Wax and wane of *Zostera marina* on the tidal flat Hond-Paap/Hund-Paapsand in the Ems estuary; examinations of existing data

Study commissioned by NLWKN (D)
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TABLE OF CONTENTS

1 INTRODUCTION

The seagrass *Zostera marina* is an angiosperm that is adapted to living in the marine environment, in temperate as well as (sub)tropical regions. Common names for it are 'common eelgrass' or 'seawrack'. Common eelgrass (*Z. marina*) grows in the Wadden Sea, together with its congeneric species Dwarf eelgrass (*Zostera noltii*) (Figure 1). In the intertidal and particularly in the subtidal zone seagrasses can build a habitat that is important for macrobenthos and fish, therefore it is a valued part of the marine ecosystem. Worldwide, there is a concern about the decline of seagrass habitats.

Common eelgrass has two phenotypes, a flexible annual form growing in the intertidal and a robust perennial form growing in the sublittoral. The sublittoral form of *Zostera marina*, which until the 1930's covered areas up to 150 km^2 in the western Wadden Sea and had high economic importance, disappeared since 1932 and never recovered (Van Katwijk 2000).

In the international Wadden Sea, seagrasses (only the perennial *Zostera noltii* and the flexible annual form of *Zostera marina*) are nowadays encountered in the intertidal zone. Although mixed populations of both species do occur, most sites have mono-specific seagrass occurrences of either Common or Dwarf eelgrass.

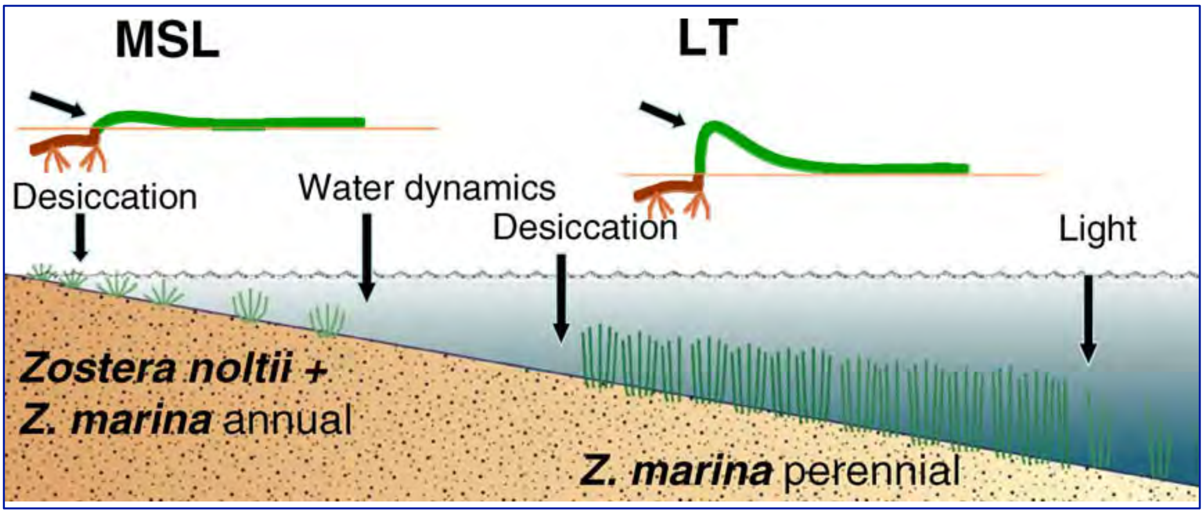


Figure 1. Zonation of different seagrass species and types in the tidal environment (Van Katwijk, 2000).

Common eelgrass showed a steep decline in the Dutch Wadden Sea, in contrast to Dwarf eelgrass which seems to be doing relatively well in recent years in the Dutch and in the Lower Saxony Wadden Sea (Figure 2, Figure 3). On Knechtsand and Eversand, two locations on the Lower Saxony coast, Common eelgrass areas of alltogether 420 ha have developed in recent years (Adolph 2010). In the Dutch Wadden Sea, except for Hond-Paap, only limited areas of *Zostera marina* are found on Balgzand (Western Wadden Sea) as a result of experimental transplantations (Bos & Van Katwijk 2007). In 2011 and 2012, *Z. marina* seed distribution experiments have been conducted by RWS/Deltares and the Dutch Wadden Sea Society on 3 locations in the Dutch Wadden Sea, of which the results remain to be seen in this and coming years.

Until recent years, the largest meadow (c. 300 ha) of *Zostera marina* of the Dutch and Lower Saxony Wadden Sea was found on the tidal flat called Hond-Paap (NL) or Hund-Paapsand (DE), situated in the middle part of the Ems estuary (Figure 4).

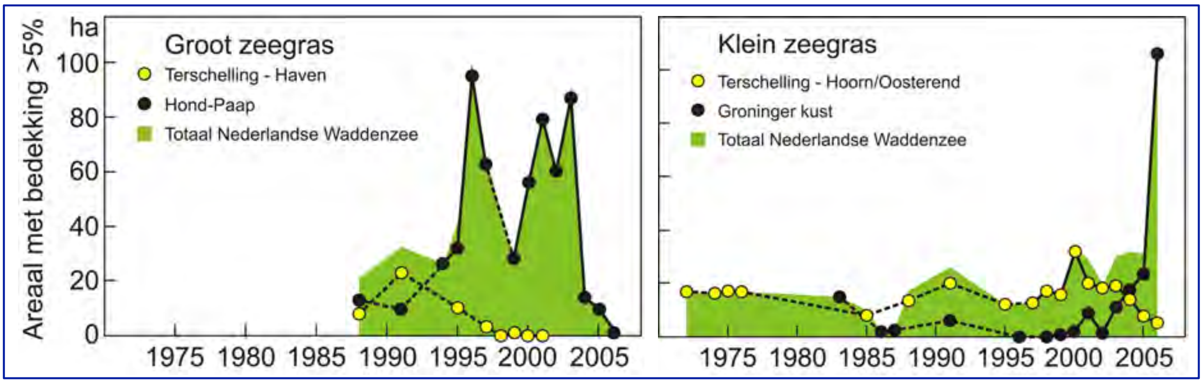


Figure 2. Area (ha, with cover >5%) and development between 1975 and 2006 of (left) *Zostera marina* (Groot zeegras) and (right) *Zostera noltii* (Klein zeegras) in the Dutch Wadden Sea. Source: Wanink & Van der Graaf, 2008.

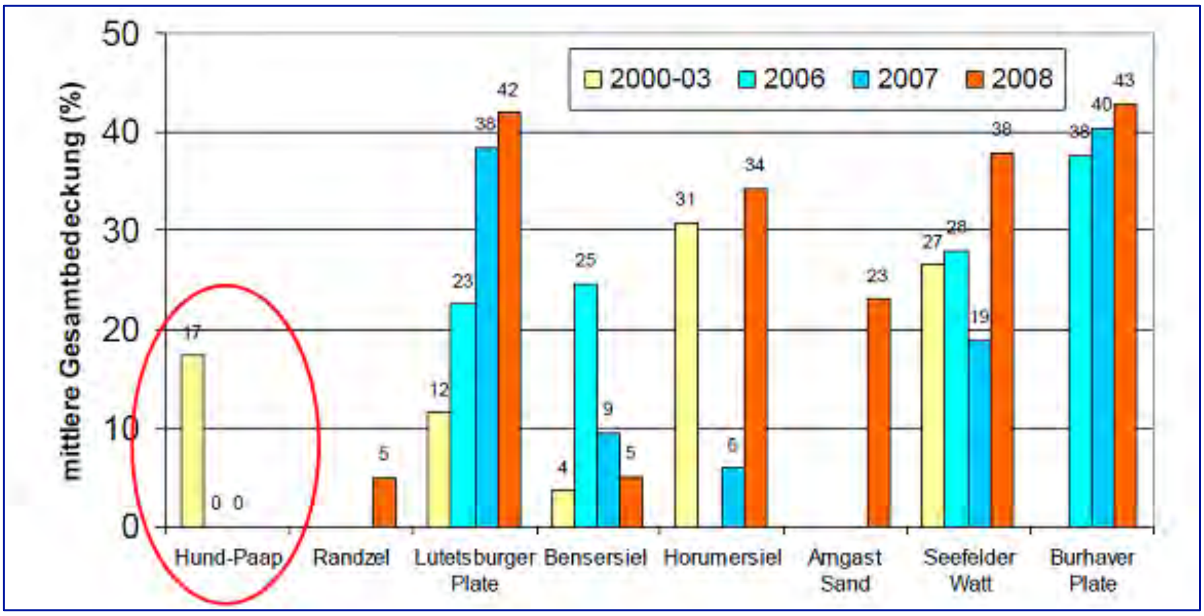


Figure 3. Average cover of Lower Saxony seagrass areas in 2008 compared to earlier investigations of Ritzmann & Herlyn 2007 and Adolph 2010 (Adolph, 2010.). These data relate to Dwarf Eelgrass (*Zostera noltii*), with exception of Hond-Paap which has *Zostera marina*.

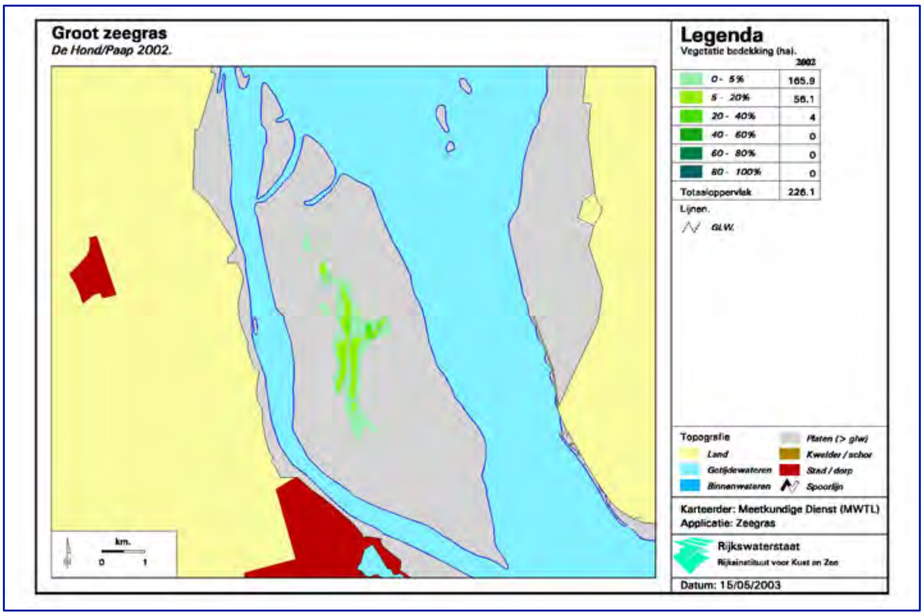


Figure 4. Location of the seagrass-meadow on Hond-Paap in 2002. Source: Rijkswaterstaat.

