< 1 cm deep) over time. The colours (orange-yellow-brown) scale with the grain size. All values are based on all samples per compartment (duplet samples at the same location have not been averaged first).

Compar-timent	May '19		November '19		April '20		September '20	
	Mean % mud	*SE**	*Mean % mud*	*SE**	*Mean % mud*	*SE**	*Mean % mud*	*SE**
B - 5%	8%	9	17%	20	23%	12	23%	4
C - 20%	33%	33	46%	30	53%	28	45%	23
D - 50%	58%	58	64%	20	66%	9	63%	9
E - 50%	26%	26	40%	NaN	32%	24	37%	28
F - 20%	13%	13	9%	9	11%	10	15%	15
G - 5%	4%	4	2%	4	3%	5	8%	13

5.5. Vegetation development

5.5.1.Seedbank

The fine sediment used to build the pioneer salt marsh contained seeds of several different plant species, with the highest numbers being glycophytes typically found on fresh non-saline soils (Table 5-5). Although not all grasses or seedlings could be identified up to species level it became clear that these were not halophytes (plants that can tolerate saline conditions). Six species of halophytes were found in the deeper soil layer in low numbers. These species may have been present in the depot where the mud originated from or arrived during the construction of the salt marsh and were buried in the soil during construction. *Phragmites australis* most likely arrived with rhizomes already present in the mud, because multiple chunks of soil with rhizomes were observed partially buried in the top layer. Most other halophytes did manage to reach the newly developed salt marsh through wind and water dispersal or clonally by plant parts (such as bulbs of *Bolboschoenus maritimus*).

Table 5-5 Plant species germinated from soil collected in the deeper soil layer (~40 cm depth) and the top layer (top 4 cm) in the climate chamber under controlled environmental conditions. The number of soil samples where that specific plant species germinated is given with the total number of individuals given in brackets. For comparison, the number of plots that same species was found in the field is given in the right column. The seeded Salicornia procumbens is excluded from the seeded permanent plots. Halophytes are shown in grey.

Plant species	40 cm depth	Top 4 cm	Permanent plots
Chenopodium sp.	16 (30)	13 (33)	0
Ranunculus sceleratus	10 (15)	8 (10)	0
Urtica sp.	4	4	0
Rumex sp.	0	1	0
Plantago major	1	1	0
Unidentified grasses	6	4	0
Unidentified seedlings	2	1	0
Spergularia maritima	7 (7)	4 (6)	4
Atriplex prostata	2	3	1
Aster tripolium	2	1	2
Phragmites australis	2	1	1
Juncus gerardii	1	1	0
Salicornia europaea	1	1	14
Puccinellia martima	0	0	2
Puccinellia distans	0	0	5
Suaeda maritima	0	0	2
Bolboschoenus maritimus	0	0	5

5.5.2. Vegetation diversity and density

Within two years a pioneer vegetation had established on the salt marsh (Figure 5-33). The vegetation cover has increased on the salt marsh with 28 ± 2.6% between 2019 and 2020 (Figure 5-34). Sediment composition had a significant effect on vegetation cover, which increased with mud content (Figure 5-34; Table 5-6; Table 5-7). Despite the significant effect of mud percentage on cover in 2019, there was no significant difference between the different groups. For 2020 the effect of mud percentage is stronger and there is a significant difference between the 50% and 0 – 5% mud (PQ and random plots: 50% - 5%: $p = 0.020$, 50% - 0%: $p = 0.048$) and for the PQ plots all mud fractions were significantly different (PQ plots: 50% - 5%: $p < 0.001$, 50% - 20%: $p = 0.036$, 20% - 5%: $p = 0.013$). Overall, we can conclude that the vegetation cover is lower at 5% mud content. The results were similar when we analysed the effect of the measured mud content, with a higher mud content the vegetation cover was higher.

Contrary to our expectation, seed treatment only resulted in a significant difference for the PQ's in 2019 (Table 5-6), which indicates that the effect of seeding was only temporary. In 2020, there was a significant relationship between the sediment dynamics and vegetation cover. In plots with high erosion rates (>2.5 mm/month) no vegetation was present, which was mainly found in compartments F and G. The salt marsh park had highest cover in 2019 and 2020 compared to the pioneer salt marsh. However, vegetation cover was only measured in a few plots and may not represent the entire park.

Figure 5-33 View of the vegetation at the Marconi salt marsh pilot in September 2020.

Figure 5-34 Vegetation cover for 2019 and 2020, separated for the different compartments. The different colours indicate the seed treatment. The number of plots for each compartment are different since this data are the 27 permanent plots (PQ's) and extra random plots (2019 = 40, 2020 = 35)

Table 5-6 Statistical models for total vegetation cover, species richness and cover of Salicornia sp of the PQ and random plots combined. The models used are anova's, except for species richness which was analysed with a generalized linear model with a poison distribution. For the vegetation cover F-values and for the species richness chi-squared values are shown. This is only the data from the pioneer salt marsh and not the salt marsh park.

PQ's + random plots	**Vegetation cover**		**Species richness**		**Cover *Salicornia sp.***	
Factors	*2019*	*2020*	*2019*	*2020*	*2019*	*2020*
Seed treatment	2.35	0.75	5.56*	0.15	6.12*	12.93***
Mud percentage	2.89*	4.54**	24.69***	18.65***	2.83*	8.60***
Surface elevation	1.87	1.41	10.55***	34.96***	3.58•	1.69
SEB dynamics	-	-	-	-	-	-
Species	-	-	-	-	0.46	22.78***
Samples	61	57	61	57	122	114

Abbreviation: • < 0.1, * < 0.05, ** < 0.01, *** <0.001

Table 5-7 Statistical models for the total vegetation cover for only the PQ plots. The models used are anova's, where the F-values area shown.

PQ's	**Total vegetation cover**			
Factors	*Intended mud percentage*		*Measured mud percentage*	
	2019	*2020*	*2019*	*2020*
Seed treatment	6.79*	0.01	7.44*	0.01
Mud percentage	3.59*	16.82***	9.23**	35.81***
Surface elevation	0.12	2.81	0.13	2.96
SEB dynamics	1.20	8.10**	0.99	8.41**
Samples	27	27	27	27

Abbreviation: • < 0.1, * < 0.05, ** < 0.01, *** <0.001

The species richness increased between 2019 and 2020 (Table 5-8) and it mainly consisted of pioneer or lower salt marsh species (see Figure 5-35 for photos of some of the species). The species richness was significantly related to compartment, seed treatment and surface elevation in 2019 (Table 5-6). In 2020, surface elevation and mud percentage had a significant effect on species richness. More species were present at higher surface elevations, most likely due to higher inundation frequencies and stressful conditions at lower surface elevation. The relationship between surface elevation and species richness was much stronger in 2020, indicating that the salt marsh has developed further than previous year (Figure 5-36). The presence of specific plant species can also give an insight in the future development of the pioneer marsh. For example, in some plots *Phragmites australis* (Reed) was present and it is to be expected that in the future *P. australis* will increase in cover and that the salt marsh close to the dike will become dominated by *P. australis*.

Table 5-8 Most common plant species for the salt marsh park and the Marconi pioneer salt marsh with maximum cover (%) within one plot (2 m x 2m). The order of the species is based on the number of plots they were present. All plant species presented here are typically found in the pioneer zone and lower salt marsh.

Salt marsh park				**Marconi pioneer salt marsh**			
2019 (12 species)		2020 (17 species)		2019 (14 species)		2020 (17 species)	
Plant species	Max. cover (%)	Plant species	Max. cover (%)	Plant species	Max. cover (%)	Plant species	Max. cover (%)
Atriplex prostata	30	*Salicornia europaea*	40	*Salicornia procumbens*	50	*Salicornia europaea*	50
Salicornia europaea	30	*Salicornia procumbens*	70	*Salicornia europaea*	30	*Salicornia procumbens*	50
Suaeda maritima	7.5	*Spergularia sp.*	30	*Bolboschoenus maritima*	30	*Suaeda maritima*	30
Triglochin maritima	7.5	*Puccinellia distans*	20	*Atriplex prostata*	30	*Spergularia sp.*	40
Spergularia sp.	7.0	*Suaeda maritima*	10	*Suaeda maritima*	20	*Puccinellia distans*	10

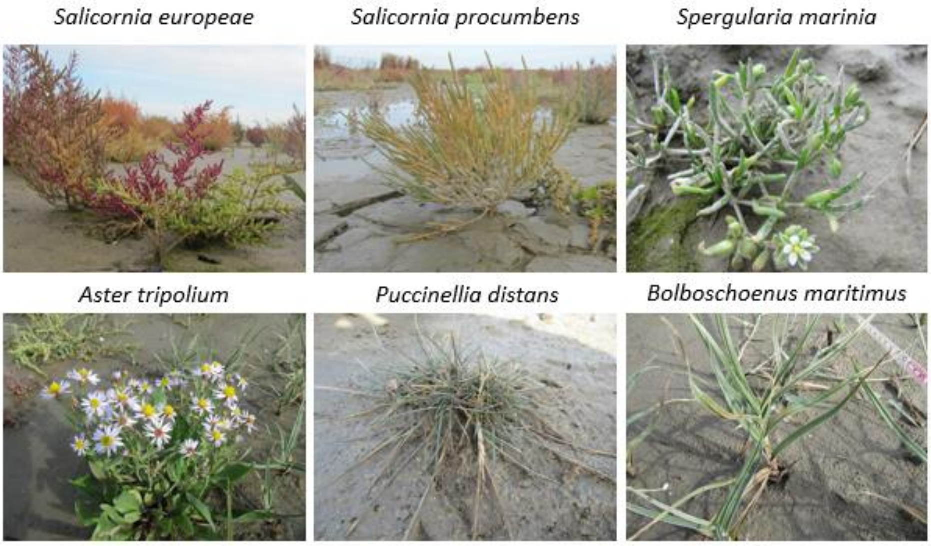


Figure 5-35 Photos of different vegetation species that were observed at the Marconi salt marsh.

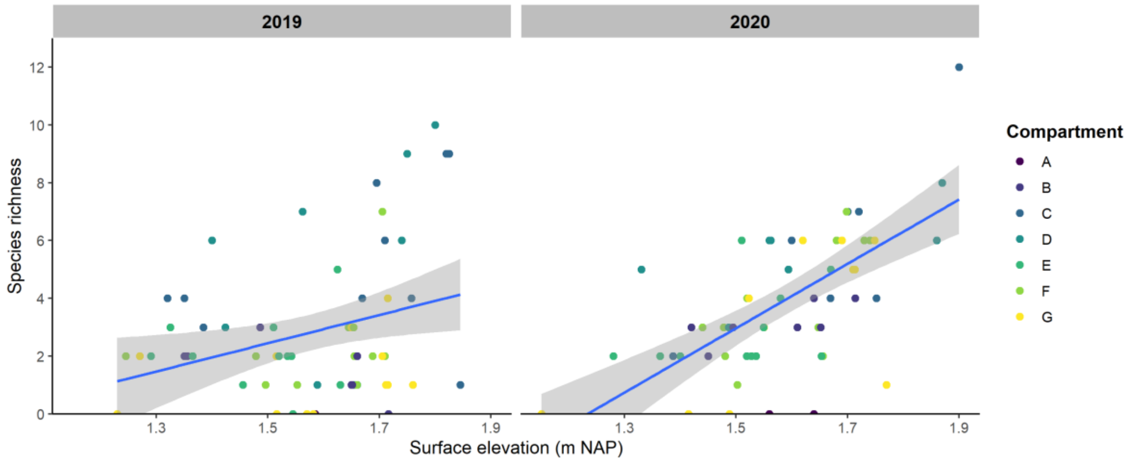


Figure 5-36 The relationship between surface elevation and species richness for 2019 and 2020. The colours indicate the different compartments. The blue line is a linear fit and the shaded area around is the confidence interval of the mean. Fit 2019: $y = -1.98+1.89x$, $p < 0.001$, Nagelkerke's $R^2 = 0.22$; 2020: $y = -3.40+2.95x$, $p < 0.001$, Nagelkerke's $R^2 = 0.62$.

In the pioneer salt marsh two species of *Salicornia sp.* were present: *S. procumbens*, which was seeded, and *S. europaea*, which established naturally. In 2019, *S. procumbens* primarily occurred in the seeded compartments (Figure 5-37). In 2020, *S. procumbens* still had the highest cover in the seeded compartments, however the cover of *S. europaea* also increased here. In a natural salt marsh, *S. procumbens* and *S. europaea* occur in different marsh zones. *S. procumbens* typically occurs at lower elevations near the edge of the salt marsh in the pioneer zone. Whereas, *S. europaea* typically occurs within the salt marsh at higher elevation with locally with poor drainage and relative high soil salinities. The pioneer salt marsh studied here is relatively young, and therefore this pattern will be less clear, although in 2020, *S. procumbens* already has a significant higher cover at lower surface elevations (Figure 5-38). This relationship may become more evident in the future.

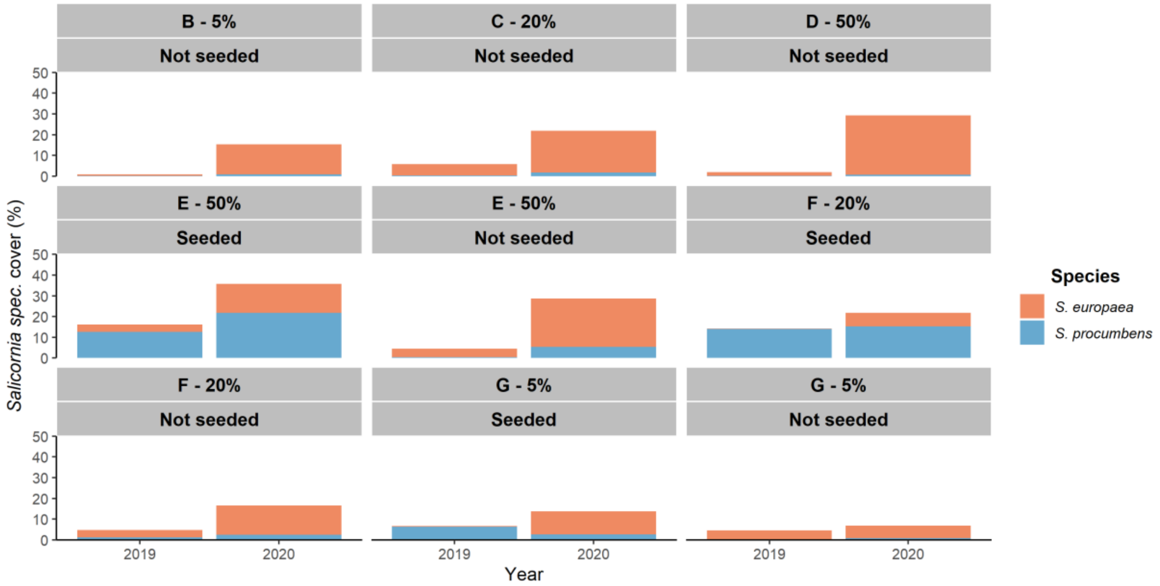


Figure 5-37 Salicornia sp. cover (%) for the different compartment and seed treatment. The colours indicate the two different species S. europaea and S. procumbens.

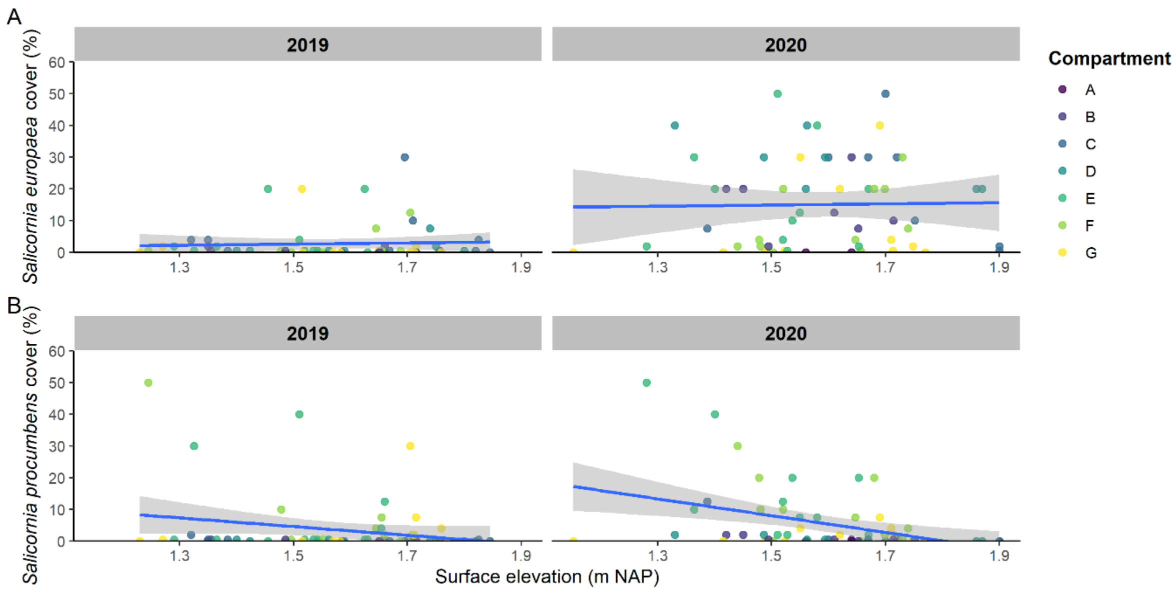


Figure 5-38 The relationship between surface elevation and the cover of A) Salicornia europaea and B) Salicornia procumbens in 2019 and 2020. Different colours represent different compartments. The blue line is a linear fit and the shaded area around it is the confidence interval of the mean. Fit: S. europaea 2019: y = -0.125+1.82x, p = 0.71, adj. R^2 = 0; S. europaea 2020: y = 12.2+1.84x, p = 0.89, adj. R^2 = 0; S. procumbens 2019: y = 25.1+-13.7x, p = 0.083, adj. R^2 = 0.03; S. procumbens 2020: y = 47.7 + -26.4x, p = 0.002, adj. R^2 = 0.14.

5.5.3. Salicornia growth and biomass

After the seeding, the seeds did not germinate immediately. The number of *Salicornia spec.* plants showed an increase after 1.5 month of the seeding in half July (Figure 5-39). *Salicornia spec.* plants start late in the growing season, however it was not expected that the seeds would be dormant for 1.5 months in the growing season. The number of *Salicornia spec.* plants in the non-seeded compartments were much lower compared to the seeded compartment and did showed little increase over time (Seed treatment x Date: $X^2_{(1,\ N=870)} = 98.14$, $p < 0.001$). The highest mud percentage had also the highest number of *Salicornia spec.* plants ($X^2_{(2,N=870)} = 27.42$, $p < 0.001$).

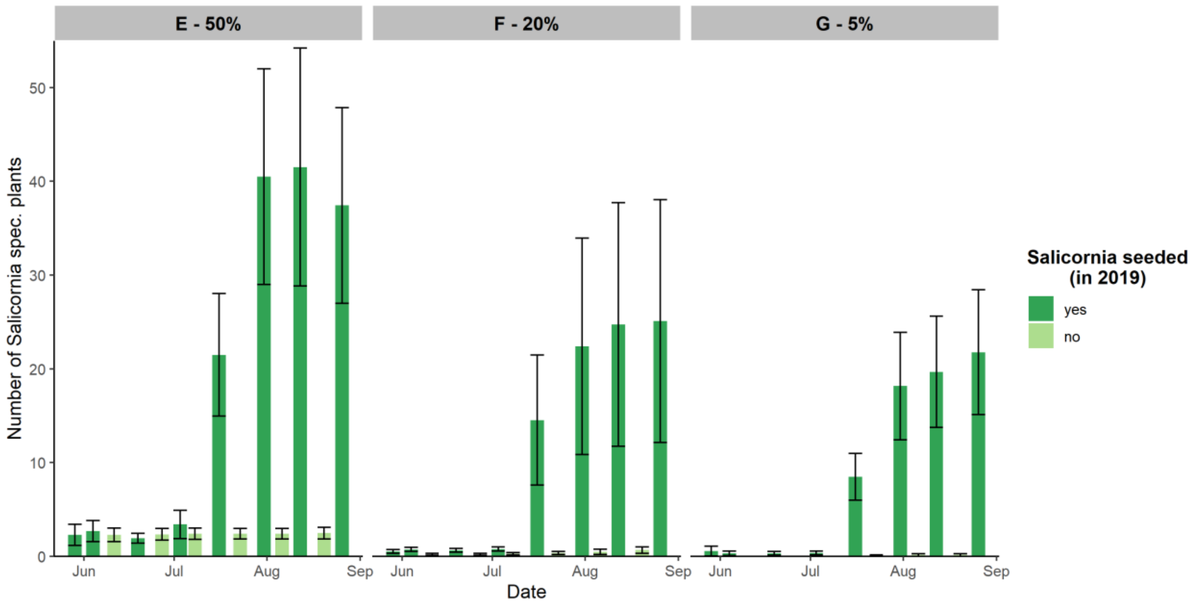


Figure 5-39 The number of Salicornia spec. plants over time in the first growing season for the three different compartments E, F and G and the seed treatment.

The number of plots where *Salicornia* was observed during 13 weeks in June and July in the seeded area was 62 of the 75 plots (83%) (Figure 5-40). The remaining 13 plots showed no *Salicornia* presence at all during the test period. Of the non-seeded control areas only 16 of the 45 plots showed presence of Salicornia (35.6%). The presence of *Salicornia* in the plots was dependent on mud percentage $X^2_{(2,\ n\ =\ 120)} = 12.53$, p=0.002 and on the seed treatment $X^2_{(1,\ n\ =\ 120)} = 27.44$, p<0.001. The biomass data shows that in contrast to the data above, there was no difference in *Salicornia* biomass between the seed treatments for the 50% mud compartment (Figure 5-41). The non-seeded *Salicornia* plants were almost all *S. europaea*, which were much more branched and had higher biomass compared to *S. procumbens.* For the two other compartments the difference in biomass between the seed treatment is, however, very clear.

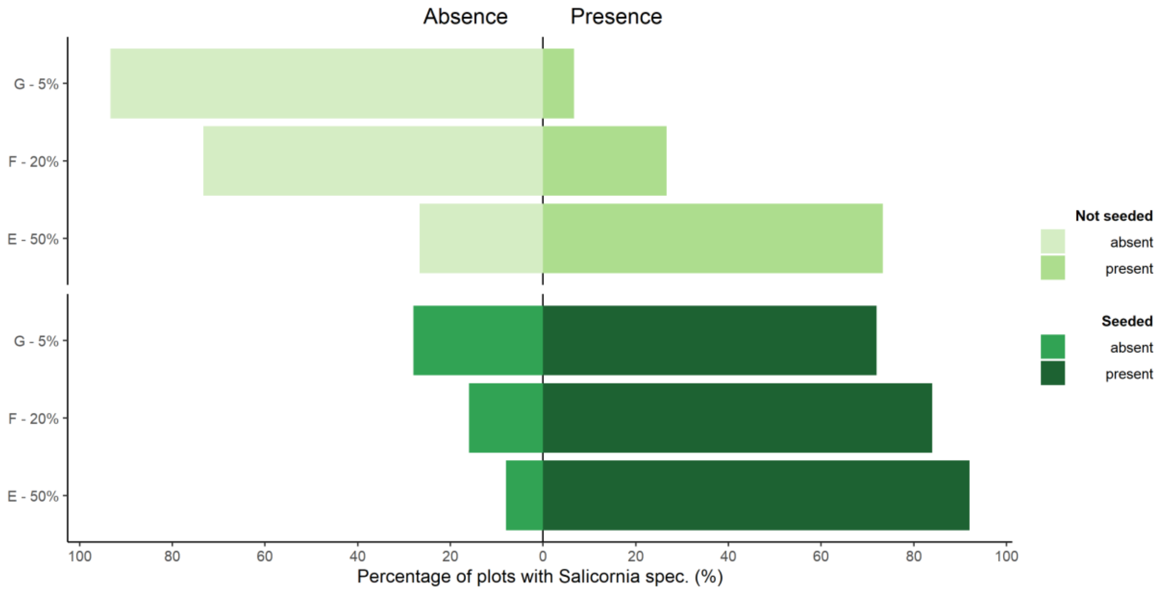


Figure 5-40 Presence and absence of Salicornia spec. in the 120 additional plots, separated for the different compartments and seed treatment.

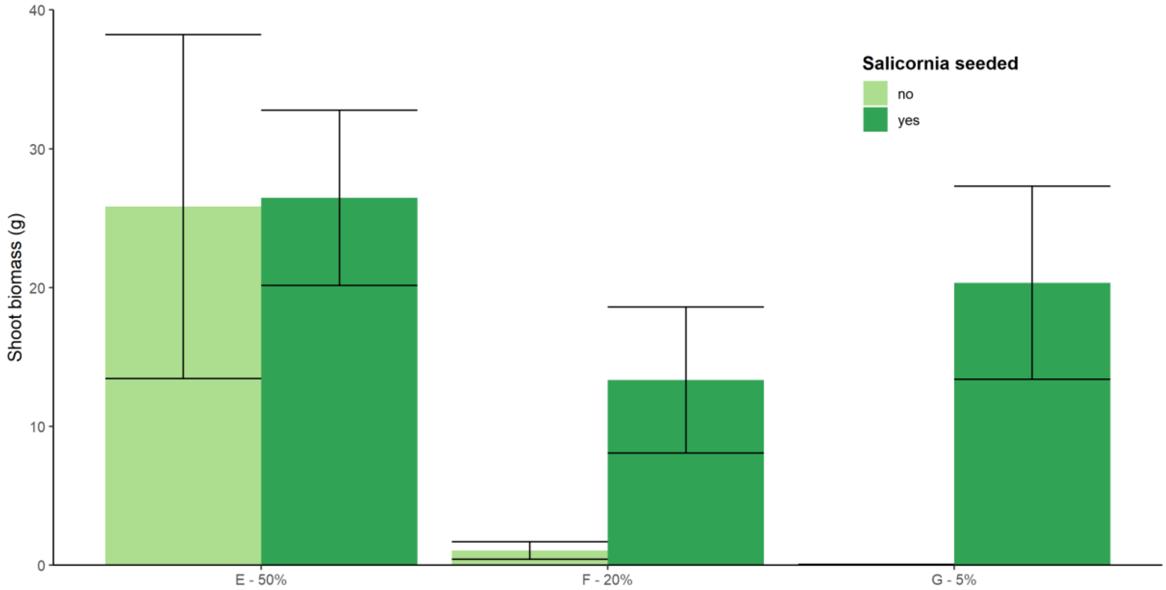


Figure 5-41 Salicornia spec. biomass (grams) for the different compartments and seeding treatment.

5.5.4. Vegetation classification orthophoto

The vegetation cover over the whole Marconi salt marsh was very low in September 2019 (Figure 5-42; Appendix 7 and 8): the compartment with the highest cover only had a vegetation cover of 1.5 percent. The compartments with 0-5 percent mud had the lowest vegetation cover, while the vegetation cover in the compartments with 20 and 50 percent mud was similar. In contrast to the results presented in Section 5.5.2, there is no difference in vegetation cover between the seeded and not seeded compartments in the orthophoto, because the small *S. procumbens* was not visible in the orthophoto.

In September 2020, the vegetation cover increased up to almost 50 percent. Like in 2019, compartment G with 0-5 percent mud has a low vegetation cover compared to the compartments with more mud. Almost no vegetation was present on top of the sandbar in compartment G, while some vegetation was present landward of the sandbar. In contrast to compartment G, the vegetation cover in the other compartment with 0-5 percent mud (B) has become similar to the cover in compartments with higher mud percentages. This may be related to the fact that compartment B is more sheltered, and the grain size data indicate that fine sediment has been deposited in 2019 and 2020, which makes it more suitable for vegetation growth. Compartment E is the only compartment where a clear difference is observed between the seeded and non-seeded section. This difference is probably not caused by the seed treatment, but caused by the presence of the sandbar which has a very low vegetation cover (Figure 5-43; see also Appendix 7 and 8). In the other compartments the effect of seeds treatment is neglectable. The vegetation occurred mainly inside the compartments, only in compartment X some vegetation was present in front of the compartment. The surface height within a compartment did not strongly affect vegetation development, as vegetation did occur above and below the mean high-water line. In areas with standing water vegetation did not develop.

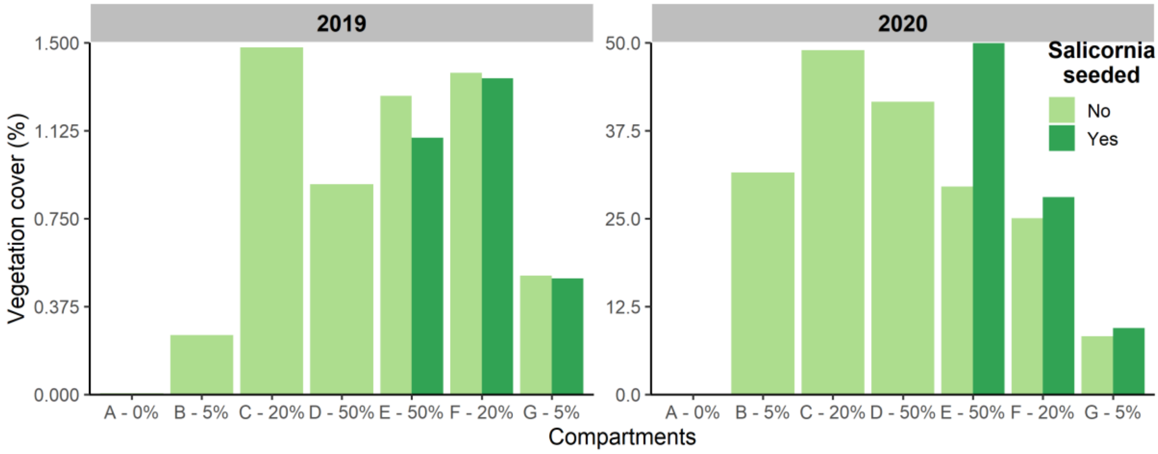


Figure 5-42 Vegetation cover in the different compartments and seed treatments in September 2019 and September 2020. The y-axes have different scales.

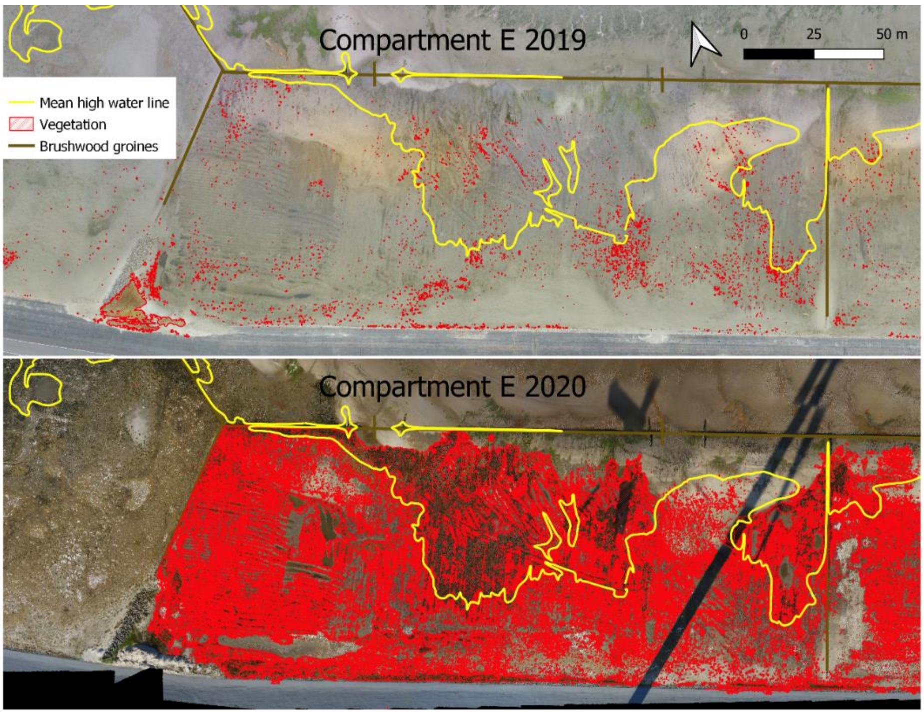


Figure 5-43 Classified vegetation (red) for compartment E for September 2019 and September 2020. In 2020 the vegetation cover is much higher compared to 2019. Low vegetation cover on the sandbar in the upper right corner of the compartment. Vegetation occurs below and above the mean high water line (yellow).

5.5.5. Microphytobenthos density

The microphytobenthos density was measured five times in spring and summer: May, June and September in 2019 and June and September in 2020. Three types of microphytobenthos were measured: diatoms, cyanobacteria and green algae. Diatoms were most common (0.49±0.04 µ chl-a/cm2 (mean±se)), followed by cyanobacteria (0.22±0.03 µ chl-a/cm2 (mean±se)). Green algae had the lowest density (0.03±0.006 µ chl-a/cm2). Since we measured in spring and summer, there is no seasonal effect of the microphytobenthos density visible. However, density was in general highest in September at the end of the growing season (Figure 5-44).

When the microphytobentos density was analysed with the intended mud percentage as explanatory variable, mud percentage had no significant effect ($F_{2,24} = 3.17$, $p = 0.06$), and there was a significant effect of surface elevation ($F_{1,101} = 4.01$, $p = 0.04$), where the density was higher at lower surface elevation. However, when instead of the intended mud percentage, the actual measured grain size was used in the statistical model, there was a significant effect of grain size on microphytobenthos ($F_{1,105} = 18.57$, $p < 0.001$). With increasing mud content there is a higher microphytobenthos density (Figure 5-45).

The results indicate that at location with a higher mud percentages and at a lower elevation the microphytobentos density might be higher. Since microphytobenthos stabilises the sediment and reduces erosion (Stal, 2010), the presence of the microphytobenthos is beneficial for further salt marsh development.

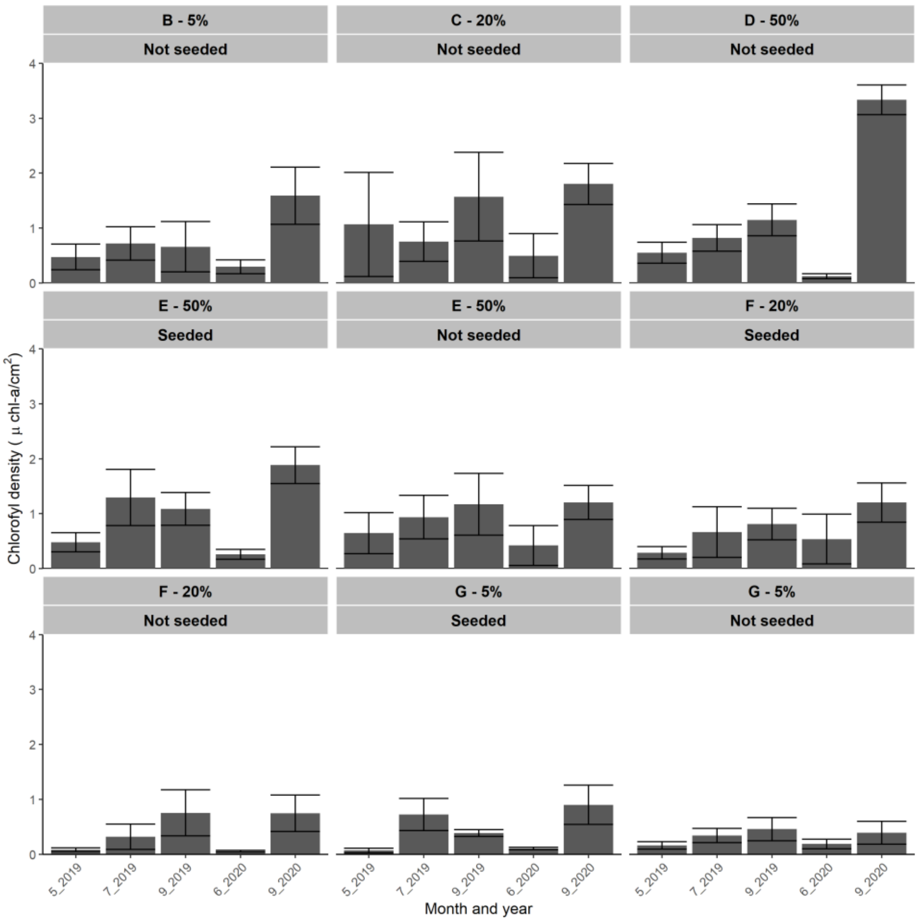


Figure 5-44 Microfytobenthos density (µ chl-a/cm²) for each compartment for each time of measurement.

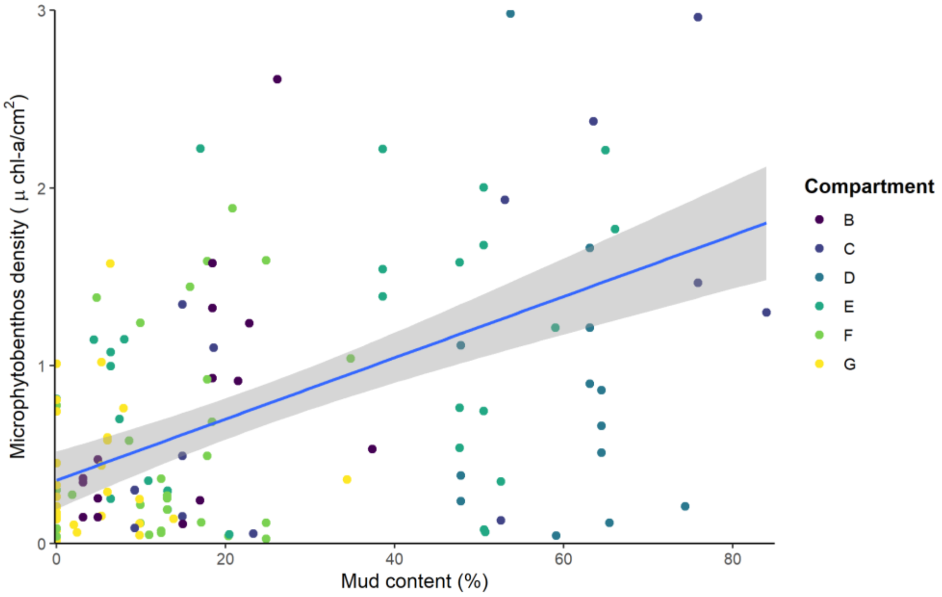


Figure 5-45 Relationship between mud content (%) and microphytobenthos chlorophyll density (µ chl-a/cm²). Different colours represent different compartments, the blue line is a linear fit and the shaded area around is the confidence interval of the mean. Fit: y = -1.34 + 0.021x, p <0.001, adj. R^2 = 0.16

6. Discussion, conclusions and lessons learned

6.1. The salt marsh pilot project

Salt marshes were constructed along the coast of Delfzijl (Netherlands) as part of the project Marconi Buitendijks. The project consists of a pilot salt marsh of 15 hectares, a bird breeding island and a salt marsh park (city salt marsh) of 13 hectares. The pilot salt marsh along the coast of Delfzijl was constructed with three main goals:

- Create a natural land-water boundary to improve ecosystem quality;
- Develop knowledge on how to design and construct a pioneer salt marsh at a location that is not suitable yet for salt marsh development;
- Develop knowledge on the way in which design and construction affect the development of a man-made salt marsh.

The pilot salt marsh consists of six compartments with three different percentages (5%, 20% and 50%) of mud (fraction <63 µm) in the upper metre of the subsurface. Some of the compartments were seeded with *Salicornia procumbens* (Long-spiked Glasswort). The development of the salt marsh was intensively monitored between November 2018 and September 2020.

The salt marsh pilot project has delivered a thriving salt marsh at a location where the natural development of a salt marsh was not possible. In addition, our understanding of the critical factors for salt-marsh development has improved and we have learned valuable lessons for the applicability of monitoring techniques.

Salt marshes in a broader context

Salt marshes are important coastal habitats that provide nature-based protection against waves (e.g. Möller et al., 2014, Willemsen et al., 2020), sequestrate carbon (e.g. Duarte et al., 2013), provide important habitats for birds and fish (e.g. Irmler et al., 2002) and facilitate growth with sea level rise (e.g. Kirwan et al., 2016). The importance of salt marshes has long been recognised and man-made salt marshes have been constructed for centuries (Elschot et al., 2020). The design of the salt marsh pilot was based on a common method used around the Dutch Wadden sea for enhancing salt marsh development: constructing brushwood groynes to reduce wave impact, create a sheltered area, drain the new land and increase sedimentation rates (Elschot et al., 2020). Once the elevation is sufficiently high and hydrodynamic exposure resulting in bed level change sufficiently low (Willemsen et al., 2018), vegetation can grow in the compartments enclosed by brushwood groynes. Generally, after 1 or 2 decades, the conditions are suitable for vegetation to develop (Elschot et al., 2020). The pilot salt marsh differs from this traditional method in that a sediment base was constructed at an elevation suitable for vegetation to establish. This approach drastically decreases the time necessary to obtain the right elevation for vegetation growth.

Although increasing the bed elevation and constructing brushwood groynes resulted in successful establishment of pioneer vegetation, multiple other methods can be considered for promoting the development of salt marshes: de-embankment of historically reclaimed salt marshes (Bernhard & Koch, 2003; Wolters et al., 2005), for example by removing a part(s) of the most seaward dike or seawall, also known as managed realignment (Mazik et al., 2007); Creating flood control areas (FCA), where the tide is controlled and reduced using sluices in a dike (Maris et al., 2007; Broekx et al., 2011); increasing the sediment availability in existing marshes or in nearby channels using dredged material (although this method has not proven to be fully successful at the test location (Baptist et al., 2019); deploying dredged material directly at a location for salt marsh development (Shafer et al., 2000; Yozzo et al., 2004). Nevertheless, the method used for the development of the Marconi salt marsh at Delfzijl might be ranked as one the quickest methods for salt marshes to develop, since pioneer vegetation was observed in all compartments a single year after construction.

The following three paragraphs present the discussions and conclusions on morphology, ecology and their interaction. They are followed by a paragraph about the insights with regard to monitoring and the lessons learned on salt-marsh development.

6.2. Morphological development

Within a year, the foreshore developed from a bare tidal flat to an area with a succession of vegetation species, less vegetated area and bare flats intersected by tidal creeks and channels. The measurements and field observations resulted in several insights in the morphological development.