The presence of solitary plants of *Zostera marina* on Hond-Paap was first recorded in 1973 (Polderman & Den Hartog 1975). The occurrence was reconfirmed in 1988 and seagrass was monitored since then (Erftemeijer, 2005); this was done at an annual frequency between 1994 and 2011 as part of the Dutch MWTL[1]-program of Rijkswaterstaat and, parallel to this, by monitoring surveys of the Niedersächsischer Landesbetrieb für Wasserwirtschaft, Küsten- und Naturschutz - NLWKN (Germany).

The Hond-Paap seagrass area increased in size between 1999 and 2003 to reach its maximum extent. In 2003 the population was apparently still thriving (Erftemeijer & Wijsman 2004), but since 2004 there has been a dramatic and continuing decline in both the area and the cover of seagrass, until in 2007 and 2008 it had nearly vanished and the cover was nowhere higher than 5%. Until 2012 (own observation, August 2012), there have been no signs of recovery and only a few isolated plants remain.

1.1 Aim of the study

The recent decline of the *Zostera marina* field on Hond-Paap contrasts with positive developments of seagrass (*Z. marina* and/or *Z. noltii*) on tidal flats off the eastern Lower Saxony coast and feeds the suspicion that specific factors inside the Ems estuary play a role. Special attention is therefore given to local anthropogenic factors. In addition, the trend of *Z. marina* in the Ems estuary seems to disagree with predictions of seagrass growth potential (De Jong et al. 2005), which estimated 40-80% suitability for seagrass on this tidal flat. This raises the question if conditions on Hond-Paap have changed and led to reduced growth conditions for *Z. marina*.

The main aim of this study is to define possible causes, related to the decline of seagrass on Hond-Paap, based on (not statistical) analysis of existing data. The growth potential of Common eelgrass *Zostera marina* on Hond-Paap in the Ems estuary was evaluated by analysing the conditions underpinning the map of seagrass growth potential (De Jong et al. 2005). The growth potential on Hond-Paap may have changed outside the optimal range for *Zostera marina* or the parameters, describing the growth potential, may be insufficient. Hypotheses about possible causes of *Zostera marina* decline on Hond-Paap are formulated.

The study comprises a literature review to add recent insights to the previously described relevant factors, such as environmental (current, waves, nutrients, salinity, turbidity, sedimentation, exposition, herbicides) and biological (growth conditions, herbivory, seed development and dispersion) parameters and an analysis of existing data of relevant factors. As a follow-up on the analysis, some measures are discussed to improve the current seagrass status in the Ems estuary on the tidal flat of Hond Paap.

The study was carried out in close cooperation between the German and Dutch authorities in the framework of the bilateral "Arbeitsgruppe Ems-Dollart".

1.2 Preface

In a literature review, the recent insights in seagrass ecology were studied. There have been numerous publications during the last few years, probably inspired by the world-wide anthropogenic impact on, and deterioration of, seagrass areas. Furthermore, it is obvious that the ecology of *Zostera marina* is complex and that the development of

[1] Monitoring Waterstaatkundige Toestand des Lands

seagrass populations reflects a delicate balance between several factors of which only few are known in detail.

This analysis focused on the relation of area, cover and spatial distribution of *Zostera marina* on Hond-Paap with the tidal flat elevation and tidal characteristics, together determining the duration of exposure during low tide. In addition, the climatic extremes of the period 1990-2010 were examined with special attention to long periods of high water temperatures or cold periods (risk of ice scour) during winters.

A selection of abiotic parameters is presented and is discussed in relation to seagrass. Detailed data on dumping of dredged material on the dumping sites K5, K6 and K7 were not available, therefore this factor could not be examined.

Biotic data such as the presence of mussel-/oysterbeds were available, as well as limited bird counts (with respect to herbivory).

Detailed investigation of the hydrodynamics were outside the scope of the present study.

All GIS-based applications were carried out by Kerstin Kolbe, NLWKN.

1.3 Acknowledgements

We like to thank the following people for their positive responses to requests for data and information:

Jeroen Bergwerff (Dataservicedesk RWS); Arie Naber, Peter Bot, Herman Mulder (RWS WD); Dick de Jong (RWS ZL); Jaap de Vlas; Tjisse van der Heide (RUG); Justus van Beusekom (Uni Hamburg); Bart Grasmeijer (Arcadis); Karin Troost (IMARES); Klaas Froma (DLV Plant); Marinus Brijker (Avifauna Groningen, Wadvogelwerkgroep); Bas van Maren (Deltares), Sjaak de Boer (Groningen Seaports).

2 ANTHROPOGENIC INFLUENCES IN THE STUDY AREA

Different aspects of the Ems estuary are described in detail in numerous reports, studies and publications. Examples of recent reviews are those of Cleveringa 2008, Bos et al. 2012, Vroom et al. 2012. The description of the study area will focus on the characteristics of the tidal flat Hond-Paap and of the relevant anthropogenic impacts. Both Germany and NL consider this area as belonging to their territory, and therefore the management of this area is regulated in the Ems-Dollard treaty of 1960.

The study area is the tidal flat of Hond-Paap (NL) or Hund-Paapsand (D), situated in the central part of the Ems estuary (Figure 5). With an area of c. 2500 ha, Hond-Paap is the largest tidal flat in this part of the estuary (Erftemeijer 2002). Originally, it was composed of two units (Hond and Paap) that have merged to one elongated, oval-shaped tidal flat with a more or less North-South orientation.

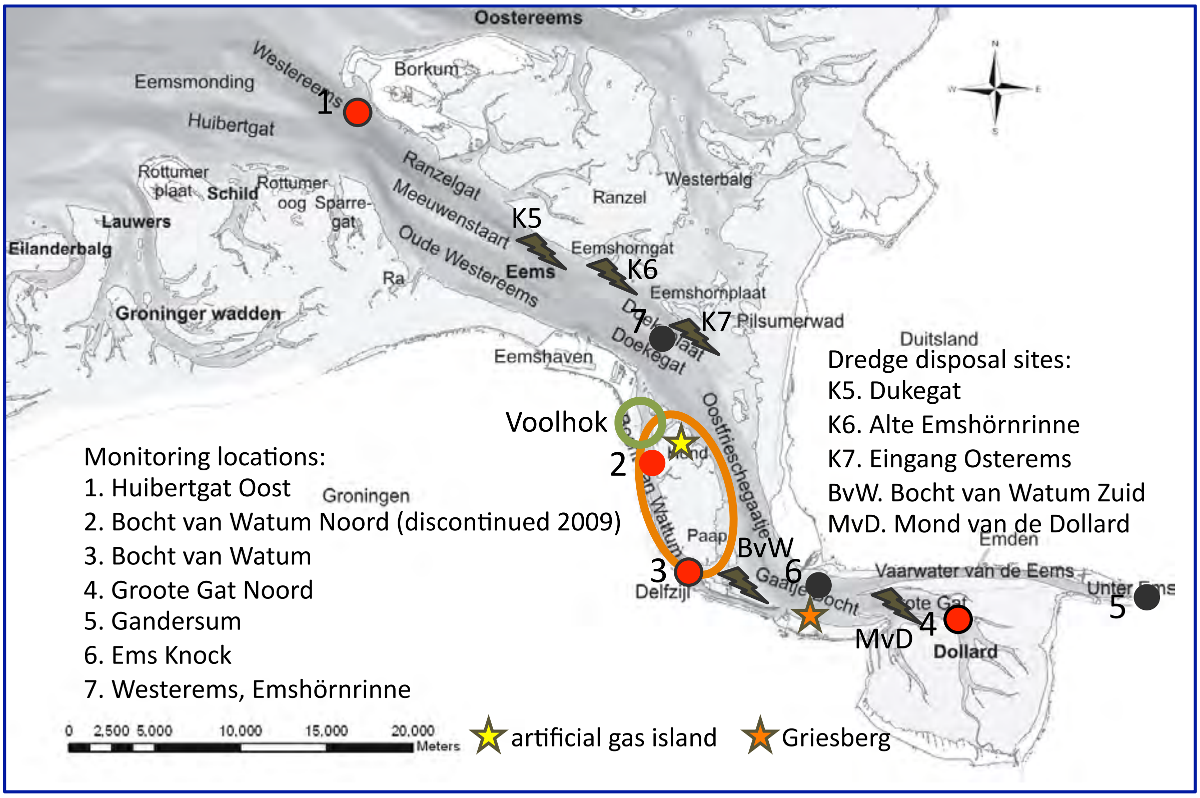


Figure 5. Situation of the tidal flat Hond Paap (orange oval) and Voolhok (green) in the Ems estuary, as well as the monitoring locations and the relevant dredge disposal sites, artificial gas-island and Griesberg (Brunner Mond). (Adapted, after: Cleveringa et al., 2008).

Hond-Paap is surrounded by several tidal channels (Bocht van Watum, Oostfriesche Gaatje, Doekegat, Gaatjebocht). The dimensions of the shipping channel Oostfriesche Gaatje (OG) are increasing at the expense of Bocht van Watum (BvW), which used to be the main shipping channel in the estuary. The importance of the ebb-dominated BvW steadily decreased since the beginning of the 20^{th} century, because the tidal currents were forced in a more easterly direction through OG. In addition, a dredge disposal site was situated in the southern entrance of Bocht van Watum and the former northern entrance of the Delfzijl harbour was replaced by a 3 km long channel, Zeehavenkanaal. The combination of these led to rapid filling with sediments of the ebb-channel Bocht van Watum, which also affects the hydrodynamic circulation cells (Cleveringa 2008).

The tidal flat consists of fine sands in the eastern part and more muddy sediments in the western part (Figure 6). Its elevation is between NAP -14 dm and NAP +3 dm (Kleef 1991). The abiotic environment is highly dynamic, with seasonal and tidal variations in a.o. temperature, salinity, turbidity and current velocity. Salinity varies between 10 (winter) and 30 PSU (summer) near the Hond-Paap tidal flat.

The macrobenthos fauna includes 24 species of different groups (Polychaetes, Lamellibranchiae, Gastropoda, Crustacea and Nemertinia) and the biomass is dominated by *Mya arenaria* (Kleef, 1991).

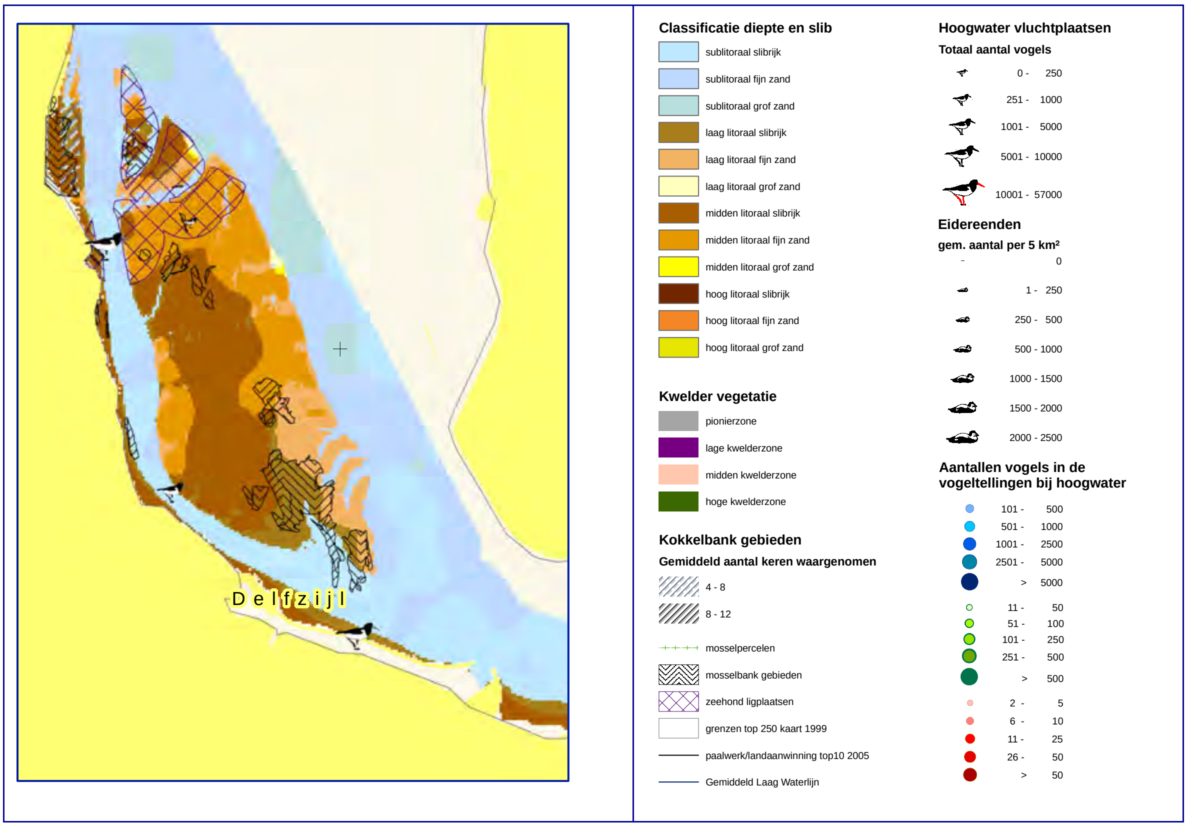


Figure 6. Ecological features of the tidal flat Hond-Paap (Dankers et al. 2006).

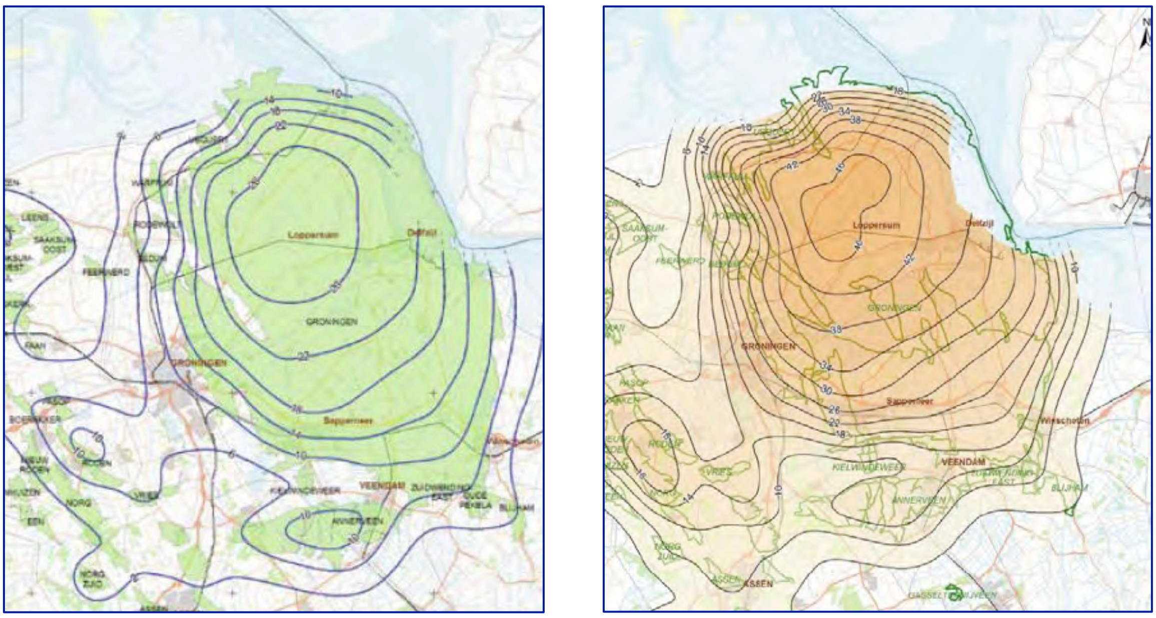


Figure 7. Realised (left) and Prognosed (right; 2070) subsidence by gas-extraction in Groningen (contours in cm). Source: Commissie Bodemdaling Groningen.

A dominant anthropogenic factor in the estuary is the continuous large-scale dredging and dumping of sediment for channel maintenance. Dredge disposal sites are situated in Doekegat (K5, K6, K7), Bocht van Watum Zuid and Mond van de Dollard (Figure 5). Of those, K7 is the nearest to Hond-Paap at a distance of c. 3000 m to the artificial Gas-island[2] on the northern part of Hond-Paap. However, K5 is the most intensively used and with flood tide, the sediments are likely to be distributed in the direction of Hond Paap. In addition, there is sandmining in Oostfriesche Gaatje, adjacent to Hond-Paap.

The Hond-Paap is at the outer contour of the area that is subject to subsidence by gas-exploitation of the so-called Slochteren or Groningen field. For Hond-Paap a subsidence (since 1964) of 10-20 cm was reported in 2008; the prognosed subsidence until 2070 is 20-40 cm (Figure 7).

Just east of the harbour of Delfzijl, at the edge of Gaatjebocht, there is a 22 ha chemical disposal site of the soda producing industry of Brunner Mond, which is now no longer in use but which created a very basic (high pH) mount of calciumcarbonate (called 'griesberg') during the past years (see Figure 5).

Figure 8. Pipeline for gas transport crossing Hond-Paap (De la Motte, Spiekhout & Lentfert 2004).

During 2003, the fundation of a pipeline for gas transport had to be reconstructed because erosion in the tidal channel had undermined it at the southeastern side of the Hond Paap (Figure 8). This operation, which was carried out between June and August and involved dredging and excavation of 250.000 m^3 of sediment and dumping of material, was accompanied by biological monitoring between April and September 2003. This monitoring only mapped the short-term effects on seagrass and birds. Although turbidity was not measured, the additional turbidity because of the operation was likely to occur during the period between June 3rd and August 15th (Erftemeijer & Wijsman 2004). The whole operation was carried out during the growing season of seagrass *Zostera marina*, growing nearby on the tidal flat.

[2] Gas-island, created in the 1960's; serves nowadays to measure the gasvolumes and gaspressure.

3 LITERATURE REVIEW OF SPECIFIC SEAGRASS PARAMETERS

Eutrophication, high water temperatures and dredging are regularly mentioned as environmental causes for the degradation of seagrasses in temperate regions, together with biological causes such as wasting disease (*Labyrinthula*) and herbivory, and extreme (climate) events such as ice scour (destroying the seed bank by removing the top-sediment layer) and heat waves (Orth et al. 2006).

Only two factors, 'light attenuation' and 'pore water RedOx' (related to toxic sulfide levels), explained 77% of the presence/absence data of *Zostera marina* populations in European marine waters (Van der Heide et al. 2009). Indicators of light stress in seagrasses may include decreases in below-ground biomass and carbohydrate contents of rhizomes, tissue nutrient contents, Chl-a contents of leaves and various photosynthetic growth parameters (Erftemeijer & Lewis 2006).

Major meteorological events and direct grazing are mentioned as factors that play a secondary role in the decline of submersed plants (Kemp, Boynton & Means 1983).

3.1 Reproduction of *Zostera marina*

Zostera marina can spread through its rhizomes (vegetatively) or through seeds; flowering occurs seasonally from May through September (Zipperle 2012). The seeds are relatively heavy, non-floating, and usually are dropped nearby the plant; on the other hand, floating shoots containing seeds can be transported with tidal and wind-driven currents over tens of kilometers of distance at the end of summer (Erftemeijer et al. 2008). In this way, new areas can get colonised by *Zostera marina*, which may actually have occurred at the location Voolhok (discovered in 2003 and still persisting) in the vicinity of Hond-Paap.

On the tidal flat Hond-Paap, Erftemeijer & Wijsman (2004) observed that *Zostera marina* reproduces predominantly through seed, and not by vegetative roots. This makes the species vulnerable and highly dependent on the production of sufficient seed and on successful germination in the next year. Plus et al. (2003) observed rapid initial recolonisation followed by vegetative expansion after an anoxic event. However, during the first year of recolonisation no flowering shoots were observed. Two consecutive events at the same site would deplete the seed bank and several failing years in a row can thus lead to a fast reduction of a seagrass population unless seeds are imported from other areas (e.g. from a few plants on Voolhok or Randzel, but otherwise not available in the vicinity of Hond-Paap).

In a field experiment, *Z. marina* seed set decreased markedly when there were less than five flowering shoots m^{-2}, hence low densities of flowering ramets and meadow fragmentation may result in widespread limitation of seed set and reproductive output in seagrasses (Reusch 2003). At the current low plant density on Hond-Paap, well below 5 shoots m^{-2}, the seed production may have become limiting. Seed can be lost for Hond-Paap by export of shoots with seed in autumn, and also by seed predation (e.g. by crabs or herbivorous birds) or by unfavourable conditions, such as high hydrogen sulfide concentrations in the bottom. Unfortunately, monitoring data of these parameters are not available for Hond-Paap.

Once in the sediment, the seeds of some seagrass species remain dormant for some time before germinating, and have a documented dormancy period of about half a year for *Zostera marina* (Borum et al. 2004). Seed survival for more than one year appears to be a rare situation in seagrasses; therefore the seedbanks of *Z. marina* are short-lived and are of a transient nature (Orth et al. 2000). This means that effects of failing seed production or germination will manifest from one year to another in a predominantly annual seagrass population, such as present on Hond-Paap.

Seed dormancy has not received much attention in seagrass studies; the focus has been on germination of seeds. Factors that have been investigated in relation to germination are: salinity, temperature, light, scarification, and more recently also the oxygen-reducing properties of sediment where seeds germinate (Orth et al. 2000). According to Orth et al. (2000) no effect of low salinity on germination was found in the annual form of *Z. marina*, and light has not been considered important in germination of *Z. marina*. Scarification of the seed coat led to increased germination rates, especially in interaction with (low) salinities. Many experiments were conducted without sediment and with this a very important factor may have been overlooked: the oxygen conditions or redox potential present in the sediment. The sediment quality may be of high relevance on Hond-Paap, but no monitoring data are available to test it.

There are indications of enhanced germination at low oxygen conditions, although prolonged anaerobic conditions lead to development failures or reduced seed survival – which may be attributed to toxic sulfide conditions (not measured in the experiments). Orth et al. (2000) conclude that an interaction of temperature and sediment oxygen levels determines the variation in timing of seed germination in the field and suggest that the photoperiod does not influence buried seeds. They also think that, although implicated in many studies, the role of (low) salinity in germination of *Z. marina* may need to be reexamined. In a field study, Probert & Brenchley (1999) found that T = 6 °C was the optimum temperature for germination at anaerobic conditions and that temperature effects much depend on the oxygen concentrations. At aerobic conditions, more rapid germination occurred at lower salinity (c. 15 g/l). The germination rate of *Z. marina* seeds is generally low (<10-40%) in field situations, although under laboratory conditions it may be as high as 90% (Marion & Orth 2010). A rare positive effect of sediment trapping is an increased germination rate, as documented in *Zostera marina*. Seeds buried 15–25 mm below the surface had a significantly higher germination rate (63%) than seeds buried at 5 mm (De Boer 2007).