6.2.1. Combine techniques to gain insight in morphological change

Morphological change was observed using different techniques with a broad range in spatial and temporal resolution. Elevation measurements fully covering the salt marsh were obtained bi-yearly, point measurements of the bed level were systematically obtained at multiple locations every 2, 3 or 6 months and continuous measurements were collected at 9 locations. The combined set of measurements captured different morphological dynamics, e.g.: fully covering the marsh to assess the development of tidal creeks and water retaining volume, point measurements to systematically assess and compare the development of compartments with SEBs (e.g. Baptist et al., 2019) and continuous measurements with ASEDs to enable assessing the short-term bed level change that drives the establishment of vegetation (Bouma et al., 2016; Willemsen et al., 2018).

6.2.2. The salt marsh as a sediment trap

Coastal environments such as salt marshes can function as sediment traps and can decrease the turbidity in the surrounding water and grow, to a certain extent, with sea level rise (e.g. Kirwan and Megonigal, 2013; Willemsen et al., 2016). The observations of the bed level at Marconi did not show a clear net increase, or decrease, of salt marsh elevation. However, indications for positive bed level change (i.e. net deposition, even with subsidence of the bed), were found in the ASED data in the growing season (Figure 5-23). Furthermore, in compartments B, C and D, the sediment in the upper centimetre became finer over time, indicating deposition of fine sediments (Table 5-4). The average sediment characteristics of the top layer in compartments E, F and G did not show a consistent trend. This is mainly due to due to sandbar dynamics in these compartments at the seaside.

It seems that there is a balance between sedimentation and erosion/subsidence in the Marconi salt marsh. The fact that observations of the bed level change and sediment characteristics did not explicitly highlight sediment deposition is at least partly related to the fact that the some of the techniques measured the net effect of sedimentation, erosion and subsidence instead of sedimentation alone. Because subsidence and erosion rates could not be significantly observed at mm/yr accuracy, the sedimentation rate (expected to be in the order of mm/yr) cannot be deduced from the measurements. Longer term monitoring is needed to determine the functioning of the pilot salt marsh as sediment trap.

6.2.3. Tidal creek development

One of the goals of the pilot was to monitor tidal creek development and determine the driving factors of the morphological development of tidal creeks. The formation of a creek system is important for the supply of sediment and nutrients, drainage of the salt marsh (Dijkema et al., 2001; Van Duin and Dijkema, 2012) and creeks are valuable habitat for example as they serve as nursery for juvenile fish (e.g. Minello, 2003). Drainage via a creek system affects growth of salt marsh vegetation species and promotes succession (Van Loon-Steensma et al., 2012). The amount of sedimentation at a location in the salt marsh decreases with distance from a creek (Dijkema et al., 2007). Earlier salt-marsh restoration sites have shown that tidal creeks are able to develop from a constructed artificial tidal creek (D'Alpaos et al., 2007). In the pilot salt marsh it was decided not to use artificially constructed tidal creeks but to let nature take its course. However, the tire tracks might have served as artificial tidal creek initiators at some locations.

The construction of a tidal inlet by brushwood groynes did not always force the development of tidal creeks through that tidal inlet. Tidal creeks developed in all compartments except G, both at the landward and seaward side of the brushwood groynes. Tidal creek formation already started before the brushwood groynes were constructed. Only through the inlet of compartment B and D a tidal creek formed. Other tidal creeks run through the permeable brushwood groynes. The presence of initial channels before the construction of brushwood groynes seems to be a driving factor for tidal creek development. Based on the observations we can conclude that the storage volume of the compartment, shelter from waves (waves can form sandbars that block tidal creeks and sediment transport by waves can result in infilling of tidal creeks) and the presence of fine sediment may all play a role in tidal creek formation and development. The relative high elevation of the salt marsh probably slowed down the tidal creek developments as this results in a lower volume of water flowing in and out of the salt marsh each tide.

Time is probably also an important factor in tidal creek development, and the monitoring period of two years is relatively short. In the more exposed compartments (E, F and G) several small tidal creeks have developed. Recent observations (November 2020) show the tidal creek cutting through the sand bank. In due time these tidal creeks might evolve towards larger and more interconnected tidal creek networks. Longer term monitoring can increase the understanding about the factors that influence the (possible) evolution towards more interconnected creek networks and the effect of creek networks on the overall salt marsh development.

6.2.4. Development of sandbars

Sandbars formed and migrated in the high-water swash zone of the southern compartments E, F and G. This was not anticipated. This kind of sandbars did not form in the western compartments, probably because the western compartments were sheltered from waves by the riprap groyne, a submerged sandbar and because of the larger tidal flat in front of these compartments.

The sandbar was already present before construction of the groynes. After construction of the brushwood groynes, the sandbar became less pronounced in compartments E and F but developed further in compartment G where a second bank developed seaward from the initial sandbar (Appendix 2 and 3). This difference might be related to various factors such as slight differences in exposure, the lower bed level at the brushwood groynes in compartment G and differences in the amount of brushwood still present in the brushwood groynes.

Whether the construction and presence of the brushwood groynes influenced the sandbar development and vice versa is not known. It is likely that the brushwood groynes alter the hydrodynamics in such a way that this affects the sandbar. The sandbar mimics cheniers that sometimes can be found in intertidal areas at a larger spatial scale (Augustinus, 1989). The development of cheniers can have a positive effect on vegetation development (Tas et al., 2019).

However, a migrating sandbar may also cause burial of established vegetation. The future influence of both the sandbar and brushwood groynes on the development of the vegetation may provide useful information on the need for constructing brushwood groynes in case sandbars form.

6.2.5. Subsidence lower than expected

Subsidence rates were monitored because compression of low energy intertidal sediments is poorly understood (Brain et al. 2011). At the salt marsh, 30 cm subsidence was expected over the initial 3 years after construction. Bed level change including subsidence was measured with LiDAR (all changes), SEBs (changes in the top 1.4 m), ASEDs (changes in the top 50 cm to 75 cm) and RTK DGPS measurements of the SEB poles (subsidence below 1.4 m depth) and of the poles of the brushwood groynes (subsidence below 3.0 m depth). The expected subsidence rate was not observed: the subsidence was in the order of centimetres only (Figure 5-31; Figure 5-32). The subsidence rate was generally in the margin of error of the measurement instruments and in the same range as the expected deposition. This made it impossible to allocate bed level change to either subsidence or deposition of sediments

6.3. Vegetation development

The presence of vegetation in a salt marsh is normally determined by the result of a balance between bed elevation (i.e. inundation time and frequency), hydrodynamic exposure, sediment characteristics and seed availability (Balke et al., 2016; Bouma et al., 2016; Willemsen et al., 2018). Here we discuss the influence of bed elevation, hydrodynamic exposure and seed availability on the vegetation development at the pilot salt marsh. The effect of sediment characteristics is discussed in Section 6.4.

6.3.1. Elevation and hydrodynamic pressure

At the pilot salt marsh, vegetation developed almost only within the compartments enclosed by the brushwood groynes. The areas seaward of the brushwood groynes have a lower elevation and are therefore inundated more often and longer. This indicates that probably inundation frequency is, also in this project, an important factor in vegetation development. We expect that the sheltering effect of the dams also helps in vegetation development (c.f. Callaghan et al., 2010; Van der Wal et al., 2008; Willemsen et al., 2018), but this cannot be concluded from our results.

6.3.2.Seeding

Part of the research focussed on the effect of adding seeds to the top layer of the pioneer salt marsh in order to see whether this influenced the speed of development of the marsh. Several studies indicated that seeds could be limiting in the pioneer zone (Morzaria-Luna & Zedler 2007, van Regteren et al. 2019, Wolters et al. 2005, Zhu et al. 2014). Therefore, seeds were added in several compartments to the top layer of the marsh.

The monitoring results showed that in the Marconi case seeds of pioneer salt marsh plants were not limited. At least 16 plant species managed to establish naturally at the salt marsh. The seed treatment had a positive effect on vegetation cover in the first growing season after seeding. In the second year this effect was no longer present. Moreover, *S. procumbens,* which was seeded, was not common outside the seeded compartments while *S. europaea,* which was not seeded, was common in all compartments from the second year onward.

The consolidated mud that was used to improve the top layer of the pioneer salt marsh had been resting in a land located deposit for some years. As a result, this consolidated mud had a seedbank (= seeds that are present in the soil) that mainly consisted of freshwater species. The plants that developed at the Marconi pioneer salt marsh, however, were mainly saltwater species. This means that the seeds must have come in with water or wind dispersion from nearby salt marshes. The salt marsh closest to Marconi is 'Punt van Reide' at 10 km from Marconi. This distance does not seem to be a problem for seed dispersal of at least some species. This agrees with Wolters et al (2005) who found that even for de-embankments with a seed source distance of 80 km, 30% of the species in the local species pool had established. However, Wolters et al (2005) also indicated that sites that are far away from the seed source, could have a lower species number even after 20 years. Further monitoring of the salt marsh will indicate if this is the case for the pioneer salt marsh on Marconi.

6.3.3. Future vegetation development of the salt marsh

It is expected that in the next five years the pilot salt marsh will develop further. Most likely, the vegetation cover will increase to between 50 and 100 percent. The different mud compartments will have different species compositions, since nutrient availability affects salt marsh succession. The presence of reed in compartment D does indicate that the area close to the dike will probably be dominated by reed in the future. More seaward, a lower salt marsh vegetation will probably develop with *Puccinellia spec.*, *Sueada maritima* and *Salicornia spec.* Overall, it can be stated that the used method of salt marsh construction makes it possible to create a salt marsh in a very short time period. It would be interesting to monitor the actual succession of the vegetation in the future, especially since the vegetation development affects the amount of mud deposition in the salt marsh.

6.4. Interaction between morphology and vegetation

In salt marshes morphology and vegetation influence each other and some specific interactions are mentioned here.

6.4.1. Sediment dynamics and seed availability

Seed availability has been found to be limited by sediment dynamics (van Regteren et al. 2019). Sedimentation or erosion of the sediment will cause the seeds to be either buried and unable to germinate or eroded away with the sediment. However, the bed level at Marconi was relatively stable and not very dynamic. This supports the fact that at Marconi there were no issues with germination of seeds.

6.4.2.Mud percentage and vegetation development

We hypothesized that different sand/mud mixtures affect the presence of seeds and the growth of plants (Houwing et al. 1999, Olff et al. 1997). Therefore, in the pilot project, we used different percentages of mud in the top layer to investigate this hypothesis. The monitoring results showed that vegetation cover and species richness were highest in the compartments with a higher mud percentage (20% and 50% mud). The positive effect of a higher mud percentage on vegetation can have multiple reasons:

- First, a higher mud content in the soil reduces erosion (Houwing et al, 1999). Soils with less than 20% mud are considered as non-cohesive soils and have a lower resistance to wave and current erosion. Washing away of seeds and seedlings by waves and currents has been found to be the cause of substantial seedling mortality (Houwing et al. 1999, Wiehe 1935, van Regteren et al. 2019). However, in general, bed level changes were rather low in the Marconi salt marsh indicating that erosion was probably not the main driver of differences in vegetation cover in the various compartments. Compartment G was an exception in this. As the sandbar moved into this compartment it suffered from erosion rates up to 4 cm in 2020. This resulted in a very low vegetation cover or no vegetation at all.

- Another explanation for the difference between the compartments with 5% mud and 20% and 50% mud is that soils with higher mud content have a better retention soil moisture (Crawford & Stone, 2014). Lower soil moisture could especially affect the germination of seedlings, as during that stage plants are less stress resistant. It is unknown if this had an effect at the Marconi salt marsh. It is however a reasonable explanation as the summers of both 2019 and 2020 were relatively dry, giving an advantage to the compartments with a better soil moisture content.
- Finally, the difference between the different compartments could also be caused by the lower availability of nutrients. Nutrient availability has been known to affect plant growth and vegetation succession (Kiehl et al. 1997, van Wijnen and Bakker 2001, van Ollf et al. 1997). On the Marconi salt marsh however, it is unclear if there is an effect of nutrient limitation on vegetation establishment.

Overall, the lower vegetation cover and species richness is most likely caused by a combination of these three effects.

It was apparent that in compartment A hardly any vegetation was present. This is a further indication that the absence of mud hampers vegetation development. The causes for the absence of vegetation in that specific compartment are not clear, in this compartment no PQ's were present and there is no data available on local sedimentation or erosion. The LiDAR data do show some bed level lowering, this could be due to subsidence.

6.4.3. Dynamic sandbars hampered vegetation growth

The presence of a sandbar was already mentioned earlier. The sandbar moved into some of the compartments and had a clear influence on the vegetation development in these compartments. In compartment E, F and G (Figure 5-43, Appendix 7) vegetation was not able to grow, either due to bed level dynamics exceeding certain thresholds (Houwing et al, 1999, Poppema et al., 2019) or because sand is a less suitable substrate for vegetation development (Crawford & Stone, 2014).

6.4.4. A homogeneous vertical layer and vegetation development

The upper metre of the subsurface was mixed with mud during the construction of the salt marsh. This was mainly done in order to monitor the morphological development of tidal creeks. As plants generally only root in the top 30 cm of the soil, this mixing of mud in the upper 1 m was not expected to be necessary for vegetation development. This was proven at the salt marsh park where only a small layer of mud was placed over the sandy subsurface and still the vegetation flourished. The vegetation cover at the salt marsh park even seemed to be higher than in the pilot salt marsh, however the random vegetation plots might not be good representation for the whole salt marsh park. The results do seem to indicate that only adding a layer of mud on top is adequate for vegetation development. This method is consistent with the natural development of salt marshes at back-barrier islands. These salt marshes have a sandy base on which thin layers of mud are deposited and vegetation develops. An alternative or additional explanation for the rich vegetation development in the salt marsh park could be that the thin mud layer that was placed on top of the sand already had many vital salt marsh seeds in it.

6.5. Monitoring insights

A range of different instruments and methods was used to monitor the morphological and ecological developments, including some novel ones. This led to some valuable insights.

ASED sensors contribute to capturing short-term bed level change

The development process of the ASED sensors had just finished when they were installed at Marconi. They were successfully validated for the first time at Marconi (Figure 5-25). Measurements at Marconi show that the ASED sensors can contribute to capturing short-term bed level change. Unfortunately, the ASED measurements at the higher elevated areas did not result in complete timeseries. ASED sensors only measure when inundated and the higher elevated areas did not inundate as frequently as anticipated from the original design.

More insight needed in short-term bed level changes and conditions that result in deposition and erosion

Although bed level change of the top layer of the substrate is generally forced by hydrodynamics, wind transport and subsidence can play a role. Bed level changes of the dry marsh were not captured with the ASED sensors. Sensors measuring continuously when the marsh is dry can contribute to a more complete time series including other processes, such as wind transport, that lead to deposition and erosion (Hu et al., 2015a; Willemsen et al., 2008).

Good insight in developments at PQ's and additional vegetation plots

The vegetation cover was measured at the 27 PQ plots and at additional vegetation plots in September 2019 and 2020. September is at the end of the growing season and the cover is at the highest in September. The combination of the 27 PQ plots with additional vegetation plots gave a better spatial coverage than the 27 PQ plots alone.

Orthophoto interpretation would benefit from use of near-infrared

For the overall vegetation presence, we classified the orthophoto of September 2019 and 2020. The classification was pixel-based with RGB colours as predictors. This classification can result in wrong classification when the colours for vegetation are almost similar to the colours pixels without vegetation. Another source of error are different light conditions during the drone campaigns which results in an orthophoto with different colours for the same kind of vegetation cover. Because vegetation often includes shadow, extra differences can be introduced by shadows of wind turbines and brushwood groynes. These classification errors can be reduced by checking the classification by hand, but this takes a lot of effort. In the future it would be better to use a camera with near-infrared spectrum to calculate the normalized difference vegetation index (NDVI). This NDVI is a proxy for the "greenness" of the vegetation and distinguishes vegetation much better from non-vegetated areas.

LiDAR UAV measurements are worthwhile

The use of an UAV with a LiDAR proved very useful to make detailed digital elevation maps that revealed many morphodynamic features in the highly heterogenous area. These would remain unnoticed with point measurements.

6.6. Lessons learned on salt marsh development

Two goals of the salt marsh pilot were to develop knowledge on (1) how to design and construct a pioneer salt marsh at a location that is not suitable yet for salt marsh development and (2) how design and construction methods affect the development of a man-made salt marsh. This knowledge is globally applicable to stimulate salt marsh development and promote salt marshes as sustainable coastal protection.

The most important lessons learned from the two years of intensive monitoring of the salt marsh are therefore summarized below:

- The design and construction of the salt marsh successfully enabled the rapid establishment and growth of pioneer vegetation.
- Fine sediment is key for vegetation development. The vegetation cover was higher in the compartments with 20 or 50% mud in the upper meter of the subsurface and relatively low in the compartments with only 5% mud. Because between 20 and 50% mud there is not much difference in vegetation cover a mud percentage around 20 percent is recommended.
- Seeding Salicornia had no longer a significant effect on the vegetation development after the first growing season.
- The contractor successfully realized compartments with different mud percentages in upper 1.0 m, although some local variation seems inevitable. The method applied in the salt marsh park that involved the top layer only was less challenging.
- The initial elevation of the salt marsh is important for vegetation and tidal creek development. To construct the marsh at the desired elevation, accurate estimation of (initial) subsidence rates is important. This requires detailed geotechnical information about the original and new substrate.
- Brushwood groynes alone are not enough for steering tidal creek formation at specific locations. In case tidal creeks are desired or unwanted at specific locations it may be needed to:
    - Dig an initial tidal creek;
    - Construct brushwood groynes immediately after the sediment base is installed;
    - Limit the permeability of groynes at locations where channel formation is unwanted;
- Construction of a new salt marsh including the foreshore can result in unforeseen - but not necessarily negative - morphological developments, such as the formation of sandbars. These sandbars have a sheltering effect in the case of Marconi.

The lessons learned about the development of the project, design and construction and the applicability of the acquired knowledge can be found in the report ''Kwelderontwikkeling als Nature-based Solution, Kennis en ervaring van de Proefkwelder Marconi' (Leuven et al., 2021) (in Dutch).

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8. Appendices

Appendix 1 – Overview map of measurement locations

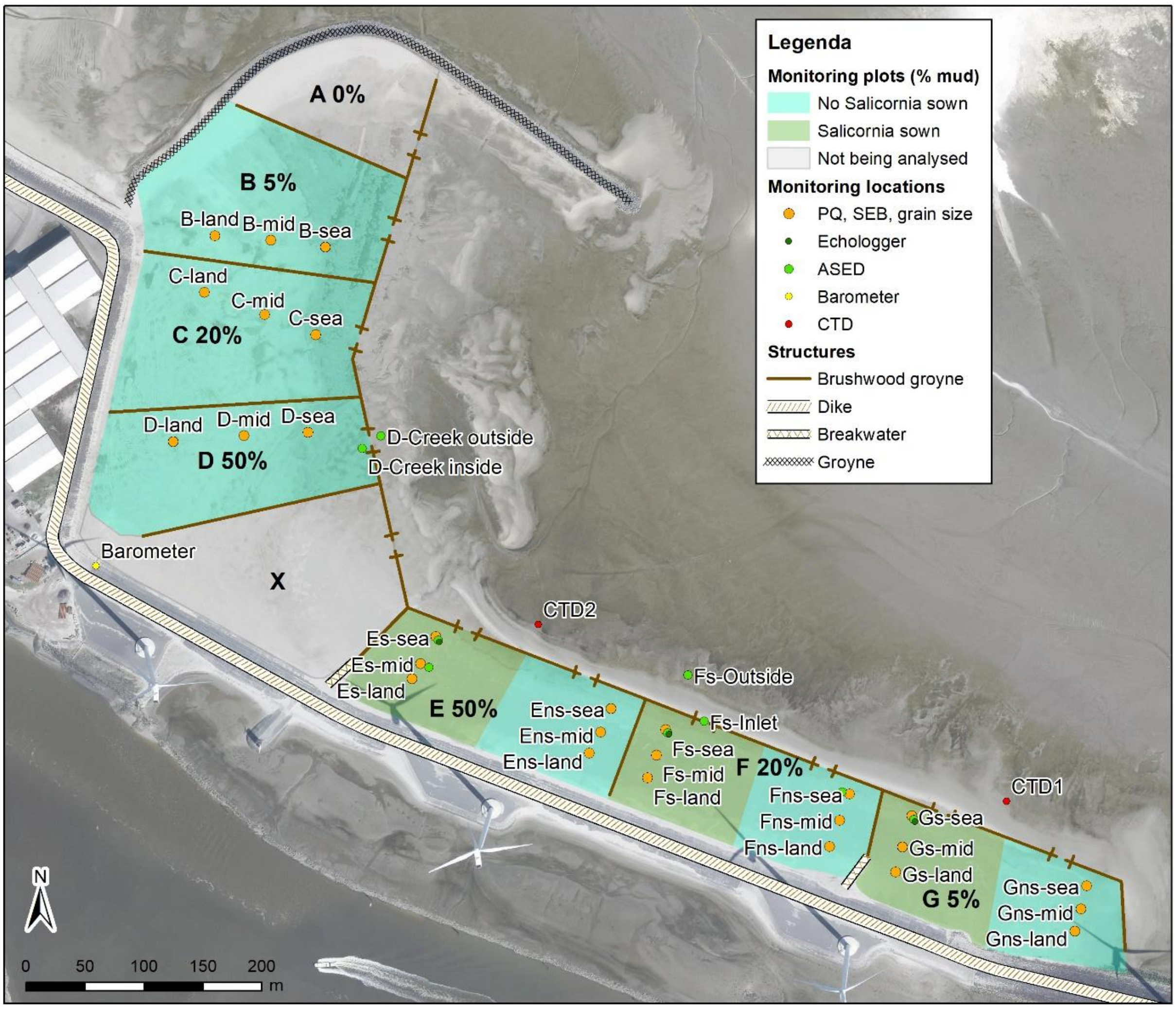

Figure 8-1 Overview of the measurement locations at the pilot salt marsh Marconi Delfzijl. Ns = not seeded, s = seeded. Background: aerial photograph of 2018 (beeldmateriaal.nl/Kadaster).