The reviewed literature does not give conclusive ranges of optimal salinity or temperatures for seed dormancy and germination and there is a general lack of information on the role of internal physiological cues. The existing seagrass monitoring does not examine the germination in spring, and not much can be said about these aspects.

3.2 Abiotic parameters

3.2.1 Elevation

The upper levels at which intertidal seagrass can grow are determined by the wave mixing depth (orbital velocity) and tidal amplitude, dessication and freezing. The lower elevation levels are determined by the light availability, beside minimum and maximum current velocities (De Boer 2007). The relative duration of tidal flat exposure during low tide ('droogvalduur', % of the day) is considered a relevant parameter, describing the interaction of tidal characteristics and tidal flat elevation. The optimum for seagrass is an exposure duration of 40-65% of the time (De Jong et al. 2005).

3.2.2 Salinity and water temperature

Salinity and water temperature have an effect on the ecological performance of *Zostera marina*, as was demonstrated in experiments (Nejrup & Pedersen 2008) including several levels of salinity (2.5 to 35‰) and different water temperatures (5 to 30 °C). Extreme conditions may affect the fitness of eelgrass and may potentially limit its distribution in coastal and estuarine waters.

Low salinity (<5‰) increased mortality (3–6-fold) and had a strong negative effect on shoot morphology, photosynthetic capacity and growth, whereas common eelgrass performed almost equally well at salinities between 10 and 35‰. The optimum salinity for common eelgrass was between 10 and 25‰ depending on the response parameter in question (Nejrup & Pedersen 2008). In Dutch waters, seagrass is found at salinities between 16 and 29.5 PSU (De Jong et al. 2005); however, *Zostera* plants originating from the Ems estuary were negatively affected at salinities of 26 and 30 PSU (Van Katwijk et al. 1999). Therefore, an optimum range of between 16 and 25 PSU is applicable to the Ems *Zostera*-population.

Extreme water temperatures have an overall negative impact on eelgrass, although via different mechanisms. Low water temperatures (5 °C) slowed down photosynthetic rate (by 75%) and growth, but did not affect mortality, whereas high temperatures (25–30 °C) increased mortality (12-fold) and lowered both photosynthetic rate (by 50%) and growth. The optimum water temperature for eelgrass appeared to lie between 10 and 20 °C (Nejrup & Pedersen 2008).

3.2.3 Eutrophication and oxygen

Eutrophication effects may be indirect, through reduced light conditions caused by algal blooms or epiphyte growth. Or effects may be direct through toxicity, caused by the increased ammonia or high sulfide concentrations in the sediment pore water (Van der Heide et al. 2009). These pore water concentrations can easily become toxic to *Zostera marina* and this is more likely to occur at low oxygen concentrations (Pedersen et al. 2004).

Oxygen generated by seagrass photosynthesis during daylight is partly lost to the water column and partly transported to below-ground tissues and to the roots (Pedersen et al. 2004). The photosynthetic oxygen, build up during daylight, has been assumed to cover the night-time respiratory needs of roots and rhizomes. However, this photosynthetic oxygen pool is rapidly depleted in the dark. Oxic conditions in below-ground tissues are partially maintained by oxygen, diffusing from the water column to roots and rhizomes via air-filled lacunae running from leaves to roots (Greve et al. 2003). This supply may be insufficient to maintain oxic conditions, if water column oxygen concentration is low or if the oxygen demand of plant tissues or sediment is unusually high.

Experiments of Pedersen et al. (2004) confirmed the overwhelming importance of water column oxygen as a night-time supply of oxygen to above- and below-ground tissues. Following rapid shifts in oxygen concentration of the water column, it took only 30–60 min to reach new internal steady-state oxygen conditions, and when the water was depleted of oxygen it took less than 1 h before the meristem turned anoxic. These results imply that the storage capacity of (photosynthetic) oxygen in the seagrass plant is low. It demonstrates the strong influence of water column oxygen on O_2-contents inside the plant in the dark. Pedersen et al. (2004) observed anoxia and hence a risk of sulfide intrusion in below-ground tissues at water column oxygen concentrations that correspond to 30–35% of air saturation. Shoot–root ratios of seagrasses are highly variable and with higher below-ground biomass intra-plant anoxia may occur at even higher water column oxygen concentrations than observed in the experimental situation.

Poor oxygen supply might even occur during daylight if plants exhibit severe physiological stress by hypersalinity or very high temperatures, or by pathogen infection (Greve et al. 2003). Oxic stress and subsequent sulfide intrusion may arise in seagrasses for shorter or longer periods under a variety of environmental conditions. Events of sudden seagrass die-off have been observed in relation to water column hypoxia, hypersalinity and to periods of unusually warm and calm weather (e.g. Plus et al. 2003), which are conditions with high risk of sulfide intrusion.

Sulfide poisoning of the meristem has been implicated as a major cause of *Z. marina* dieback on reducing sediments during hot summers and episodes of O_2 depletion in the overlying water (Greve et al. 2003). This may already occur at water column oxygen saturations of <45% (Sand-Jensen et al. 2005) and at water temperatures of 25-30 °C (Greve et al. 2003).

At normal pH-levels and sufficient light for photosynthesis and carbon fixation, acute toxic effects of ammonia can be prevented by assimilation of NH_4^+ into free amino acid compounds. Chronic exposure to ammonia (during months or years) can give symptoms of physiological stress (chlorosis of leaves, suppression of growth); it may also make the plant more susceptible to pathogens such as *Labyrinthula*. While ammonia, given sufficient light conditions, may 'only' cause stress at pH 8, at enhanced pH (9) acute mortality may occur (Van der Heide et al. 2008).

3.2.4 Herbicides

Herbicides that are applied to agricultural crops can contaminate estuarine and coastal waters through wind-spray, wash-out from ground-water or surface run-off. Herbicides are often found in the aquatic environment (Nielsen & Dahllöf 2007) and it has been estimated that 0.2-2% of the herbicides applied to agricultural fields ends in coastal waters (Kemp et al. 1983). Widely used herbicides, such as atrazine, glyphosate (Roundup®), bentazone (Basagran®), MCPA, and antifouling agents such as cybutyne (Irgarol®), have been demonstrated to be toxic to seagrass species by photosynthetic depression (Scarlett et al. 1999, Winkel & Dahllöf 2007, Gao et al. 2011). While glyphosate, bentazone and MCPA as single components only represent a minor risk to seagrass, their effects are enhanced by synergistic effects when present as mixtures at low concentrations (Nielsen & Dahllöf 2007). Furthermore, the concentrations at which seagrass was affected are much lower and have greater impact for seedlings than for adult plants (Gao et al. 2011).

Herbicide run-off may represent an ephemerally and locally important stress to seagrasses but ranks behind the factors 'nutrient enrichment' and 'increased turbidity' (Kemp et al. 1983).

3.3 Biotic parameters

3.3.1 Wasting disease (*Labyrinthula*)

The wasting disease, that affects *Z. marina* more than *Z. noltii*, is caused by a marine slime mold-like protist, *Labyrinthula zosterae*. Wasting disease is believed to have been the major cause of the decline of seagrass in the North Atlantic, including the western Wadden Sea, in the 1930's. Its symptoms are small brown leasions that grow in size and finally cover the whole leaf and that lead to defoliation (Giesen 1990).

There are no indications of it, but it is not really known if wasting disease is still an important factor in the Wadden Sea. However, several publications point out that *Labyrinthula* is always present in the marine environment and that it strikes if the resistance of the plant is weakened by stress, making it susceptible to wasting disease (Raghukumar & Damare 2011).

In common eelgrass, stress and increased susceptibility is caused by water temperatures >25 °C, salinity >32-42 PSU or low light levels. Water temperatures >20 °C, salinities >30 PSU and reduced light conditions are more favourable for the parasite *Labyrinthula* than for the host *Zostera marina* (Giesen 1990, Sullivan 2011).

3.3.2 Herbivores

In temperate areas, waterfowl are generally considered the major seagrass herbivores (Thayer et al. 1984), of which: 2 species of swans (*Cygnus olor*, *C. columbianus*), 2 goose species (*Branta bernicla*, *B. canadensis*) and 3 duck species (*Anas acuta*, *A. penelope*, *A. platyrhynchos*). Different modes of grazing can be defined: pecking and swimming (remove leaves), grubbing (remove entire plants), digging (obtain rhizomes from bare areas). Some duck species can also consume seeds that are buried in the sediment. At low plant cover, the seagrass area becomes less attractive for waterfowl consumption.

3.3.3 Musselbeds

The upper limit of mussel beds is Mean Sea Level, thus mussels (*Mytilus edulis*) grow slightly deeper in the intertidal than seagrass *Z. marina* (Bos & Van Katwijk 2007). Mussel beds create increased sedimentation, stabilisation of sediments and a reduced mean grain size of sediments within the beds. They reduce wave and current activity and can facilitate the growth of seagrass by providing shelter. However, blue mussels can also have a negative effect on seagrass growth by altering the biogeochemical conditions. They enhance sulphate reduction in the sediment, thus increasing sulfide concentrations in pore water, resulting in reduced growth of *Zostera marina* (Vinther, Laursen & Holmer 2008). Mussel excretions can also stimulate growth of *Z. marina* and its epiphytes. A thick cover of epiphytes can reduce the relative growth rate of seagrass with 20% (Vinther & Holmer 2008).

3.4 Kansenkaart 2005

The habitat suitability map ('kansenkaart') of seagrasses in the Dutch Wadden Sea (De Jong et al. 2005) was based on a limited selection of relevant parameters, derived from models, namely: duration of exposure at low tide, orbital velocity, current velocity, salinity, ammonium flux from the sediment, and the interaction of ammonium and salinity. Looking at this map (Figure 9) the exposure at low tide seems to be the most determining factor. The potential growth map indicated that the Randzel, Hond-Paap and Voolhok are the only suitable locations for the occurrence of seagrass in the Ems estuary.

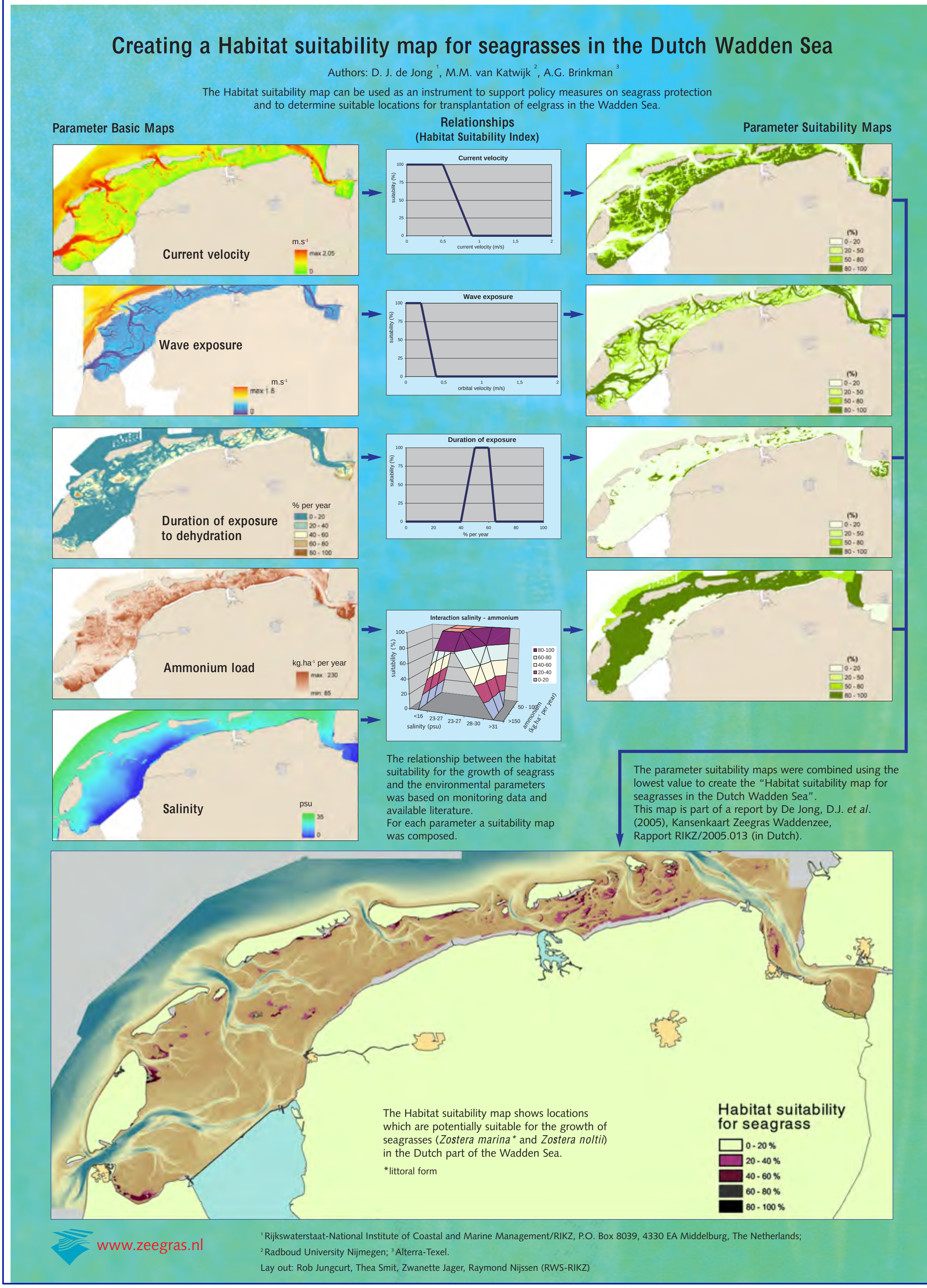


Figure 9. Map of growth potential ("Kansenkaart") for seagrasses in the Dutch Wadden Sea (De Jong et al. 2005).

4 EXAMINED PARAMETERS

4.1 MONITORING OF SEAGRASS DEVELOPMENT - ANNUAL SURVEY

Both the German (NLWKN) and Dutch (RWS) authorities monitor the seagrass population on Hond Paap (independently), because this tidal flat is situated in the common area of the Ems estuary. See 5.1.

NL (RWS)

Since 1994, the Dutch seagrass monitoring is part of the MWTL-program (Monitoring van de Waterstaatkundige Toestand des Lands), responsability of RWS. Yearly estimates of seagrass area and cover, partly based on a combination of aerial photo interpretation and field surveys, are available for the period 1995–2011 (except 1998); data of 1994 had not yet been converted by RWS and could not be used. Since 2005, the monitoring consisted of a combination of aerial and field surveys. A recent modification (since 2010) is that the field survey changed from an area- to a transect approach, without aid of aerial photo interpretation.

The seagrass habitats are systematically monitored in August or September by walking along a north-south oriented transect of several km. In each 20x20 m gridcell the cover of seagrass is estimated, and this information is used to construct a distribution and cover map of different seagrass species. The gridcell data were converted to calculate the area of *Zostera marina*. Because there were duplicates in the RWS data, a preliminary correction was made by Kerstin Kolbe (NLWKN) (see 5.1). As from 2011, RWS reduced the monitoring frequency of seagrass on HondPaap to once every 3 yrs.

DE (NLWKN)

The seagrass monitoring in Lower Saxony is carried out at a variable frequency: area wide, once every 6 years, and every year in late summer at selected locations (of which Hund-Paapsand is one) (Table 1). The methods consist of walking predefined transects of c. 1 km and GPS field mapping of area and cover of the seagrasses (Adolph et al. 2003).

On 28 August 2012 a visit to Hond-Paap was made with Marc Herlyn (NLWKN) as part of the German annual monitoring visit (see 5.2).

Table 1. Overview of German seagrass monitoring data.

Year	Area of *Zostera marina* (km^2) on Hund-Paapsand	Reference
1993-1995	1.2	Kastler & Michaelis, 1997
2000-2003	2.07	Adolph et al., 2003
2006	1.4	Ritzmann, 2007
2007	0	Ritzmann & Herlyn, 2007
2008	0	Adolph, 2008

Combination of data

The defined classes of seagrass cover differed between the countries and also changed over time, therefore we interpreted the cover classes as listed in the green column in Table 2. The description of the *Zostera* development on Hond-Paap and Voolhok (see 5.1) is based on the monitoring data from 1995-2011 of both countries. Based on a screening of the data, it was decided to proceed with a more detailed elaboration of the Dutch monitoring data because this was the more complete time-series.

Table 2. Cover classes used and interpretation for GIS analyses and maps.

Product info RWS data, Klasse-indeling		Entry in field <BED_ZOSMA> in GIS files (RWS)			Legend of WMS service RWS	Our interpretation for GIS analyses and excel files	German monitoring (Adpolph et al 2003)	Advice in TMAP Monitoring Handbook 2009
t/m 2005 & 2011ff	2006 t/m 2010	2004-2005	1995-2003, 2006,2007	2008, 2009, 2010				
				0	0%	0	0 = 0%	1 = <5% “devoid or scarce”
				0,005	>0-5%	>0-1%	1 = <1%	
				0,03				
Klasse 1 (>0–5%)	Klasse 0 (>0-1%)	0	0,5	0,5				
	Klasse 1 (1-5%)	1	2	2		>1-5%	2 = 1-5%	
Klasse 2 (5-20%)		2	12		>5-20%	>5-20% (6-20%)	3 = 5-20%	2 = 5-20% “scattered”
Klasse 3 (20-40%)		3	30		>20-40%	>20-40% (21-40%)	4 = 20-60%	3 = >20% “beds”
Klasse 4 (40-60%)			50		>40-60%	>40-60% (41-60%)		
Klasse 5 (60-80%)					>60-80%	-	5 = 60-00%	
					>80-100 %	-		

4.2 Elevation of the tidal flat Hond Paap

The elevation of the Ems estuary is regularly monitored by WSA Emden and NLWKN (Germany) and Rijkswaterstaat (Netherlands). From the German side, merely annual data of 1995–2005 and of 2010 were available. In the Netherlands, the elevation of the entire Dutch Wadden Sea, including tidal flats, is surveyed in a 6 years’ cycle (RWS Vaklodingen). Vakloding-data of 2008, 2002, 1996 were received from RWS Datacenter. Only RWS Vaklodingen 2008 have been used, because the other years were already covered by the German data (Table 3).

Table 3. Overview of used morphological data of Hond-Paap/Hund-Paapsand.

Year	Dataformat	Sourcetype	Origin
1995	grid – 25 x 25 m	continous	BSH
1996	Point Layer	discrete	RWS (NL)
1997	grid – 5 x 5 m	continous	BSH
1998	grid – 5 x 5 m	continous	BSH
1999	grid – 5 x 5 m	continous	BSH
2001	grid – 25 x 25 m	continous	BSH
2002	grid – 5 x 5 m	continous	BSH
2002	Point Layer	discrete	RWS (NL)
2003	grid – 5 x 5 m	continous	WSD
2005	grid – 5 x 5 m	continous	NLWKN
2008	Point Layer	discrete	RWS (NL)
2010	grid - 1 x 1 m	continous	NLWKN

The elevation values (continous data) were reclassified to decimeter classes (discrete data), so that e.g. dm-class “NAP/NN +0.45 m” is 0.40 to 0.50 m elevation. The area (ha) of each elevation class was calculated from the area and number of gridcells in the GIS-files. To compare the morphological development of the tidal flat with the seagrass development, the area was confined to the Hond-Paap contour (Figure 10a) or to the ‘restricted’ area in which seagrass was found during the last decade (Figure 10b).

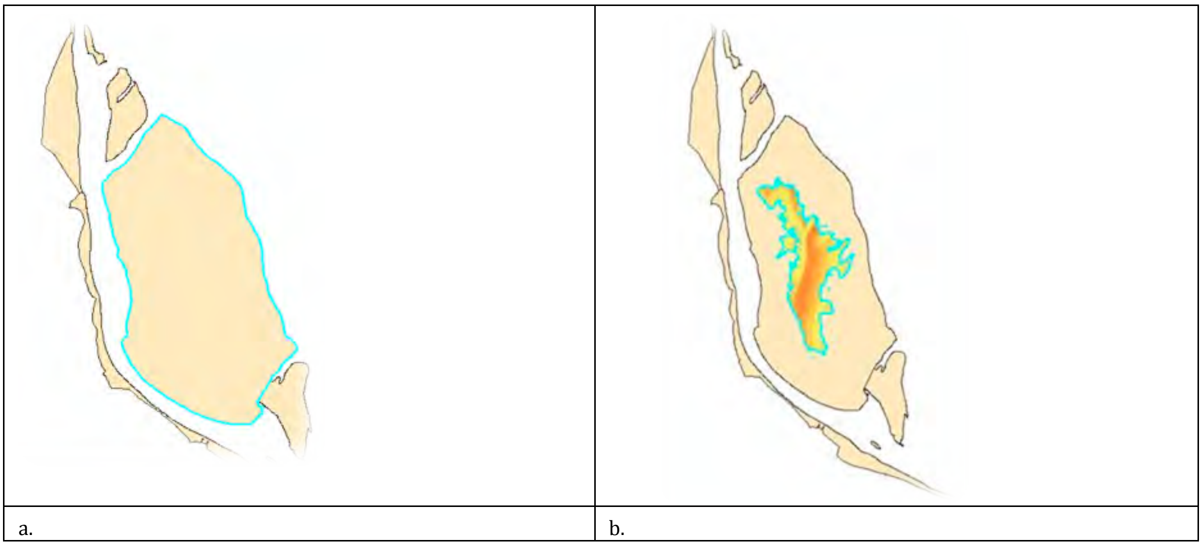


Figure 10. Contours of the tidal flat area of Hond-Paap, used in calculations of areas per elevation class. a. Hond-Paap proper (2440 ha), b. restricted area (491 ha) of potential seagrass occurrence (GIS: K. Kolbe, NLWKN).