Appendix 2 – Bed level elevation maps (DTM's)

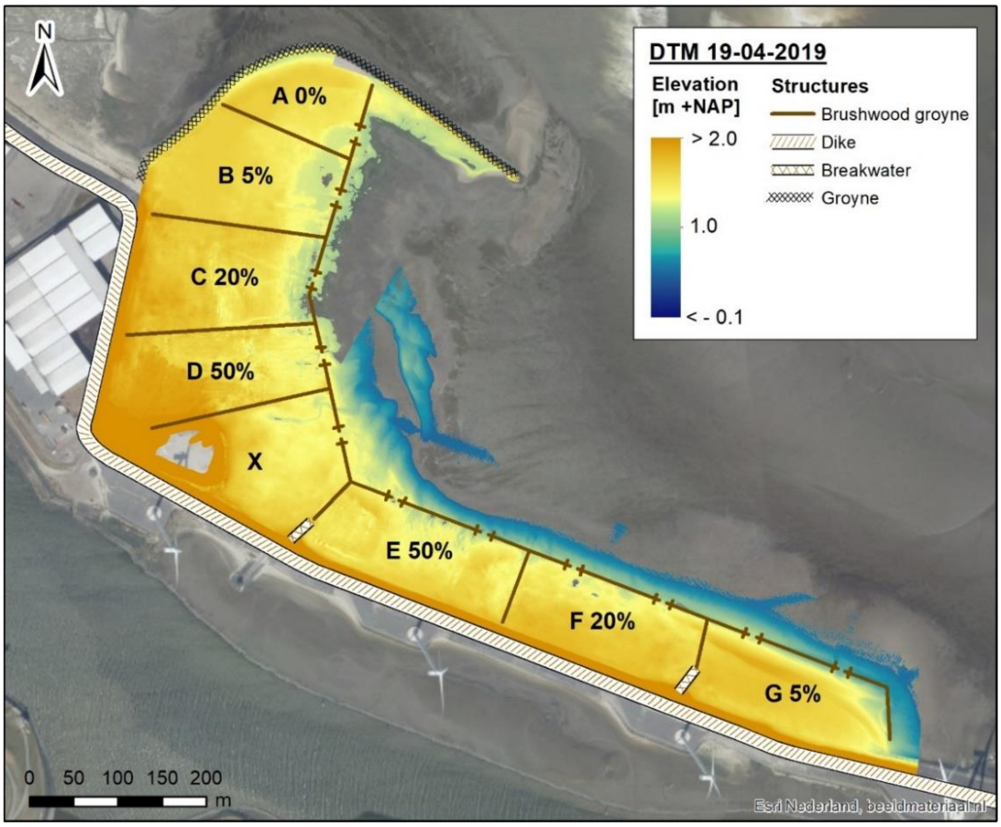

Figure 8-2 Bed elevation (DTM) of pilot salt marsh Marconi at 19-04-2019. Source aerial photograph: beeldmateriaal.nl/Kadaster.

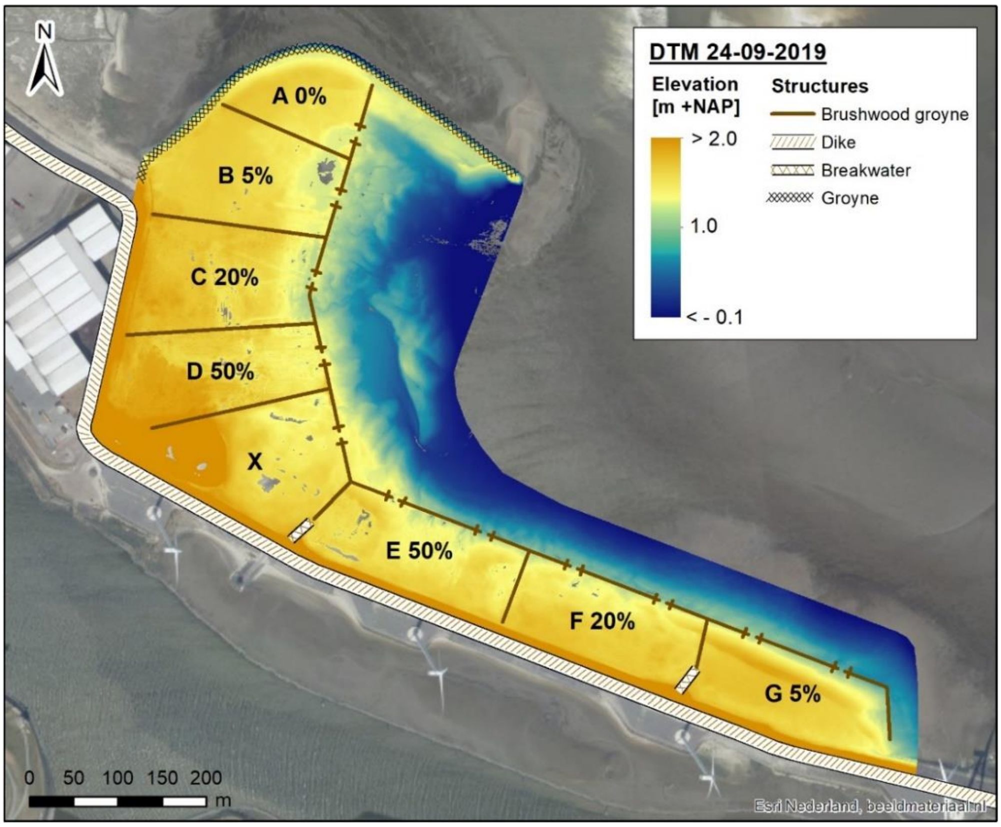

Figure 8-3 Bed elevation (DTM) of pilot salt marsh Marconi at 24-09-2019. Source aerial photograph: beeldmateriaal.nl/Kadaster.

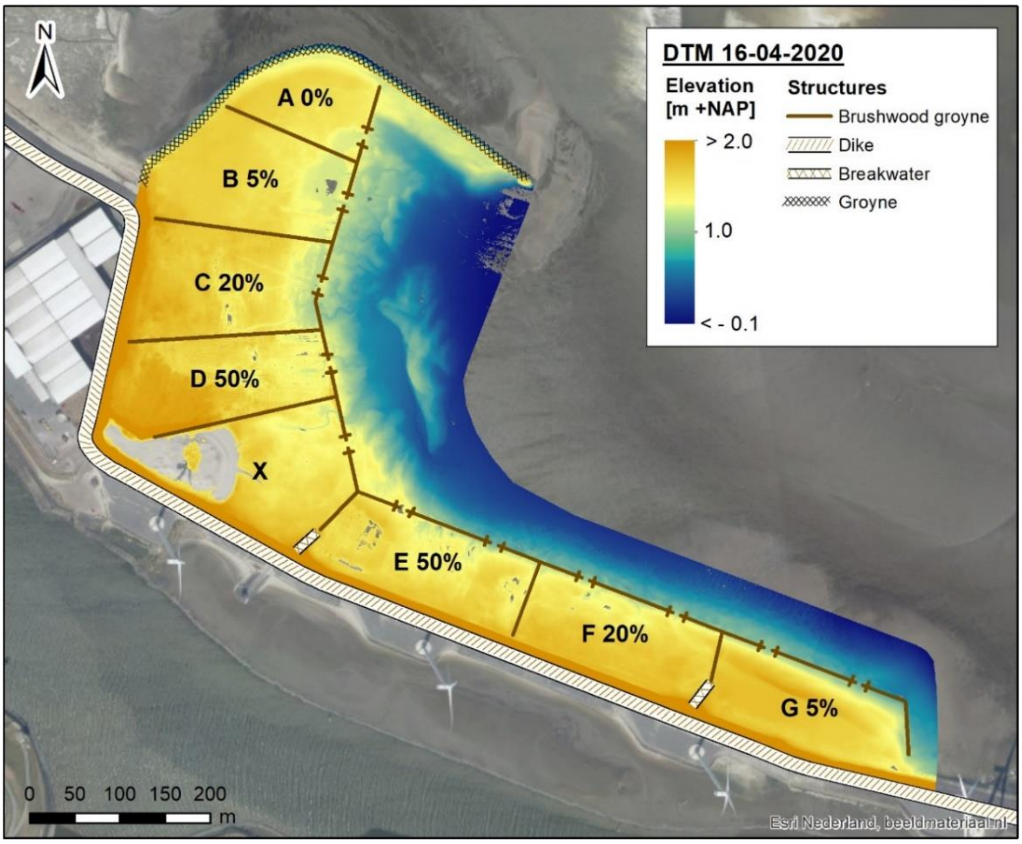

Figure 8-4 Bed elevation (DTM) of pilot salt marsh Marconi at 16-04-2020. Source aerial photograph: beeldmateriaal.nl/Kadaster.

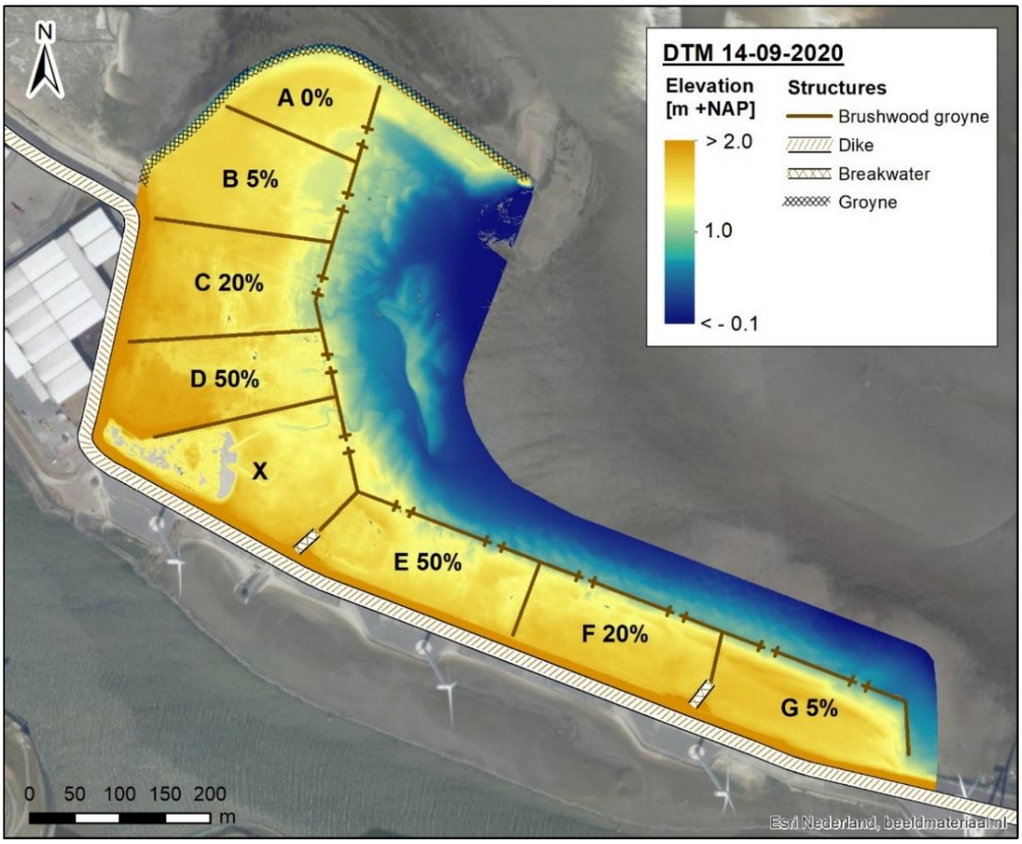

Figure 8-5 Bed elevation (DTM) of pilot salt marsh Marconi at 14-09-2019. Source aerial photograph: beeldmateriaal.nl/Kadaster.

Appendix 3 – Bed level change maps

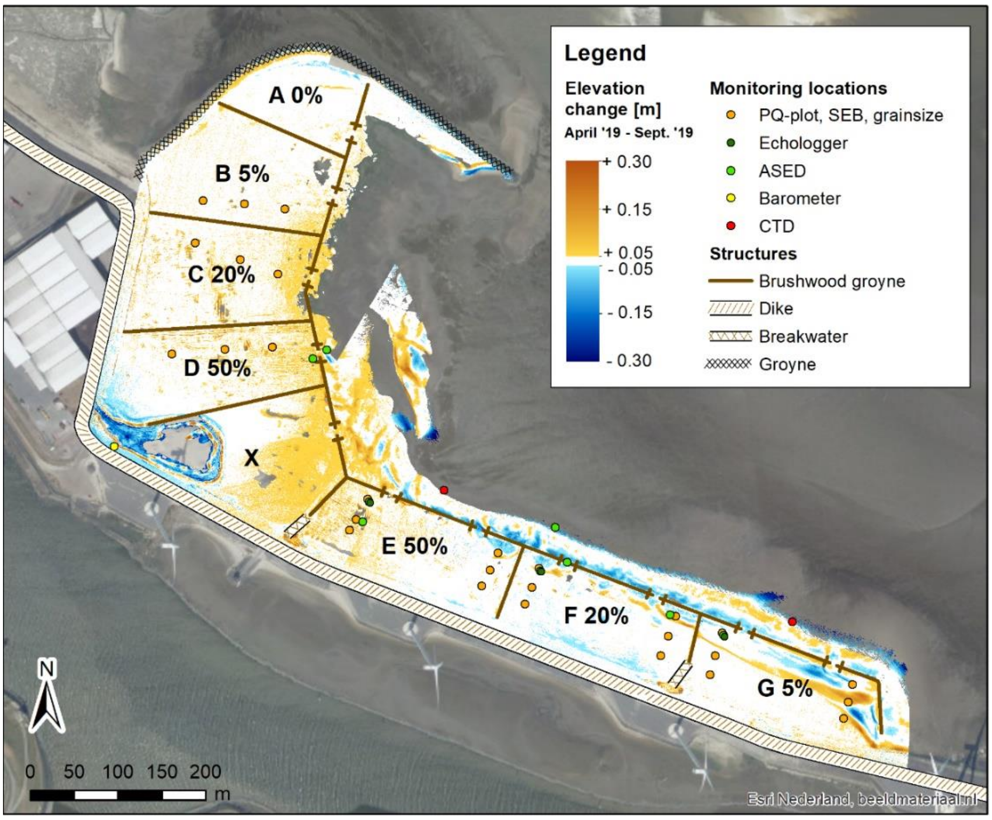

Figure 8-6 Change in elevation at the pilot salt marsh Marconi between April 2019 and September 2019. Source aerial photograph: beeldmateriaal.nl/Kadaster.

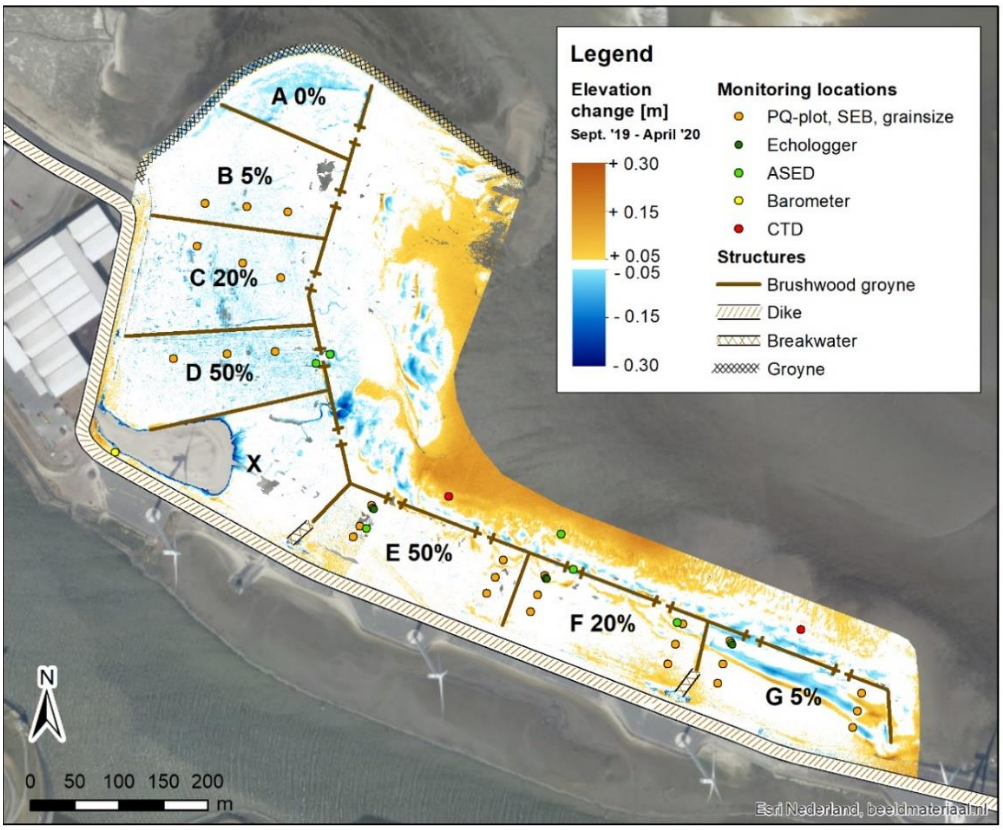

Figure 8-7 Change in elevation at the pilot salt marsh Marconi between September 2019 and April 2020. Source aerial photograph: beeldmateriaal.nl/Kadaster.

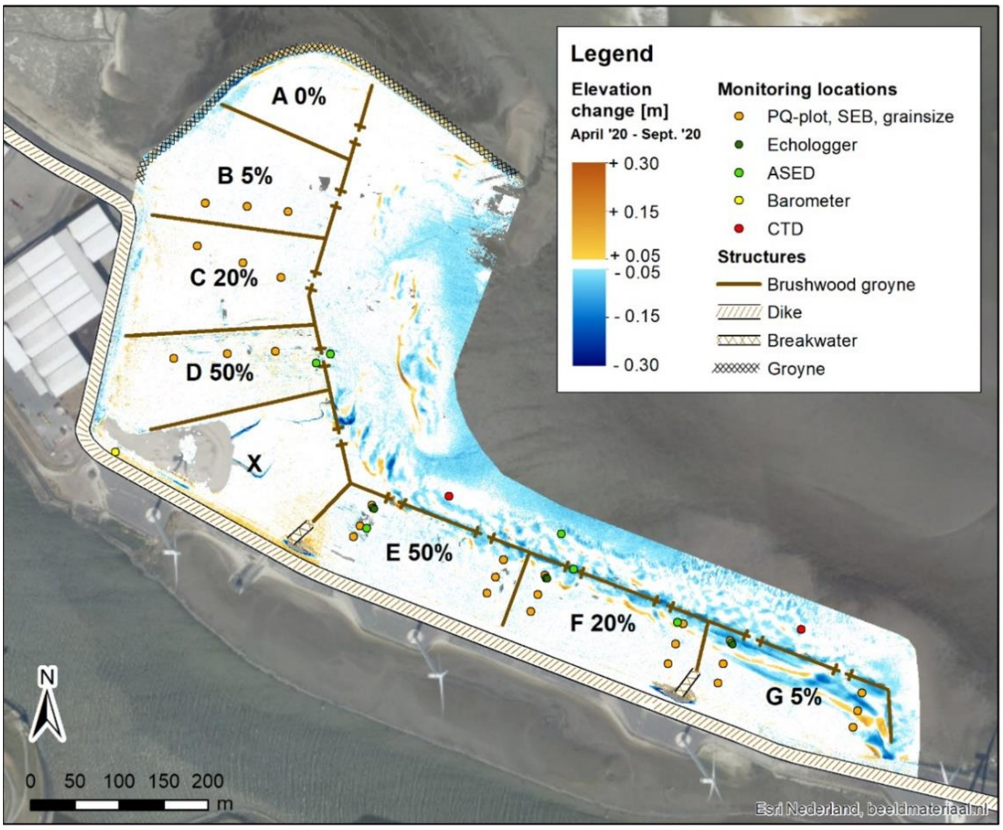

Figure 8-8 Change in elevation at the pilot salt marsh Marconi between April 2020 and September 2020. Source aerial photograph: beeldmateriaal.nl/Kadaster.