Differences between years in elevation and in sediment volume were calculated and visualised in maps and tables (see 5.3).

4.3 Exposure Time

From the combination of available elevation and actual water level measurements (www.waterbase.nl), the duration of exposure at low tide (%) was calculated and presented for each day of a month (for example July, representing the seagrass growing season) (see 5.4).

4.4 Climate indicators

Climate data were obtained from the KNMI databases (www.knmi.nl). The Hellmann "Koudegetal" (H) was used to indicate the severeness of the winter and possible ice-cover. H is the sum of the average daily temperatures below zero that occur between 1 November of the preceding year and 31 March of the current year. If the sum H (dropping the minus-sign) is smaller than 20, the winter is very mild, whereas 100<H<160 indicates a cold winter. The warmth of the summer of a certain year is indicated with the "Warmtegetal" (W): the sum of daily averaged temperatures (T) > 18.0 °C between April and October. A day with T = 20.2 °C contributes 2.2 to W. Since 1900, W ranged between 4 and 221 (KNMI).

The annual hours of sunshine were obtained from KNMI records, as well as the occurrence of heavy storms (>10 Bft). The daily precipitation amount (RD) in 0.1 mm over the period 08.00 preceding day - 08.00 UTC present day of location Delfzijl, as well as the annual precipitation sum, were used (see 5.5).

4.5 Abiotic parameters

Rijkswaterstaat (RWS) is monitoring many parameters in the Ems estuary, as part of the MWTL-network, and these data can be accessed through www.waterbase.nl. The relevant locations for seagrass are Bocht van Watum (1988 – ongoing), Bocht van Watum Noord (1977-2009) and Huibertgat Oost (1977 – ongoing). Other locations have been discontinued and were not measured during the relevant time period which is 1994-2011.

German data on a diversity of water quality parameters (nutrients, temperature, pH, oxygen etc.) were available of several stations (Westerems Emshörnrinne, Ems Knock, Gandersum, Terborg and Herbrum).

The location Bocht van Watum Noord was used for most of the abiotic parameters, because it is located most nearby the seagrass area and it covers the period when the decrease became manifest, and it had a relatively good data coverage (see Table 4). The German location Westerems Emshörnrinne could also have been used, but the data-density was less and there was a broad overlap in parameters with the Dutch data.

Table 4. Overview of the available abiotic data by RWS (www.waterbase.nl) for the time period 1990-2011. The selected Ems estuary stations are presented (Eemshvn=Eemshaven, Bochtvwtnd=Bocht van Watum Noord), with the waterbase ID, parameter name (Temp=water temperature, Oxygen, pH, SSC=suspended sediment concentration, Ammonium, Nitrite, Salinity, Extinction, Irgarol and Atrazine) and the corresponding unit of the measurements. In the columns, the annual number of measurements per parameter is given for each year (1990-2009).

Station code	Eems hvn	Eems hvn	Bocht vwtnd	Bocht vwtnd	Bocht vwtnd	Bocht vwtnd	Bocht vwtnd	Bocht vwtnd	Bocht vwtnd	Bocht vwtnd	Bocht vwtnd
ID	ID1	ID44	ID360	ID377	ID410	ID491	ID492	ID559	ID713	ID2835	ID5592
Type	Water level	Temp	Oxygen	pH	SSC	Ammonium	Nitrite	Salinity	Extinction	Irgarol	Atrazine
Unit	m to NAP	°C	mg/l		mg/l	mg/l	mg/l		/m	µg/l	µg/l
1990	52704			11	12	11	11	12			
1991	52704			12	12	12	12	12			
1992	52704			12	12	12	12	12			
1993	52704			12	12	12	12	12			
1994	52704		12	12	12	11	11	12			
1995	52704		12	12	12	12	12	12			
1996	52704		6	6	6	4	4	6			
1997	52704		5	5	6	4	4	5			3
1998	52704		6	6	5	3	3	6			2
1999	52704		6	6	6	6	6	6			1
2000	52704		6	6	5	4	4	6			3
2001	52704	133	6	6	6	5	5	6			4
2002	52704	365	6	6	6	4	4	6			4
2003	52704	365	6	6	5	4	4	6	4	3	4
2004	52704	366	6	6	5	3	3	6	2	4	4
2005	52704	365	6	6	5	2	3	6	5	4	4
2006	52704	365	6	6	6	5	5	6	6	4	4
2007	52704	365	6	6	6	4	4	6	6	4	
2008	52704	366	7	7	6	4	4	7	5	4	
2009	52704	365	6	6	6	4	4	6	6	5	5

Daily averaged discharge data of the pumping station Spijksterpompen (Bocht van Watum) were available for the period 2000-2012 (Waterschap Noorderzijlvest).

Conform the Wadden Sea Quality Status Report (Van Beusekom et al., 2009), the winter ammonium and nitrite concentrations are used as a proxy for eutrophication.

Abiotic parameters in the context of seagrass development are presented in chapter 5.6.

4.6 BIOTIC PARAMETERS

There is no information on the presence of *Labyrinthula* in the Ems estuary.

Bird counts on Hond-Paap have been carried out as part of the monitoring program for the Gaszinker (Erftemeijer & Wijsman 2004).

The presence of mussel beds (*Mytilus edulis*) on the (intertidal) Hond-Paap and Voolhok is mapped at a regular basis by IMARES. The GIS-data of 2001-2012 were made available by Karin Troost (IMARES).

Biotic parameters in the context of seagrass development are presented in chapter 5.7.

5 SEAGRASS DEVELOPMENT AND RESPONSE TO EXAMINED PARAMETERS

5.1 SEAGRASS (*ZOSTERA MARINA*) OCCURRENCE ON HOND-PAAP AND VOOLHOK

The total area of seagrass on Hond-Paap, 300 ha at its maximum extent, fluctuated considerably during the past decade (Figure 11). The area of *Zostera marina* increased since 1994 to a small peak of 183 ha in 1996, followed by a decrease until 1999. Then, the area rapidly expanded to 285 ha in 2003-2004, after which a steep and ongoing decline occurred. In 2003, a new seagrass location was discovered bordering the Groningen coast of Bocht van Watum ('Voolhok' in the legend of Figure 11), with a maximum area of 15 ha. In 2006-2007, the area on Hond-Paap with low cover increased once more (to 180 ha) to decrease again since 2008.

Not only the area of the seagrass population decreased, but also the density of the plants (% cover). Dense patches with a cover of >20% *Zostera marina* were only found between 1995-2001, in 2003 and 2005 and the cover was highest in 1996. The cover of seagrass decreased steadily; since 2007 the cover was less than 1% everywhere (Figure 11).

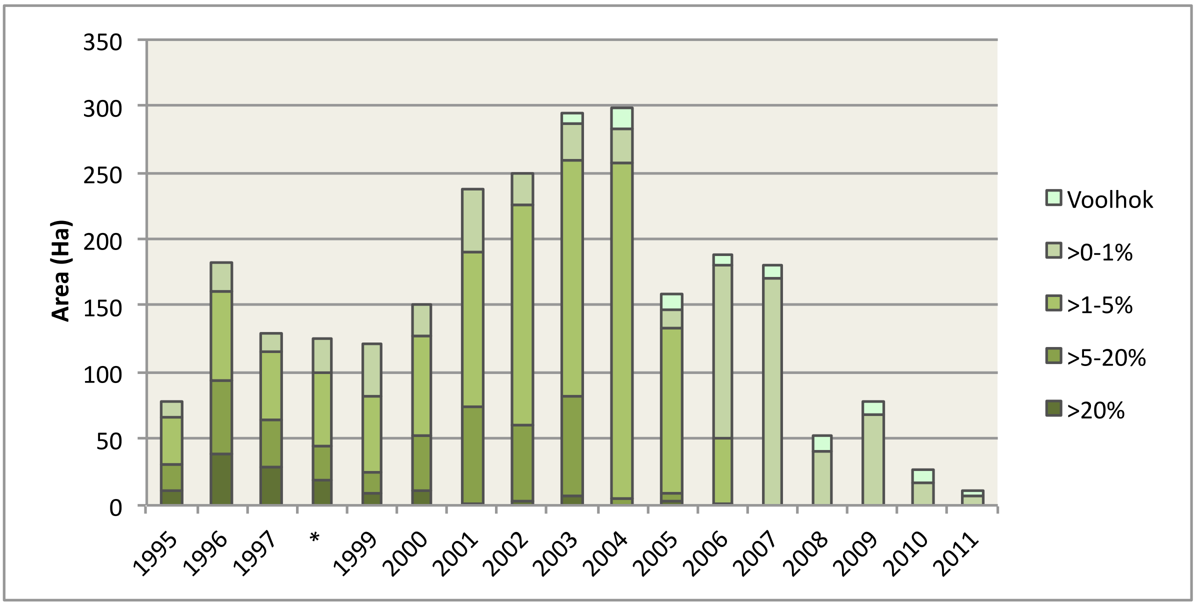


Figure 11. Area and cover of *Z. marina* on the tidal flat Hond-Paap. Cover classes: >0-1%, >1-5%, >5-20%, >20%. * 1998 interpolated.

An overlay plot of the spatial distribution of seagrass in different years (Figure 12) demonstrates that a relatively small but stable area of seagrass maintained the same position each year (indicated with dark/blue colors in Figure 12), whereas c. 78 % of the colonised seagrass area (491 ha) was covered with *Zostera* plants during less than half of the years investigated.

The spatial distribution of seagrass on Hond-Paap varied from year to year (Figure 13). Seagrass on Hond-Paap is concentrated around the elevated central axis of the tidal flat, generally North-South oriented. The highest cover of seagrass was observed in 1996, whereas the largest area was present in 2003. Since then, the distribution extended gradually less southward than before.