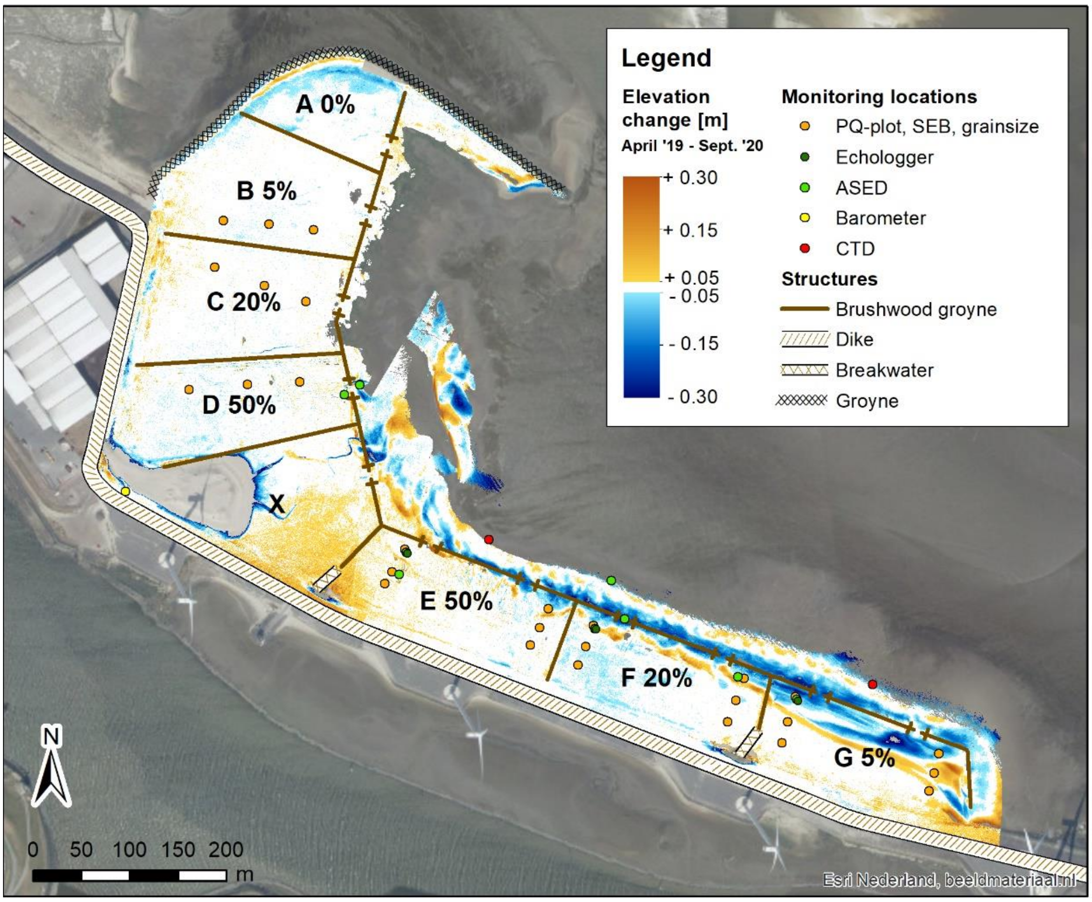

Figure 8-9 Change in elevation at the pilot salt marsh Marconi between April 2019 and September 2020 (difference between first and last DTM). Source aerial photograph: beeldmateriaal.nl/Kadaster.

Appendix 4 – Comparison of continuous bed level changes with weather data

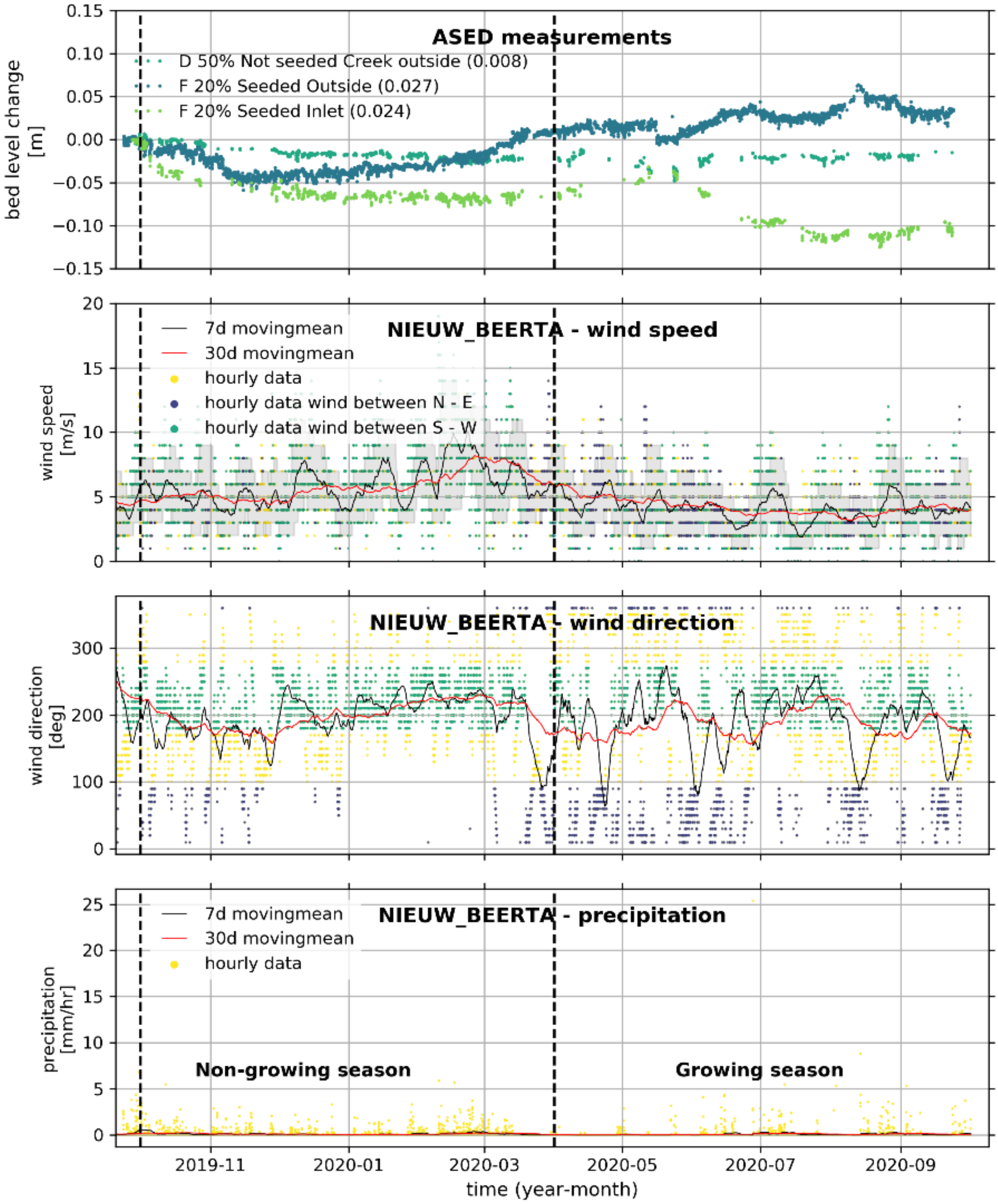

Figure 8-10 ASED measurements outside the salt marsh compartments (top panel) and weather data during non-growing and growing season measured at Nieuwe Beerta station: wind speed, with gray errorband between 15th and 85th percentile (second panel), wind direction (third panel) and precipitation (bottom panel) (source: KNMI).

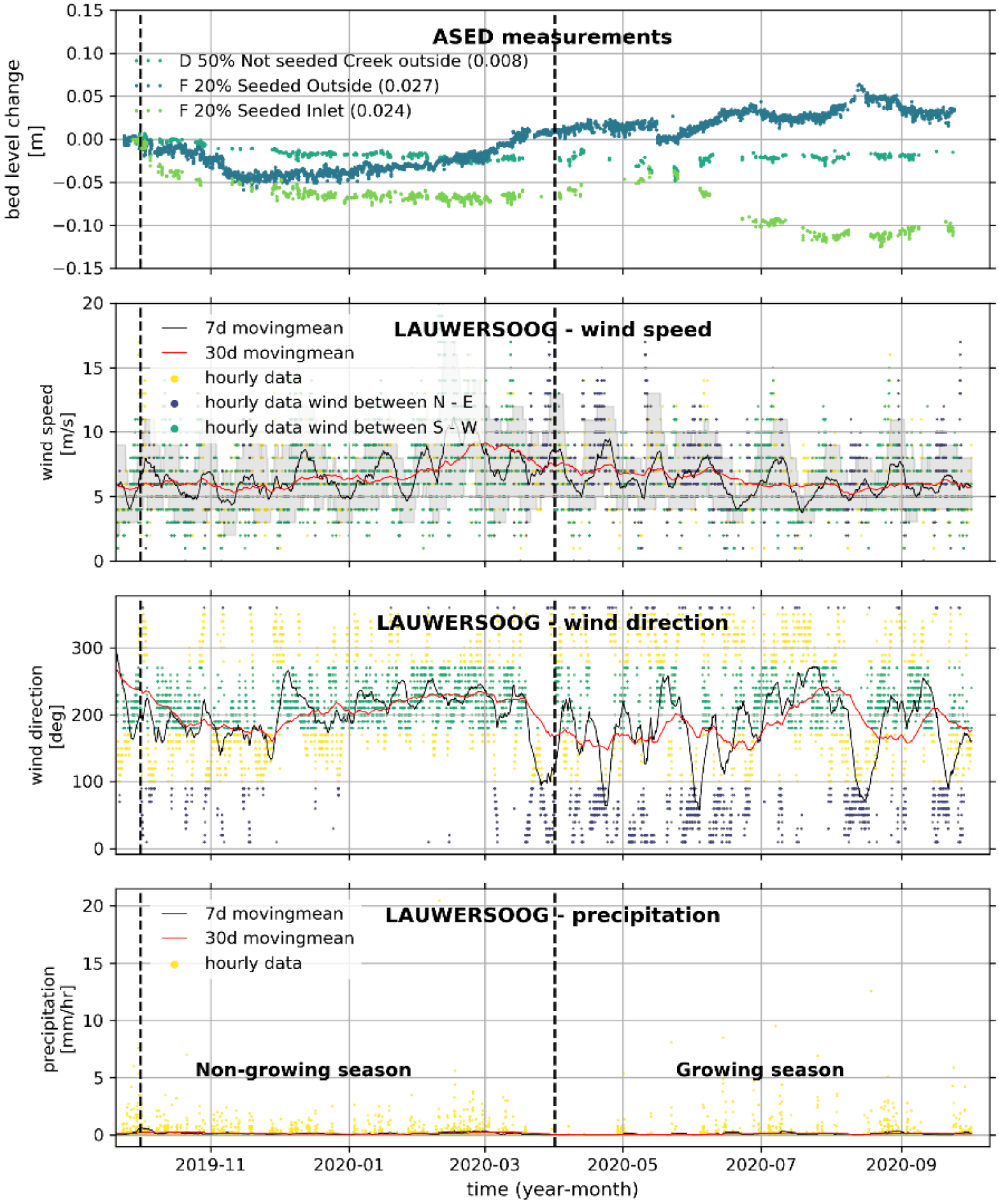

Figure 8-11 ASED measurements outside the salt marsh compartments (top panel) and weather data during non-growing and growing season measured at Lauwersoog station: wind speed, with gray errorband between 15th and 85th percentile (second panel), wind direction (third panel) and precipitation (bottom panel) (source: KNMI).

Appendix 5 – Photographs of tidal creeks

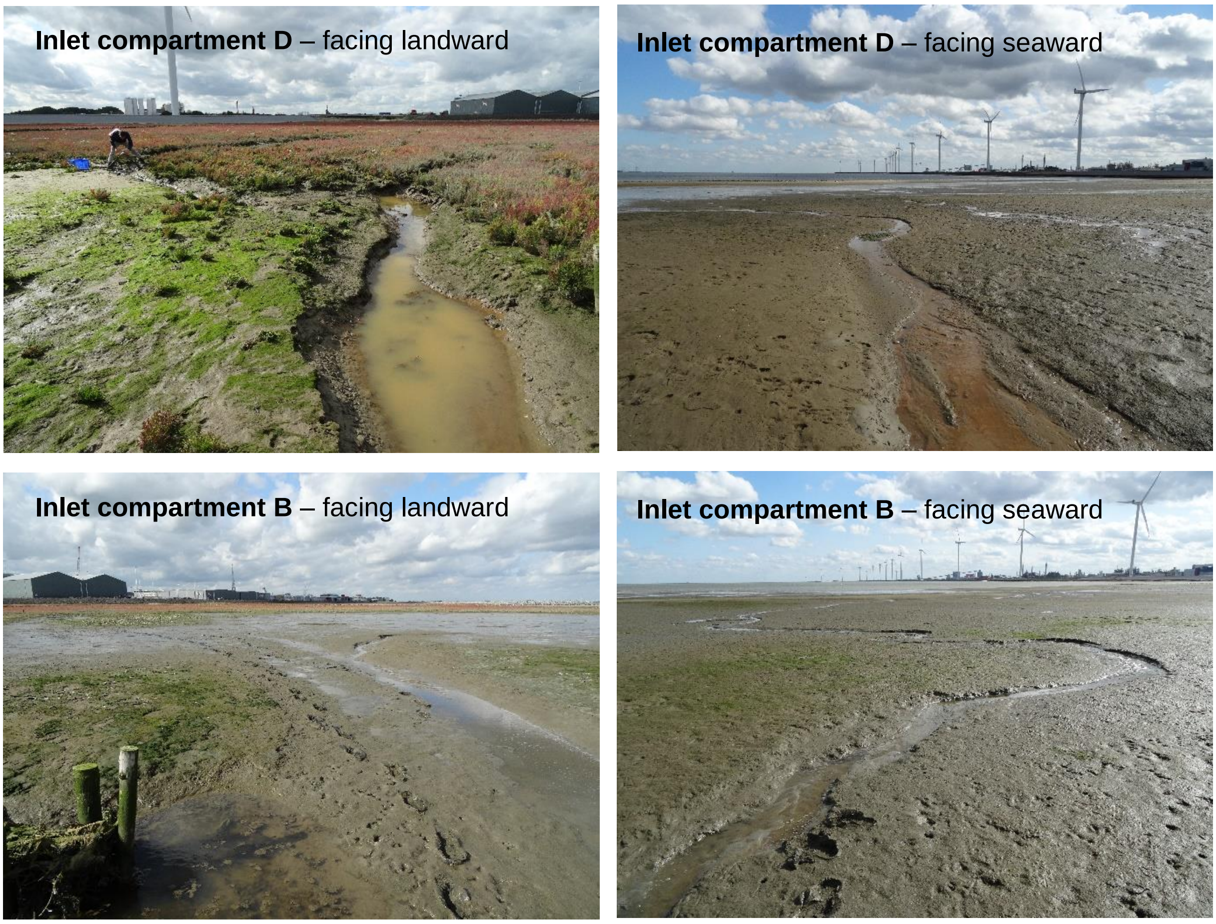

Figure 8-12 Photographs of the tidal creek through the inlet of compartment B and D at 24-09-2020.

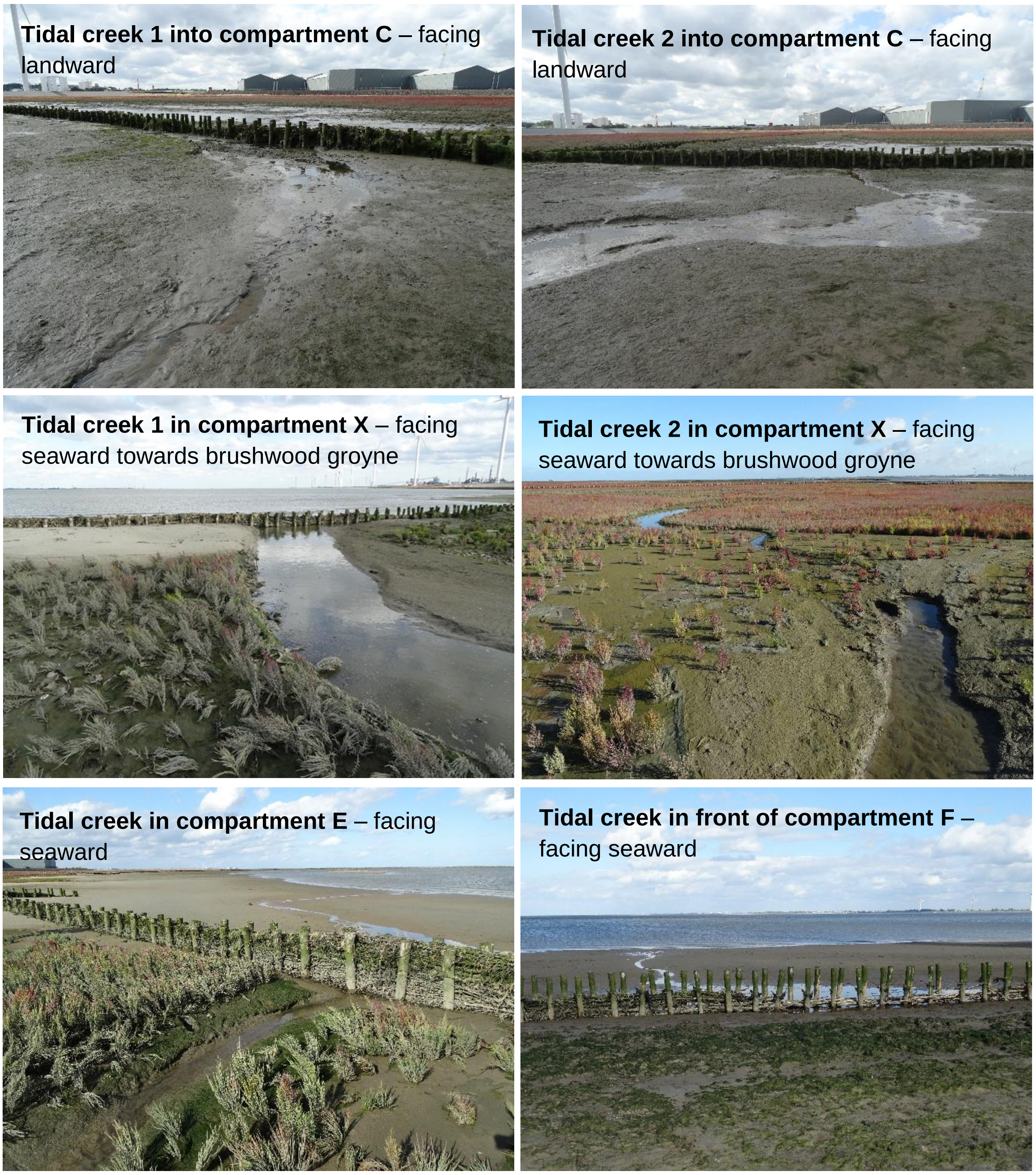

Figure 8-13 Photographs of tidal creeks at other locations than through the inlets at 24-09-2020.

Appendix 6 – Maps of sediment composition of the toplayer over time

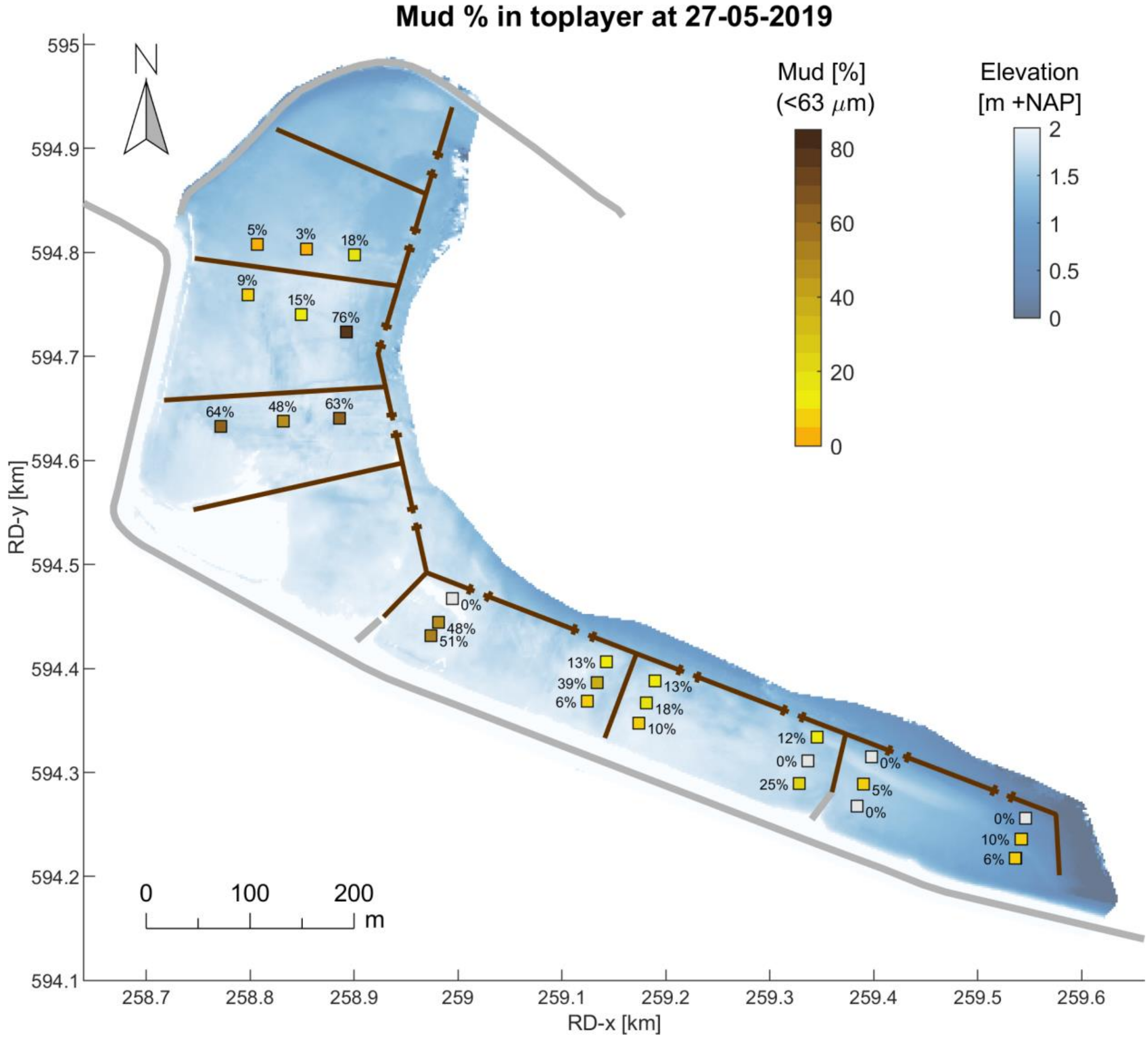

Figure 8-14 Mud percentage in the toplayer of the sediment (<1 cm deep) at all measurement locations (PQ-plots) at 27-05-2019.

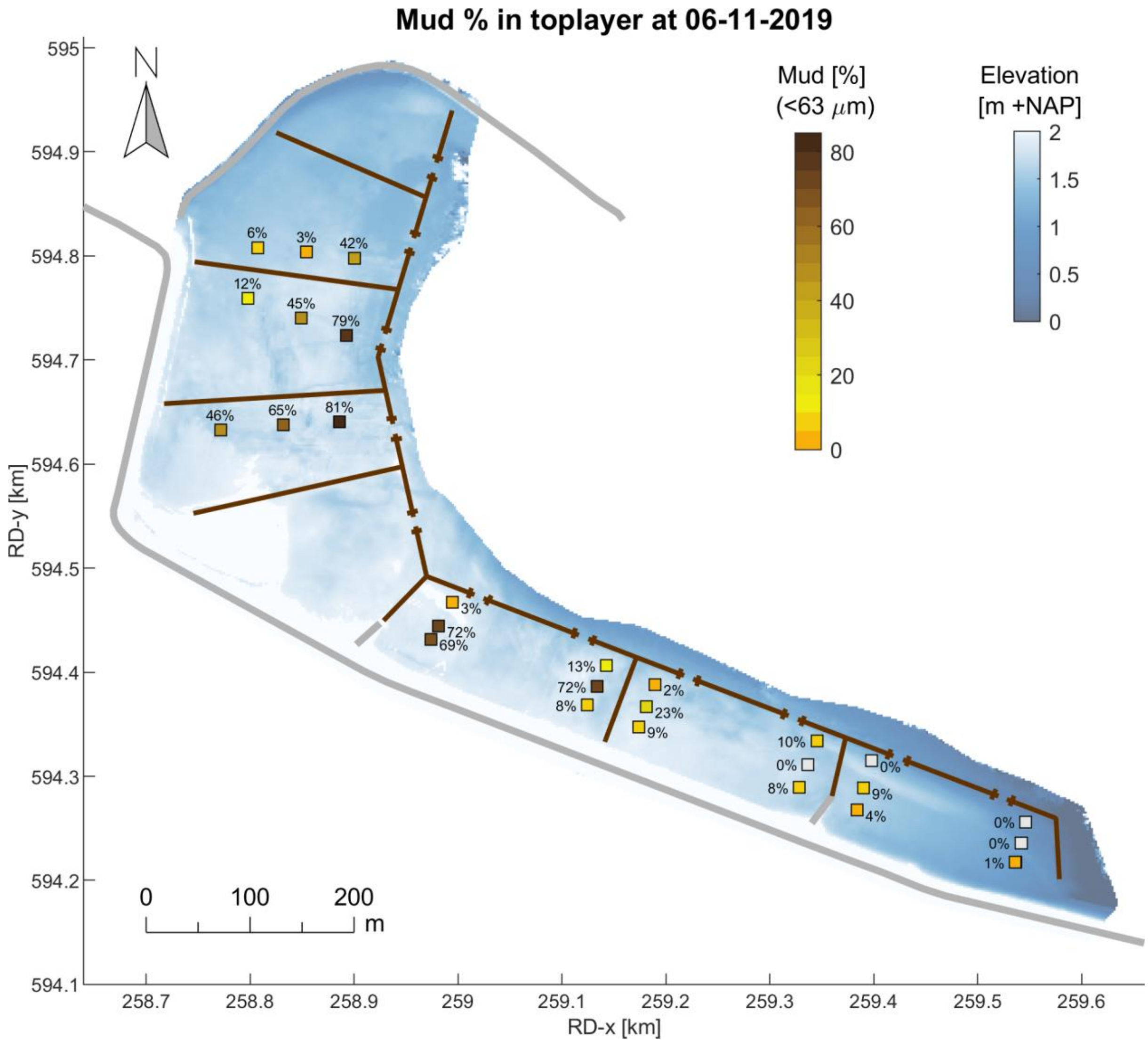

Figure 8-15 Mud percentage in the toplayer of the sediment (<1 cm deep) at all measurement locations (PQ-plots) at 06-11-2019.

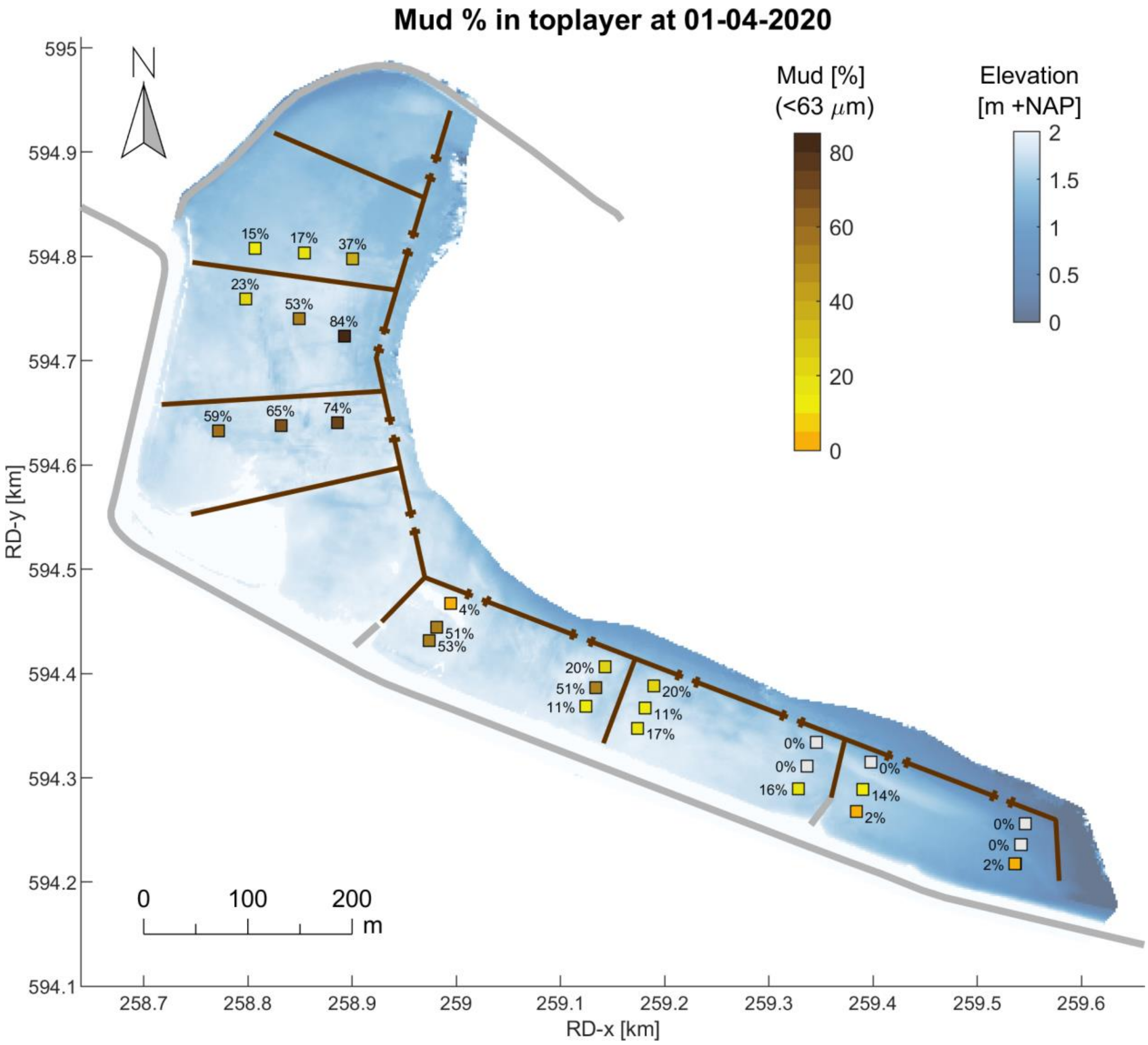

Figure 8-16 Mud percentage in the toplayer of the sediment (<1 cm deep) at all measurement locations (PQ-plots) at 01-04-2020.

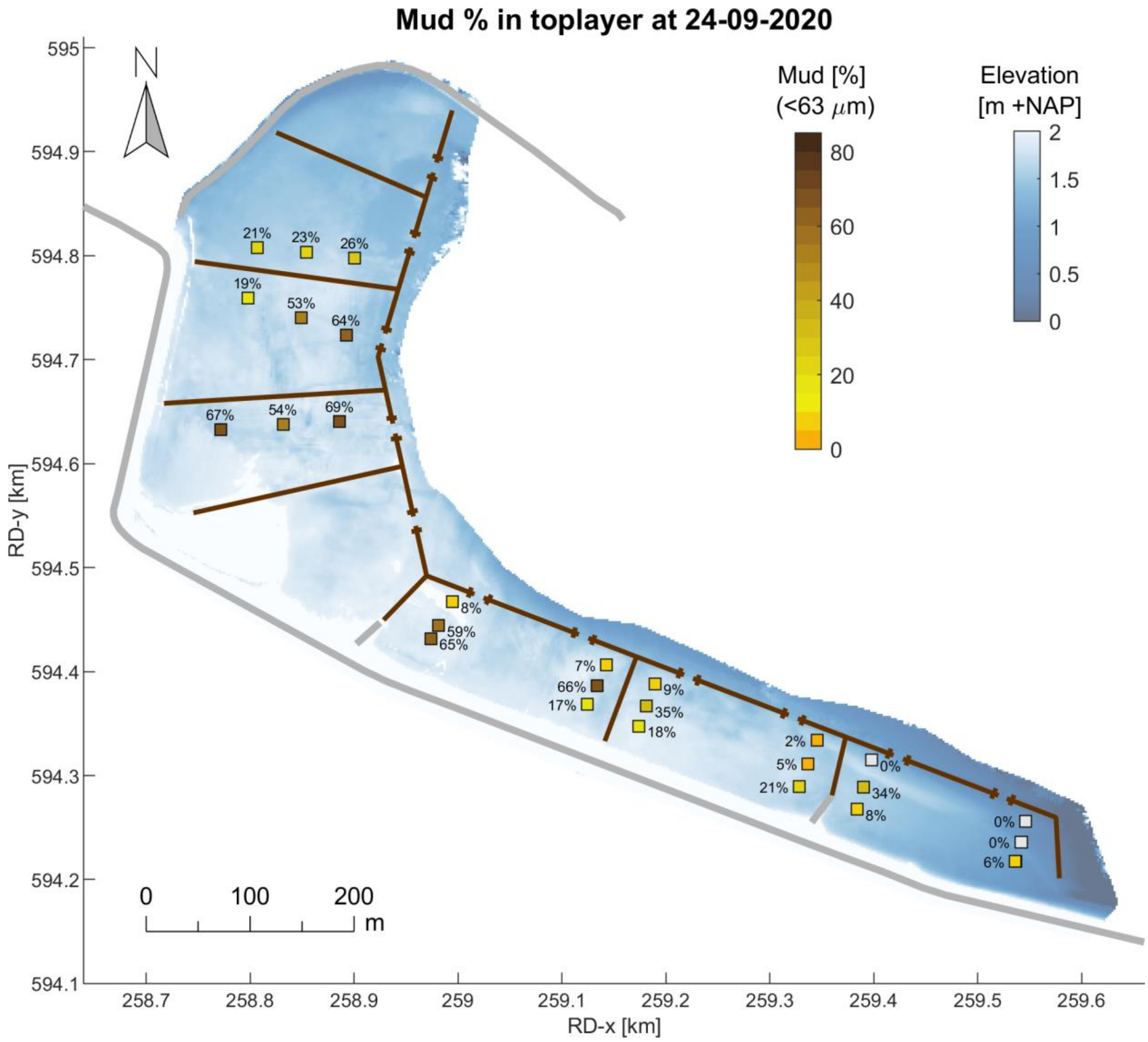

Figure 8-17 Mud percentage in the toplayer of the sediment (<1 cm deep) at all measurement locations (PQ-plots) at 24-09-2020.

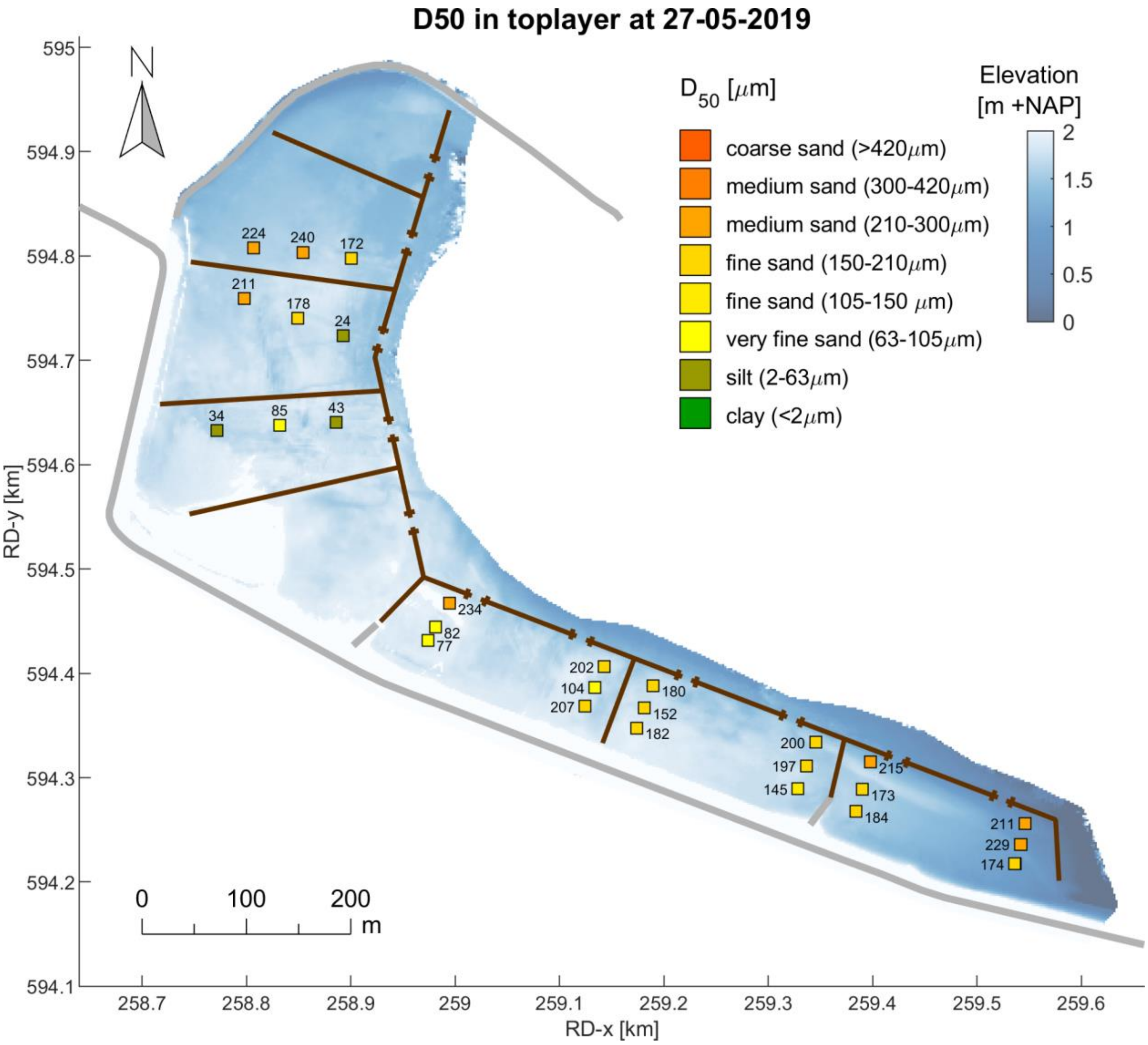

Figure 8-18 Median grainsize in the toplayer of the sediment (<1 cm deep) at all measurement locations (PQ-plots) at 27-05-2019.

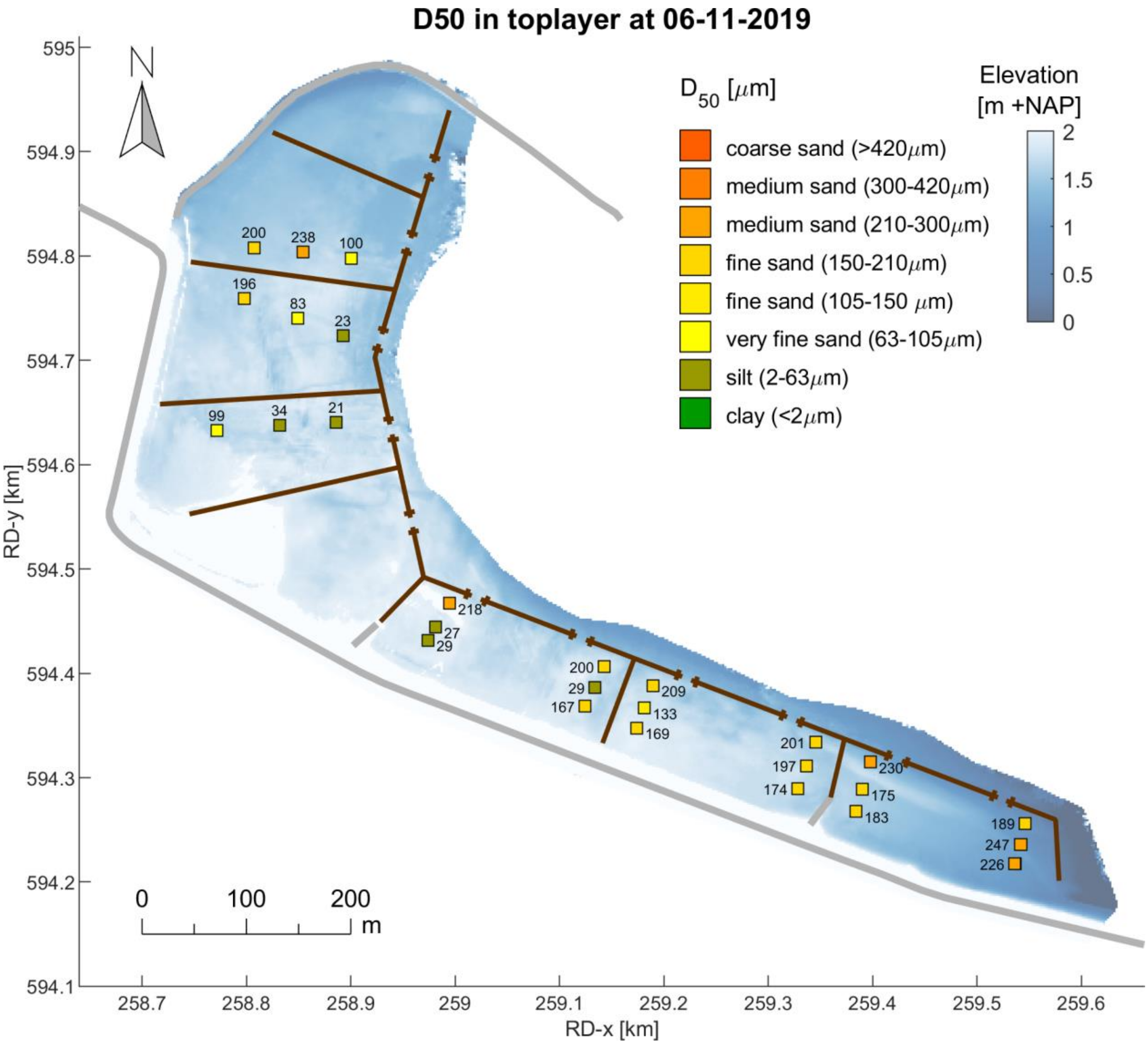

Figure 8-19 Median grainsize in the toplayer of the sediment (<1 cm deep) at all measurement locations (PQ-plots) at 06-11-2019