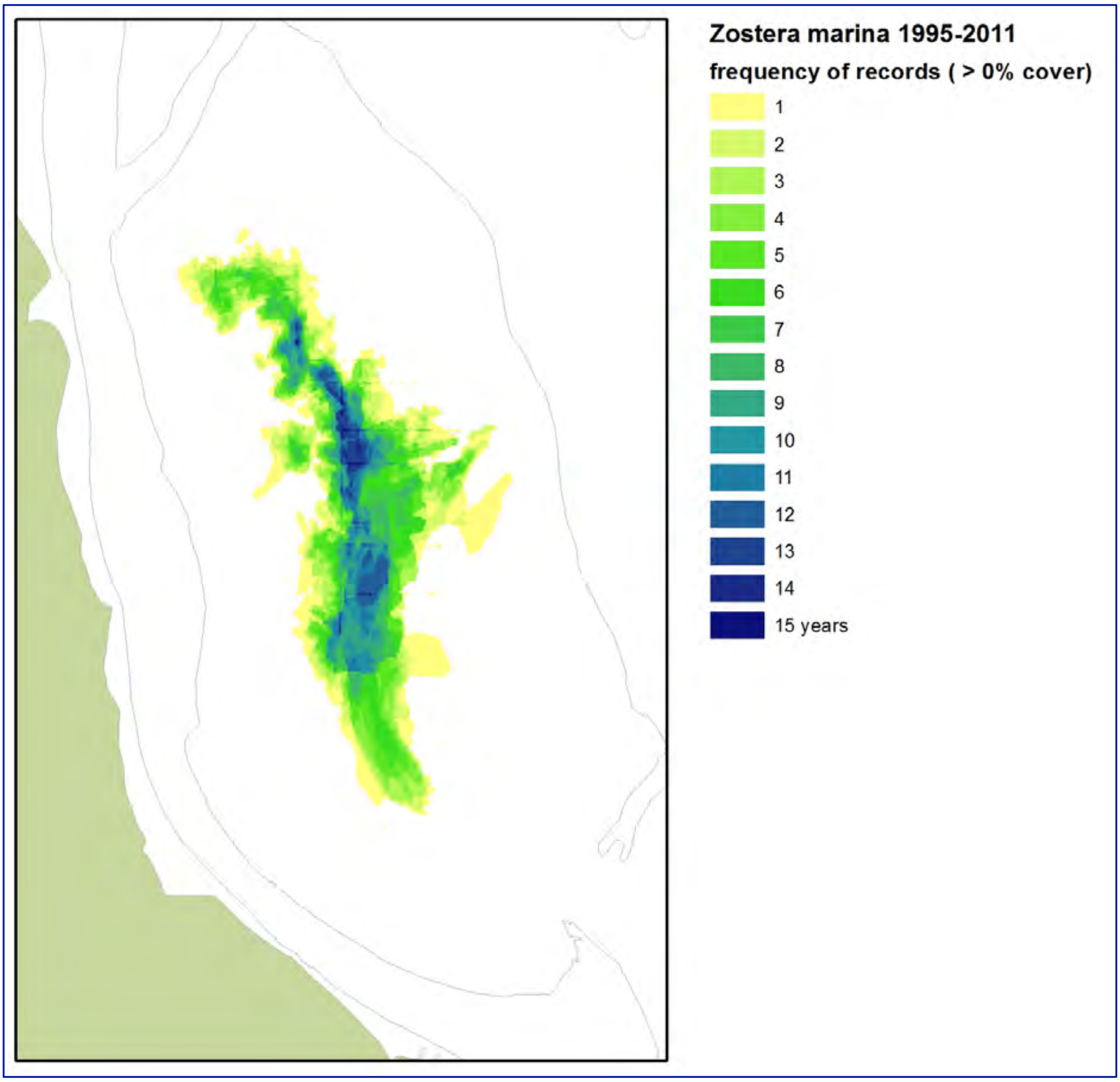
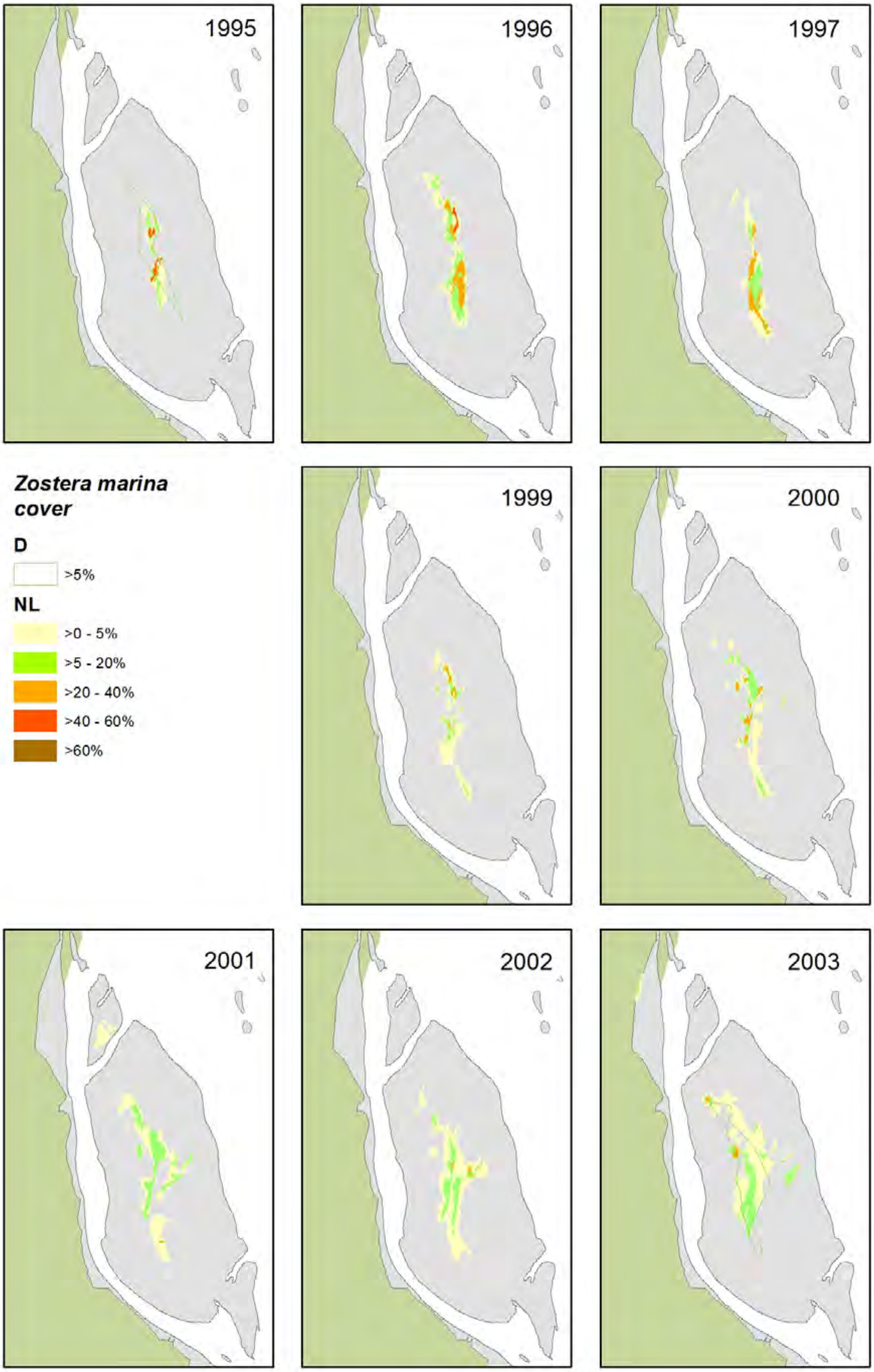


Figure 12. Overlay plot of the spatial distribution of seagrass on Hond-Paap during 1995-2011 (no data in 1998). The number of years that seagrass was registered is indicated. (GIS: K.Kolbe, NLWKN).

Differences between years are shown in detail in Figure 14. In 1996, compared to 1995, the cover on the central ridge increased and there was considerable area expansion to the West, over the whole range from North to South. However, in the following year (1997) there was again considerable reduction of area and cover at the Northern and Eastern parts of the tidal flat, but also some gain in area and cover in the South-West which was lost again in 1999. Between 2000-2001 and 2001-2002, there were some stable areas and considerable gains in area and cover in the Southern part as well as a new site on the former 'Hond' in the North. The tendency of increase persisted until 2003, but this year was the turning point to the onset of a sequence of years with considerable losses of cover and area which commenced in 2004 (Figure 14). See also Chapter 5.2 for illustrative descriptions of field observations (1994-2011).


1995
1996
1997
Zostera marina cover
D
>5%
NL
>0 - 5%
>5 - 20%
>20 - 40%
>40 - 60%
>60%
1999
2000
2001
2002
2003

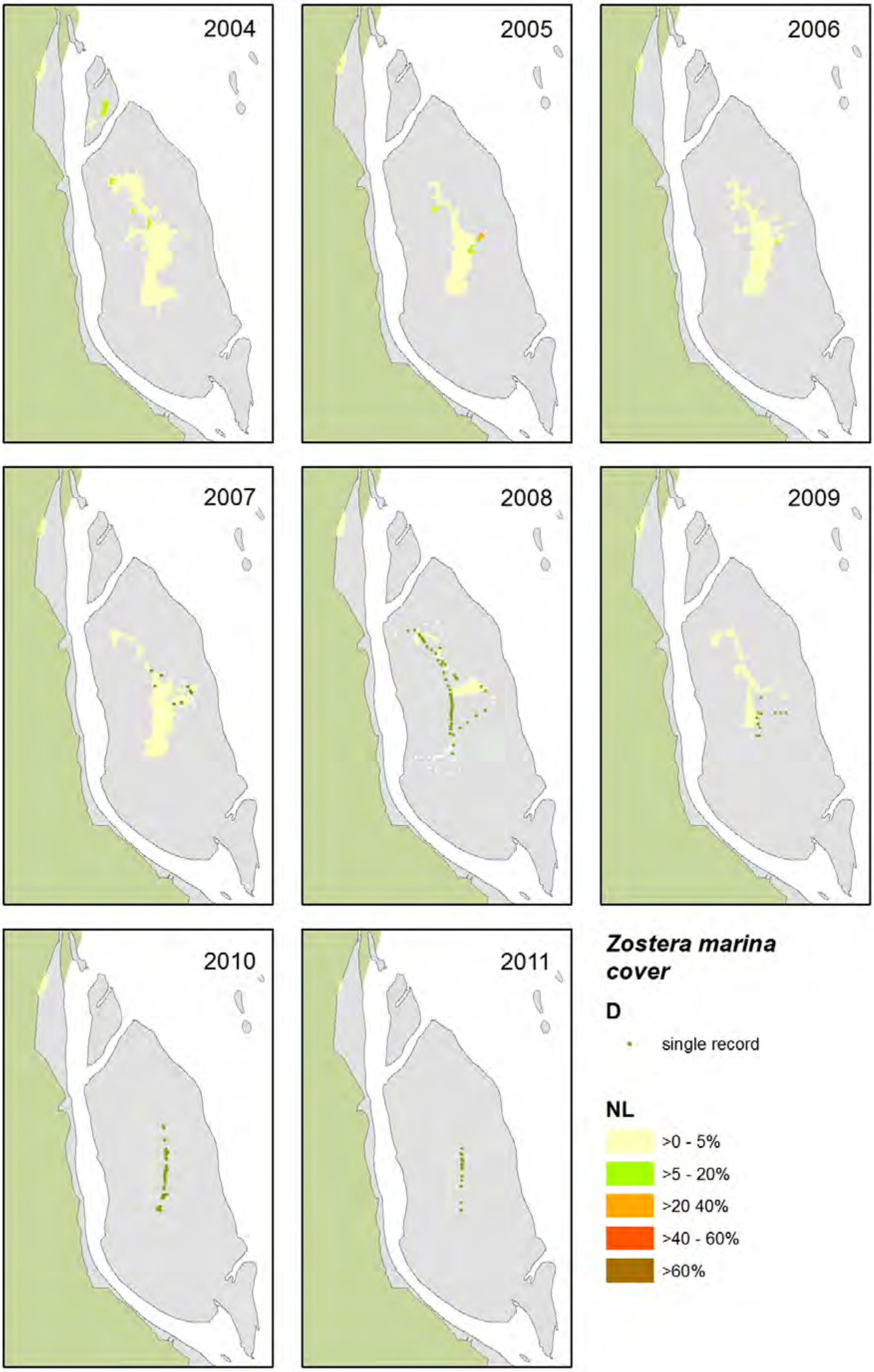


Figure 13. Maps of the spatial distribution and cover of Zostera marina on the tidal flat Hond-Paap and Voolhok in the period 1995-2011, excluding 1998 (no data). Source: RWS MWTL (GIS: K.Kolbe, NLWKN).