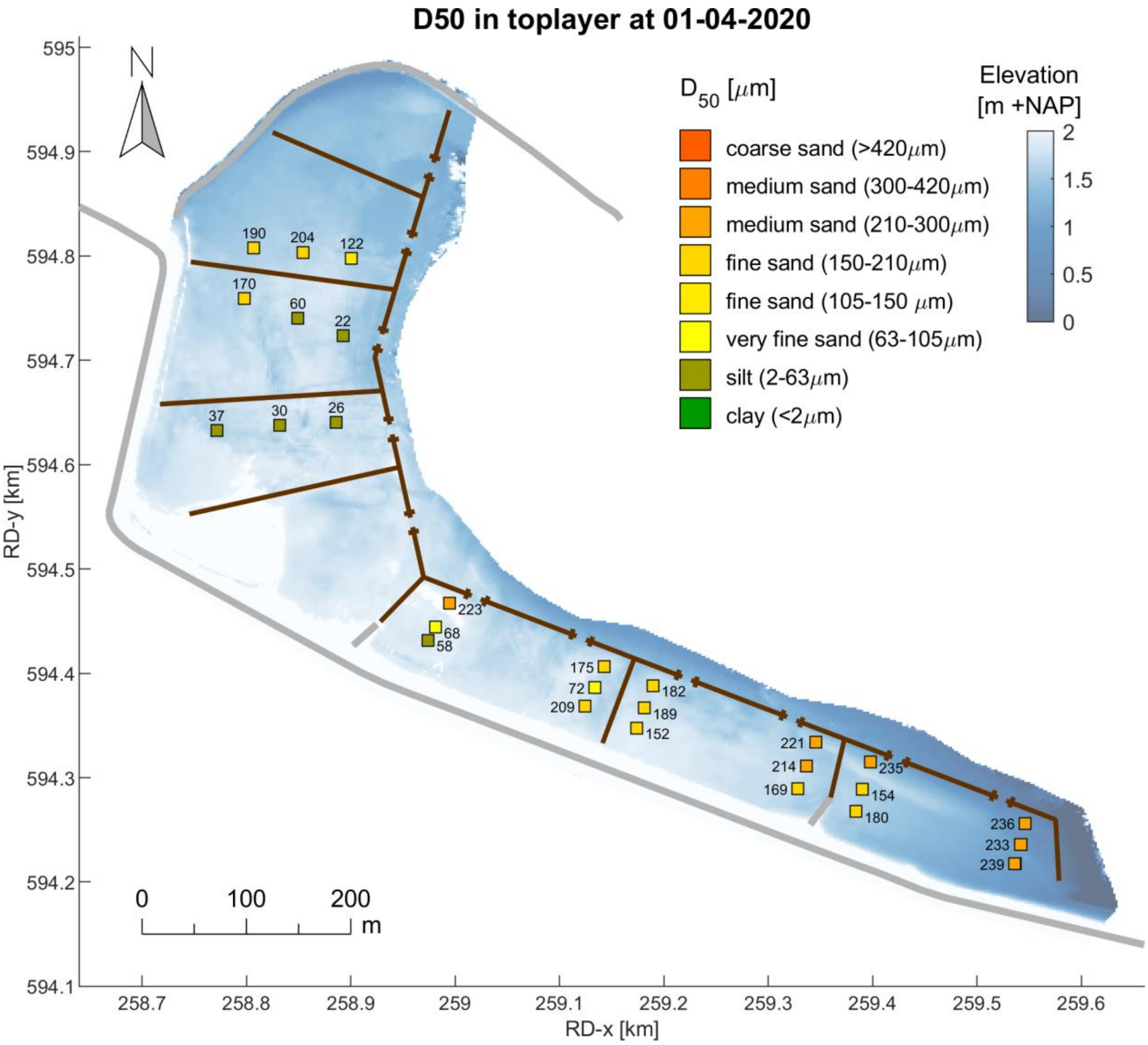

Figure 8-20 Median grainsize in the toplayer of the sediment (<1 cm deep) at all measurement locations (PQ-plots) at 01-04-2020.

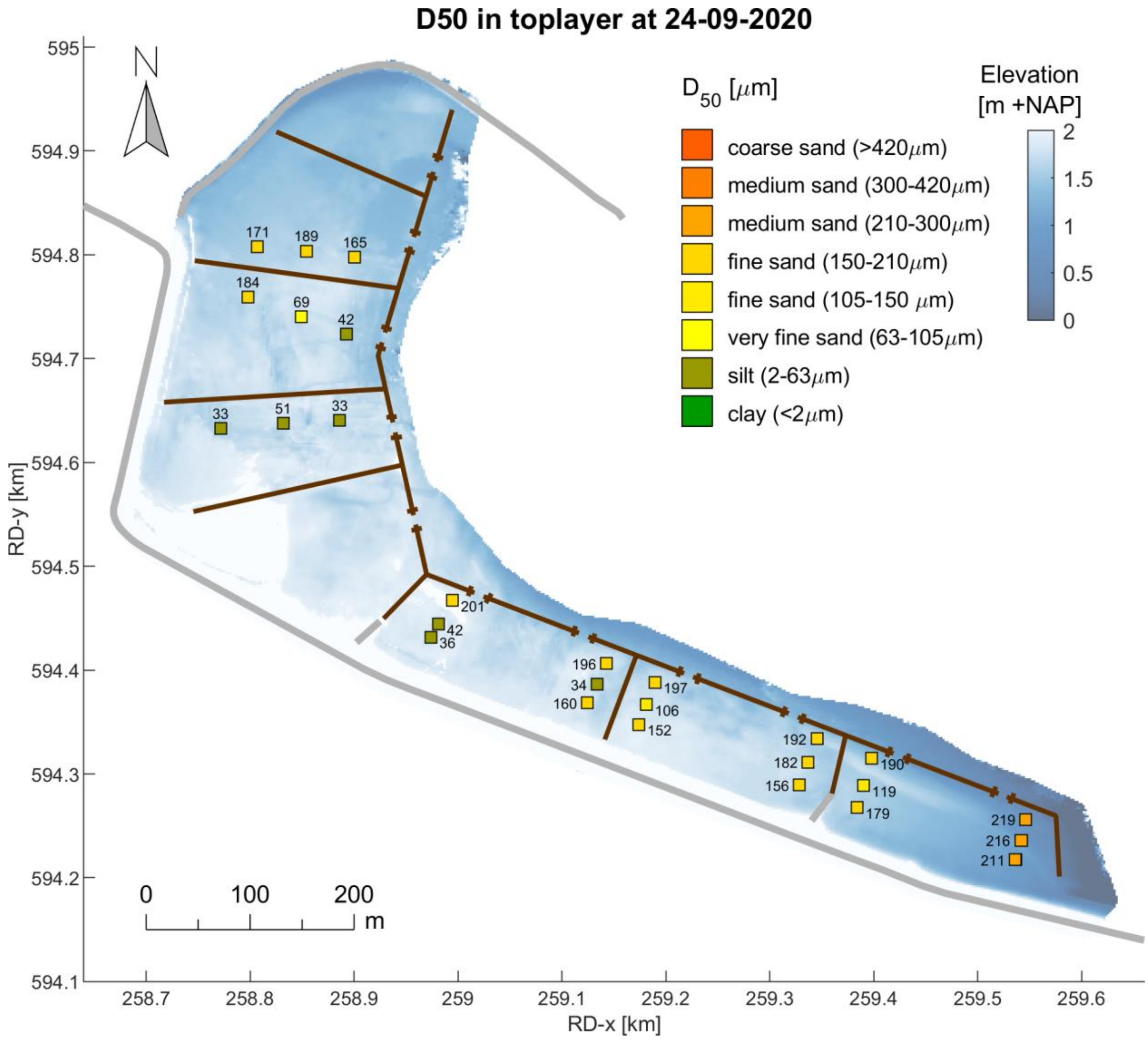

Figure 8-21 Median grainsize in the toplayer of the sediment (<1 cm deep) at all measurement locations (PQ-plots) at 24-09-2020.

Appendix 7 – Aerial photographs of the salt marsh during low tide

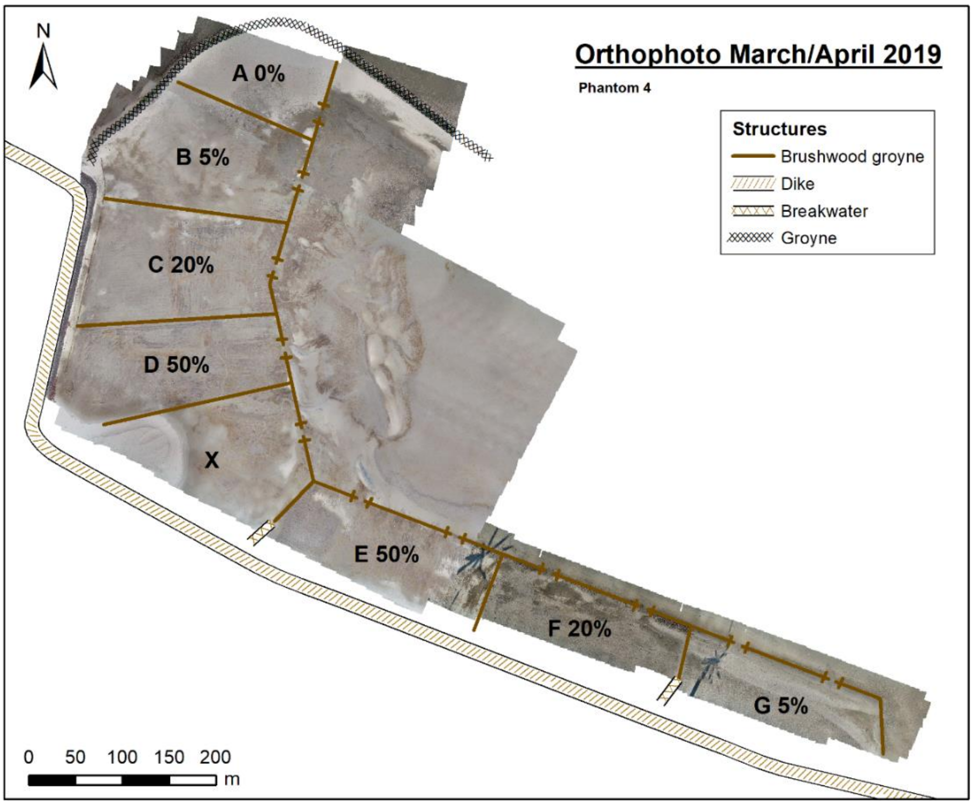

Figure 8-22 Orthophoto of the Marconi pilot salt marsh in March/April 2019, made with Phantom 4.

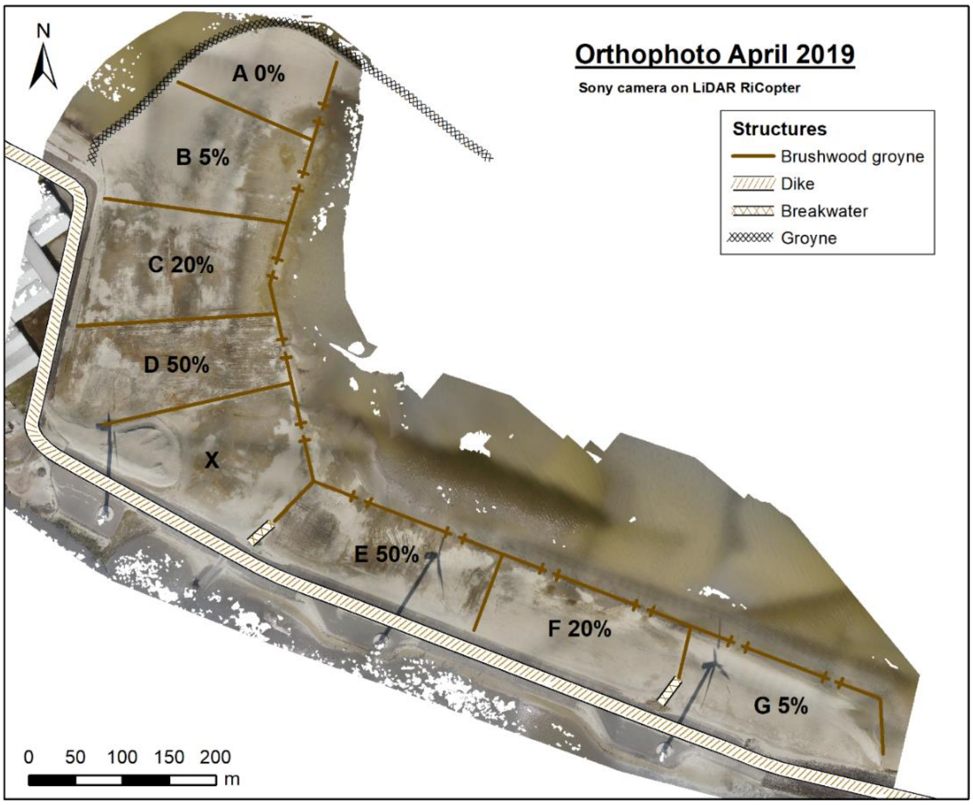

Figure 8-23 Orthophoto of the Marconi pilot salt marsh in April 2019, made with Sony camera on LiDAR RICopter.

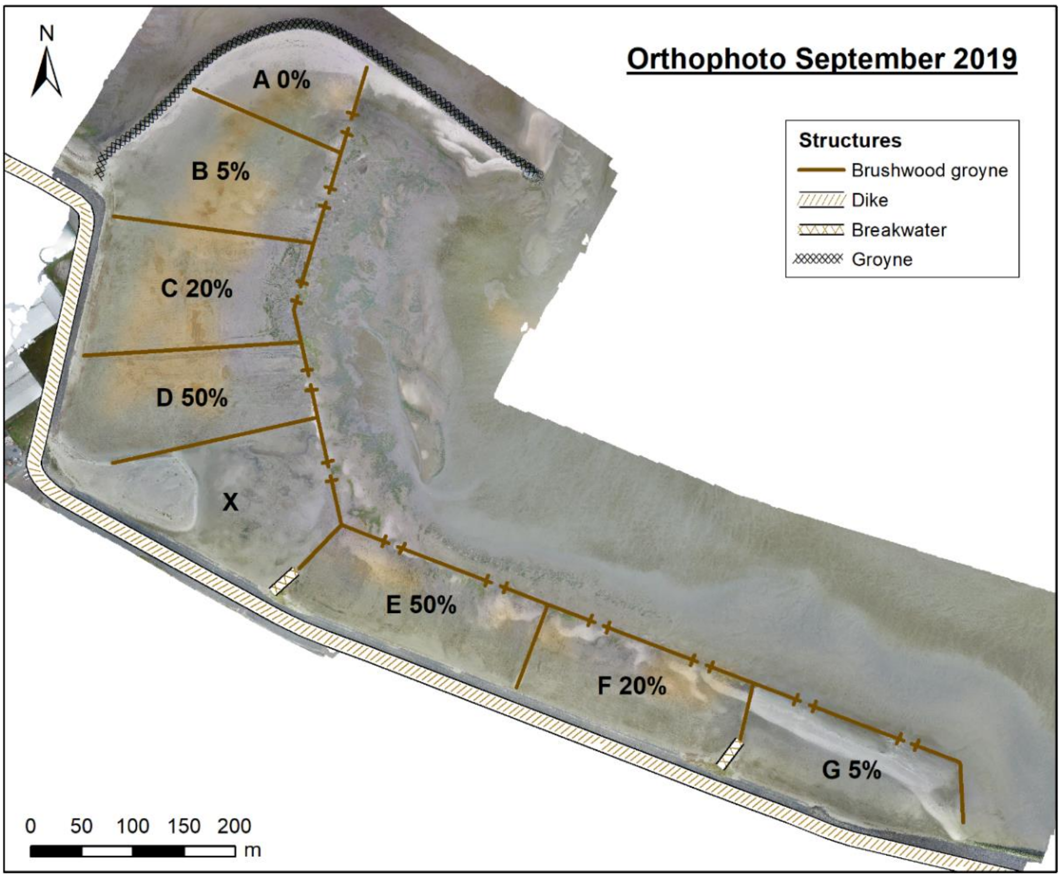

Figure 8-24 Orthophoto of the Marconi pilot salt marsh in September 2019.

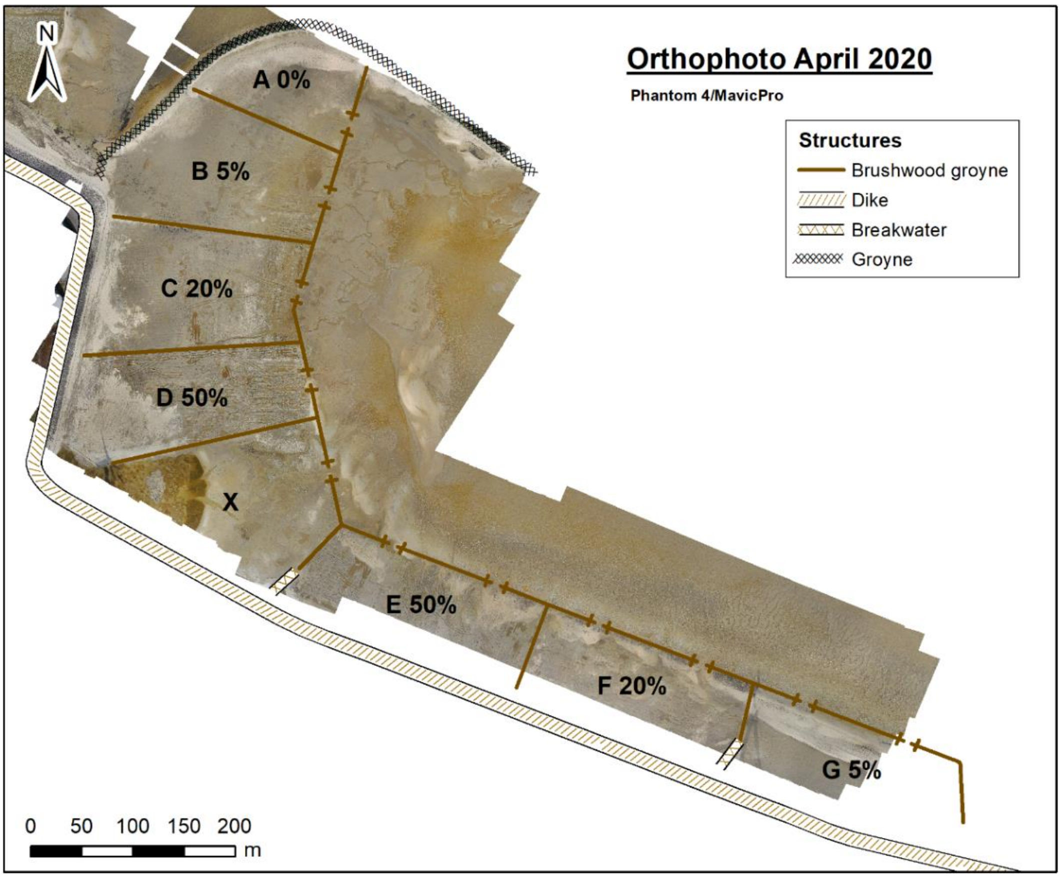

Figure 8-25 Orthophoto of the Marconi pilot salt marsh in April 2020, made with Phantom 4/MavicPro.

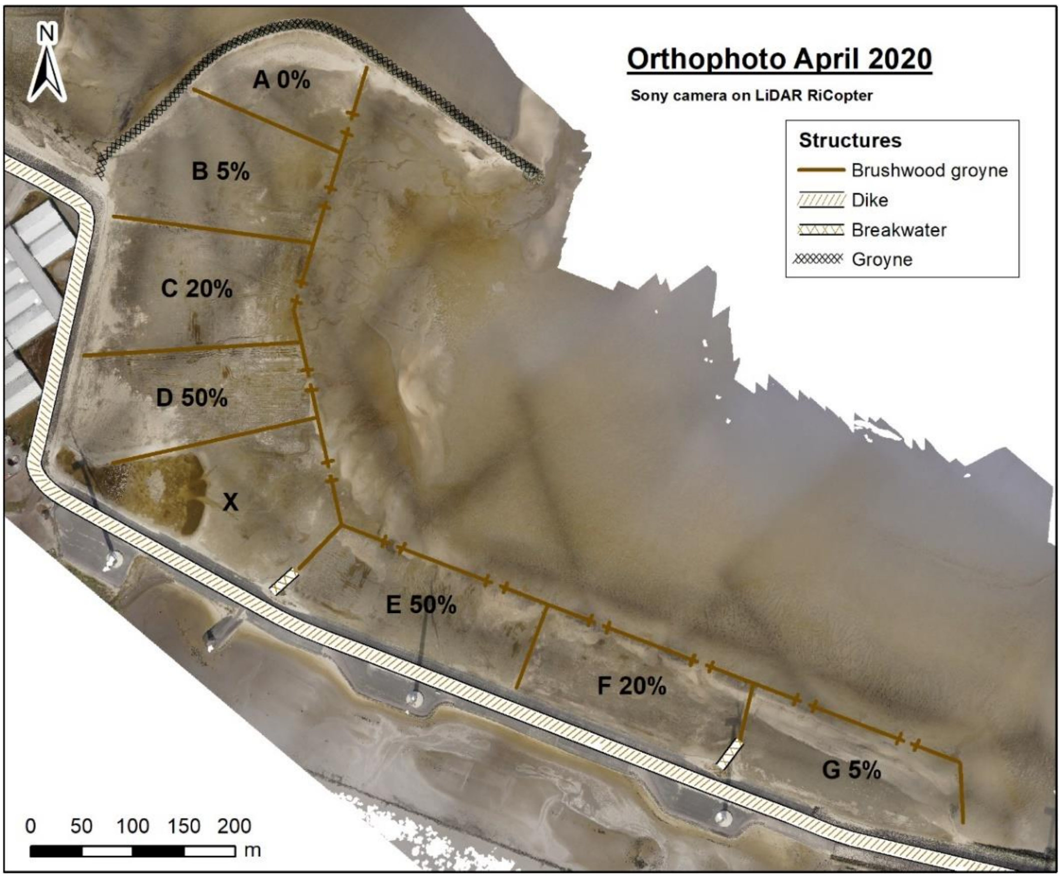

Figure 8-26 Orthophoto of the Marconi pilot salt marsh in April 2020, made with sony camera on LiDAR RICopter.

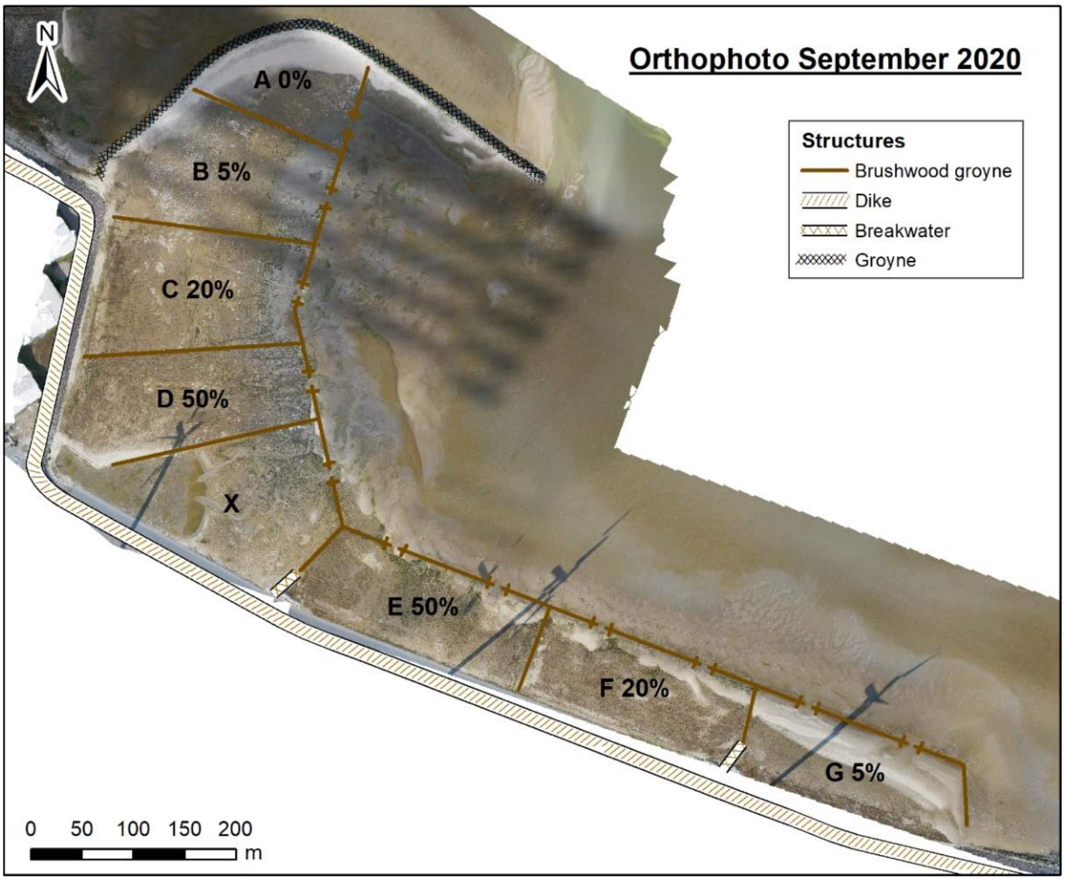

Figure 8-27 Orthophoto of the Marconi pilot salt marsh in September 2020.

Appendix 8 - Classification of vegetation based on aerial photographs for each compartment in Sep 2019 and Sep 2020

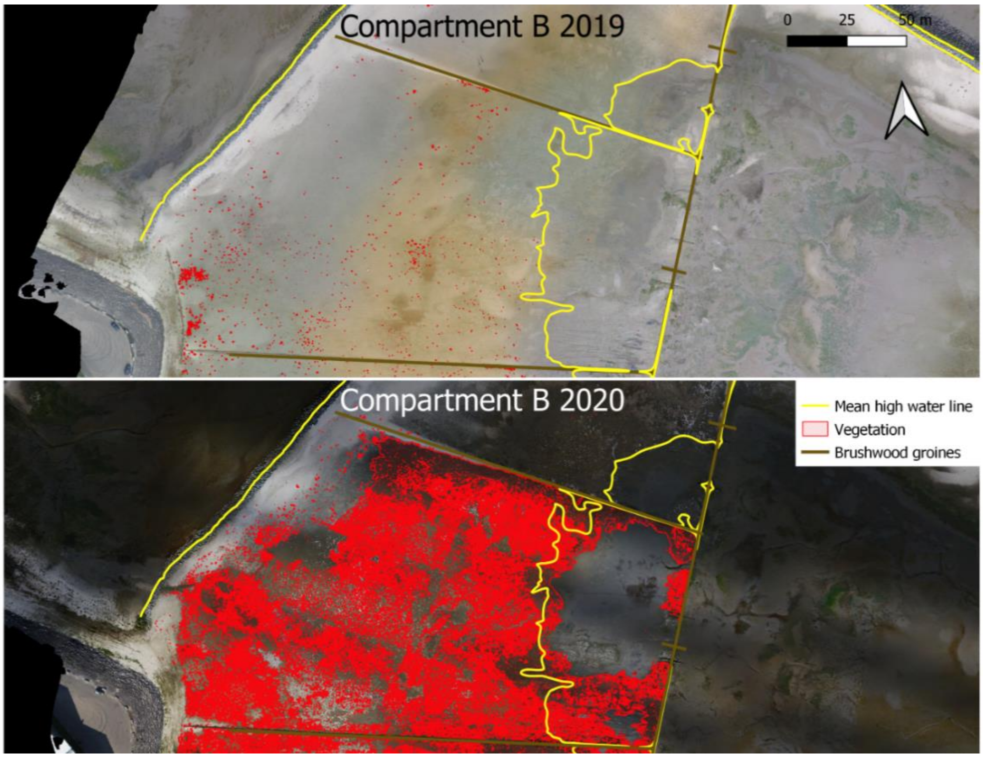

Figure 8-28 Classification of vegetation at the Marconi salt marsh pilot in 2019 and 2020 based on aerial photographs in compartment B.

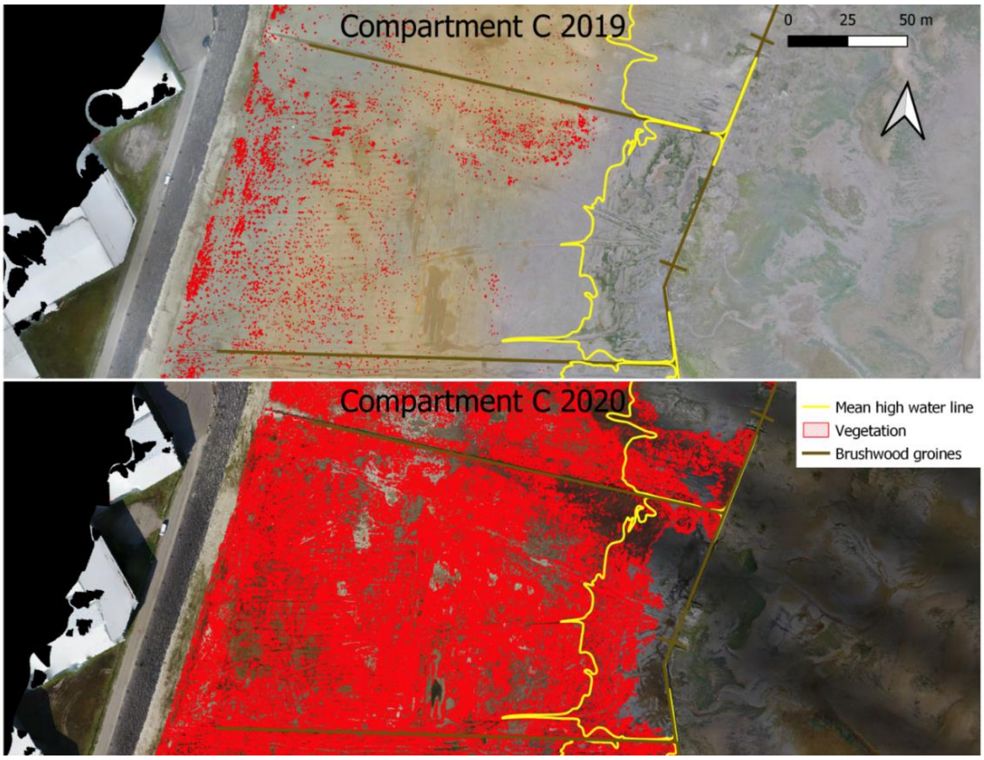

Figure 8-29 Classification of vegetation at the Marconi salt marsh pilot in 2019 and 2020 based on aerial photographs in compartment C.

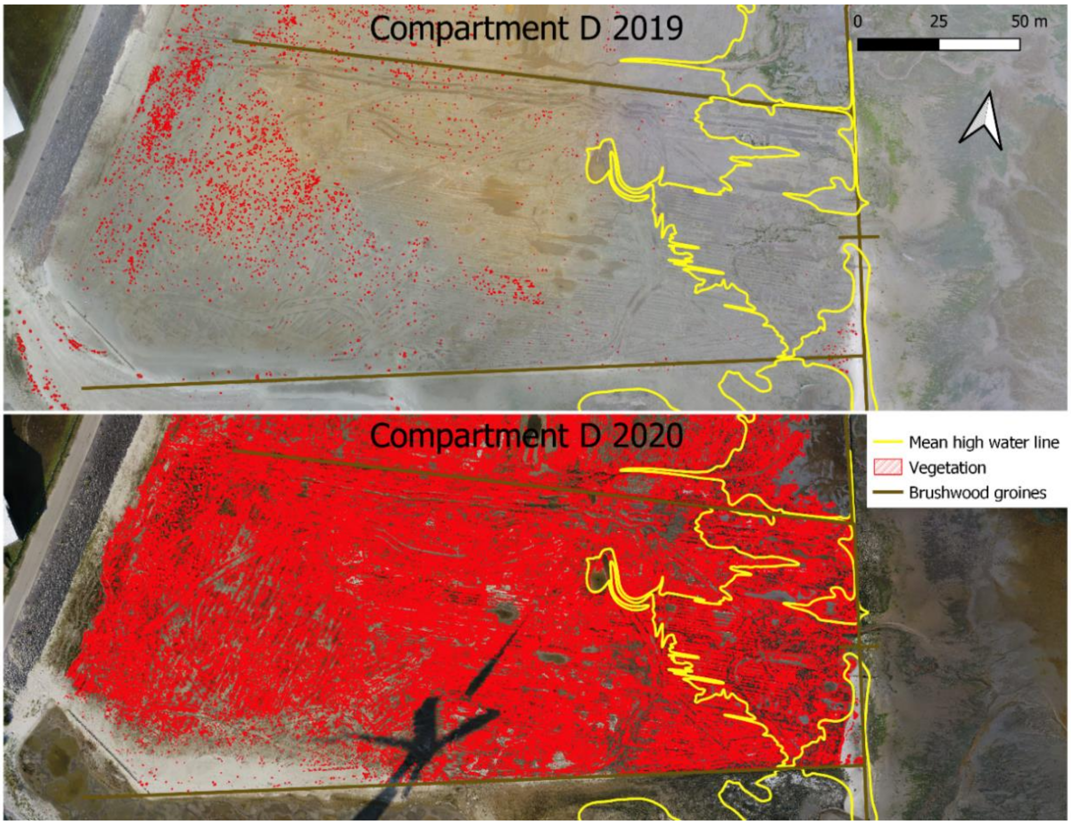

Figure 8-30 Classification of vegetation at the Marconi salt marsh pilot in 2019 and 2020 based on aerial photographs in compartment D.

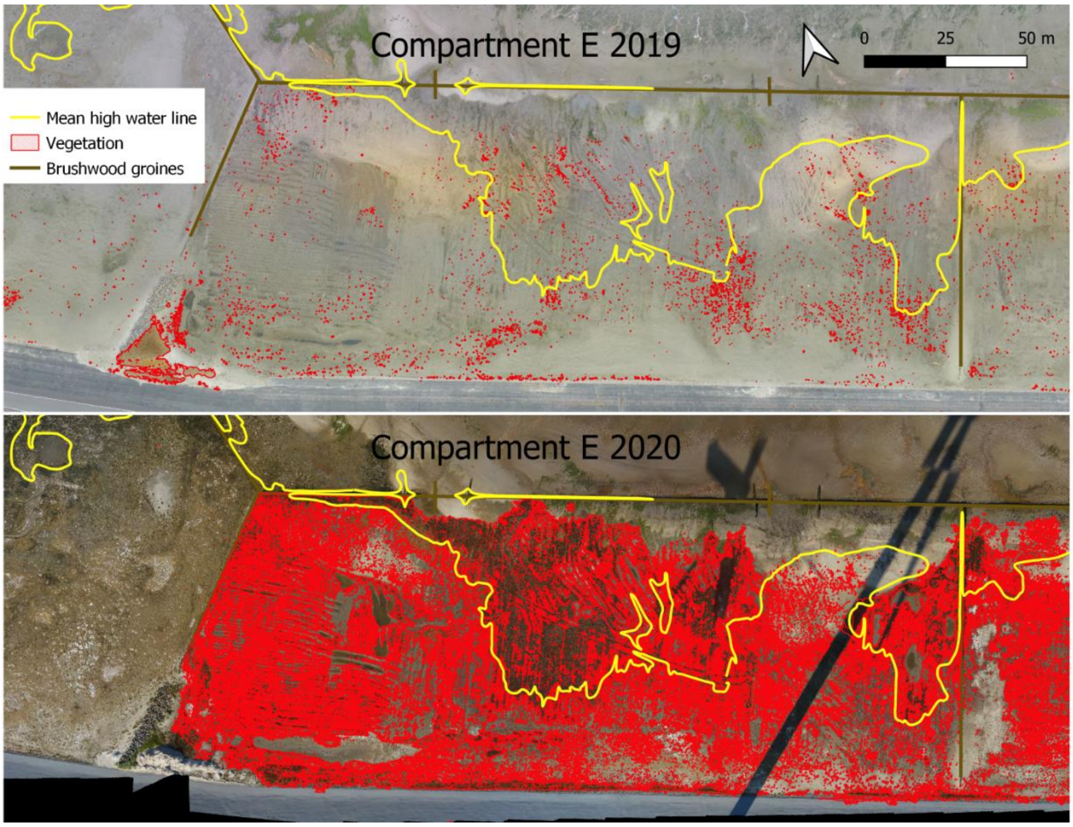

Figure 8-31 Classification of vegetation at the Marconi salt marsh pilot in 2019 and 2020 based on aerial photographs in compartment E.

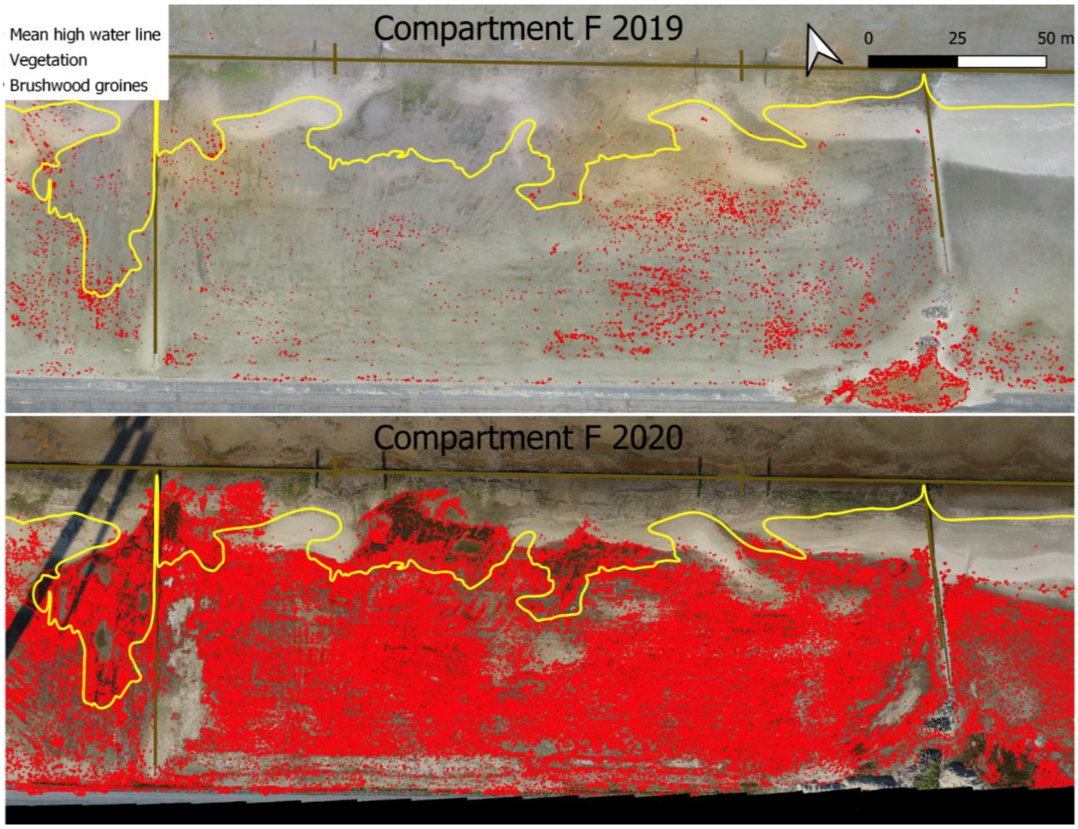

Figure 8-32 Classification of vegetation at the Marconi salt marsh pilot in 2019 and 2020 based on aerial photographs in compartment F.

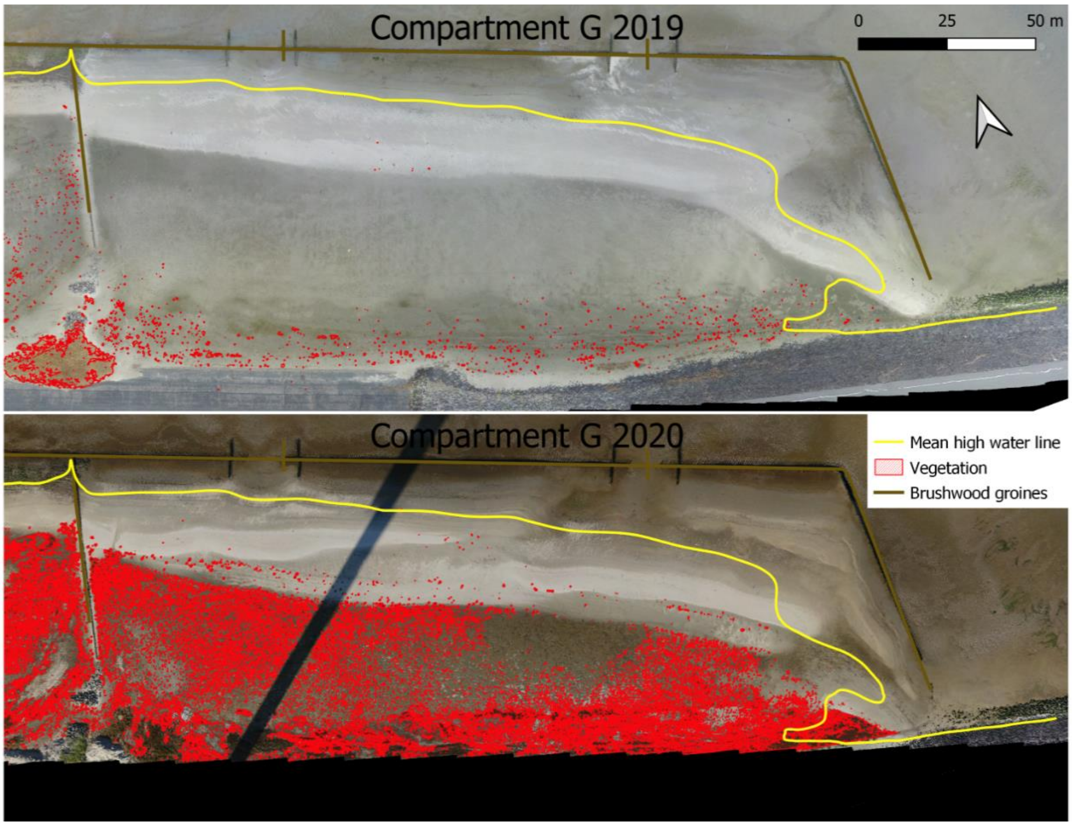

Figure 8-33 Classification of vegetation at the Marconi salt marsh pilot in 2019 and 2020 based on aerial photographs in compartment G.