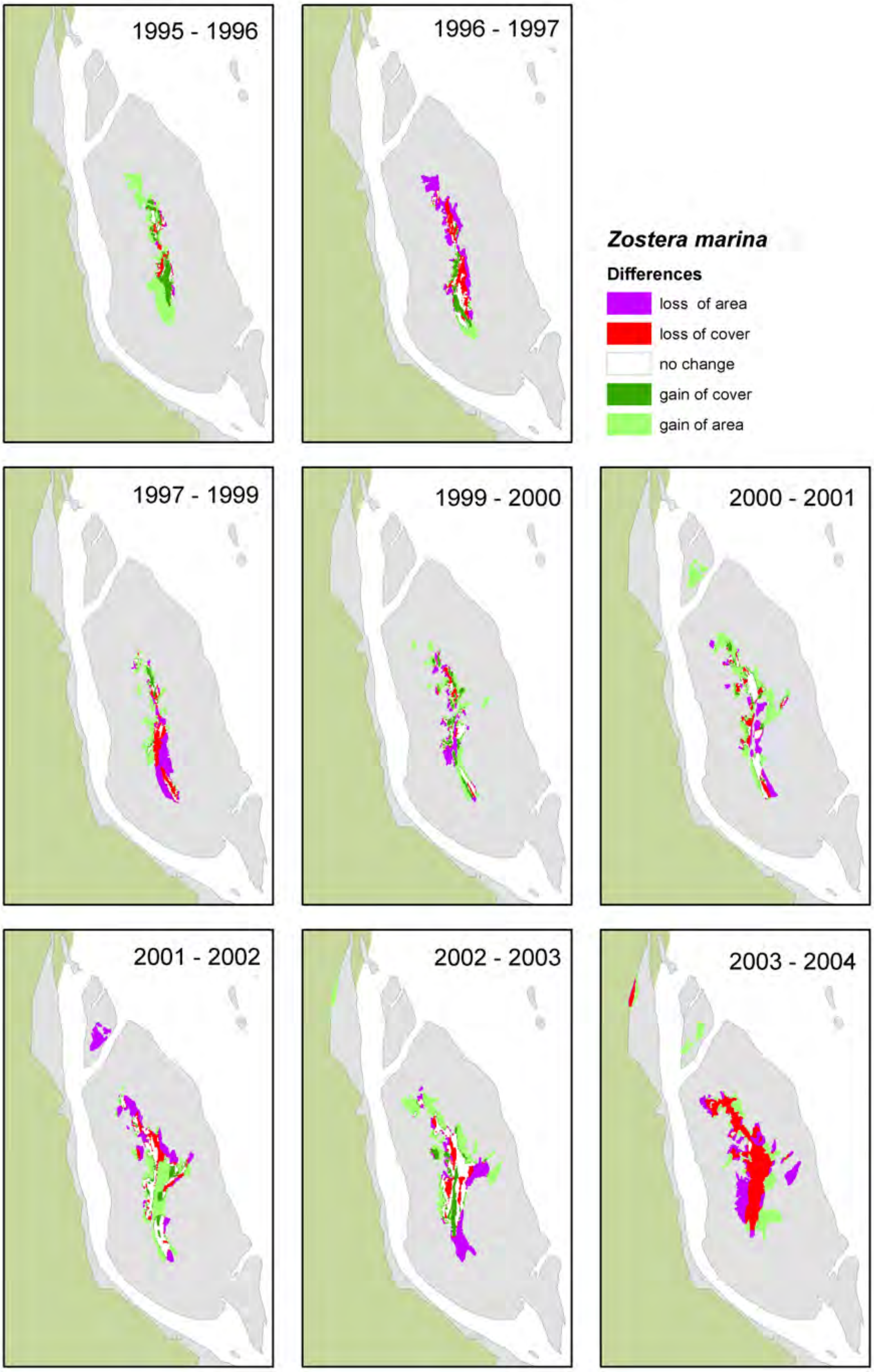


Figure 14. Differences in area an cover of *Zostera marina* on the Hond-Paap between couples of years (GIS analysis: K. Kolbe, NLWKN). The comparison between 1997-1998 cannot be made due to lacking monitoring data in 1998.

5.2 FIELD OBSERVATIONS OF ZOSTERA MARINA ON HOND-PAAP

The Dutch seagrass monitoring is documented in annual reports (Toelichting Zeegraskartering, Veldwerkverslag Zeegraskartering), commissioned by Rijkswaterstaat. In these fieldwork reports (1995-2010), the mapping methods, tidal and weather conditions and remarkable observations are reported. A selection of field observations of seagrass on Hond-Paap and Voolhok is collated in Table 5.

In 2002 and 2003, unusually high abundance of diatoms is mentioned in combination with a 'dead' (black anoxic) bottom below (Photo 1, left). In 2004, lower cover of seagrass was observed. In 2005 and 2006, the vitality of the plants seemed to have diminished. The Voolhok-decline occurred with some delay (2011); disturbance by lugworm digging was observed there (EFTAS, 2012).

The appearance of Hond-Paap was very different in 2012, compared to the situation in 2002 (Photo 1).

Photo 1. Diatoms covering the sediment in 2002 (left © A. Groeneweg); Bare sediments in 2012 (right © Z. Jager).

During the field visit of 28 August 2012 (German monitoring), only very few Zostera plants were found along the monitoring-transect. There were remains of shells at the surface, which gave the impression of ongoing erosion of the tidal flat surface (Photo 1, right).

In 2012, both area and coverage were scarce, and some plants looked desiccated and small (Photo 2a.). At the southern part of the transect, one isolated cluster of good-looking plants was found (Photo 2b, c.).

Photo 2 (© Z. Jager) a. b. c.

Table 5. Summary of observations, made during the field visits during Zostera monitoring 1994-2011. Source: Groeneweg (unpublished 1994, 1997, 2000, 2001); Groeneweg 2002; Groeneweg 2004a, 2004b; Groeneweg 2005, 2006; Vleeming et al. 2007; Boddeke et al. 2008; Damm 2009; Damm 2010; EFTAS 2010, EFTAS 2012.

Year	Observations and remarks	Citations from original text in Dutch
1994	no	
1997	monitoring hampered by strong wind (7 Bft) and high water level	*"Het bezoek aan de Hond/Paap tenslotte liep niet naar tevredenheid, dus een echt goede indruk heb ik daar niet gekregen."*
1998	no monitoring on Hond-Paap	

Year	Observations and remarks	Citations from original text in Dutch
1999	results not reported	
2000	the situation seems stable, *Z. marina* is well established. Spot close to the Gasstation, with low cover but seems to extend to NW (no photo in report)	*"Groot zeegras is nog maar sporadisch gevonden langs de Groninger kust, daar lijkt de achteruitgang zich voort te zetten. Dit in tegenstelling tot de Paap waar de situatie op zijn minst stabiel lijkt, het Groot zeegras lijkt zich daar goed gevestigd te hebben. Er is dit jaar zelfs vrij dicht onder het gasstation Groot zeegras aangetroffen, de bedekking is zeer gering maar het lijkt er op dat er sprake is van heel geringe uitbreiding naar het Noord-westen."*
2001	there is (little) increase and shift of field to the SW; no check with aerial photo possible (no photo in report)	*"Op de Hond/Paap lijkt er nauwelijks sprake van toename. Wel lijkt er enige verschuiving van de velden te zijn naar het Zuidwesten. Dit zou gecontroleerd kunnen worden aan de hand van geometrisch gecorrigeerde luchtfoto's en aan de hand van de geplotte opname coördinaten. De luchtfoto's van dit jaar kunnen echter niet gecorrigeerd worden aangezien een 1:30.000 opname ontbreekt als gevolg van de matige weersomstandigheden."*
2002	transect monitoring; no further increase of seagrass, stable situation; there were no signs of previous plant removal for the transplantation experiment *[see Van Pelt et al. 2003]*; continuation of shift to SW not clear. Immense amounts of diatoms with a 'dead' bottom below, spots inaccessible because of weak bottom; this is a remarkable change compared to previous years and it may be related to the high temp.  ***Zostera marina* Hond-Paap, August 2002**	*"Verder was het opvallend dat er enorme hoeveelheden Diatomeeën voorkwamen, zowel op de Groninger kust als op de Hond/Paap."* *"Op de Paap waren sommige plekken zo verzadigd met diatomeeën dat er daaronder een vrijwel 'levenloze' bodem lag. Deze plekken waren vaak volstrekt onbegaanbaar. Ten opzichte van voorgaande jaren is dit een nogal opmerkelijke verandering. Mogelijk heeft dit te maken met de relatief hogere temperaturen t.o.v. vorig jaar."* *"Op de Hond/Paap lijkt er geen toename meer te zijn De situatie lijkt stabiel. Er is zorgvuldig gekeken naar de relatie tussen de grootte van de afzonderlijke planten en de onderlinge afstand tussen de planten. Wellicht is het mogelijk hierin een verklaring te vinden waarom Groot zeegras zich op deze plaat niet veel meer uitbreidt." "De gevolgen van het verwijderen van planten ten behoeve van de herintroductie waren niet zichtbaar. Het is vooralsnog onduidelijk of er nog steeds sprake is van verschuiving van de velden is naar het Zuidwesten."*
2003	little increase compared to 2002; extension to W near Gasstation. Although less than in 2002, still spots with high diatom concentrations[3] and 'dead' bottom below.  **Mapping on Hond-Paap, September 2003**	*"Op de Hond/Paap is er enige toename van Groot zeegras ten opzichte van 2002. Met name bij het gasstation is uitbreiding naar het westen waar te nemen. Het zeegras wat op de plaat staat maakt een vitale indruk. Omdat het verloop van de groei, het aantal planten en de bloei zijn vastgelegd [Erftemeijer & Wijsman, 2004] kan dit aanvullende informatie opleveren voor verder onderzoek en inzichten over Groot zeegras op deze, en wellicht andere, locaties."* *"In vergelijk met 2002 kwamen er ogenschijnlijk minder hoeveelheden Diatomeeën voor. Ook langs de Groninger kust leek dit het geval. Toch werden er ook dit jaar weer plekken aangetroffen waar de bodem zo verzadigd met diatomeeën was dat de laag daaronder vrijwel 'levenloos' leek. Deze plekken, in sommige gevallen nabij mosselbanken, waren vaak moeilijk begaanbaar. Of dit te maken heeft met de relatief hogere temperaturen t.o.v. voorgaande jaren is niet duidelijk."*
2004	decrease compared to 2003; lower cover, area not so much reduced; some plants looked less vital (no photo in report)	*"Op de Hond/Paap leek dat er sprake was van een afname van het Groot zeegras ten opzichte van 2003. Niet zo zeer de oppervlakte was afgenomen, maar de bedekking van de velden was aanmerkelijk lager dan in 2003. Het zeegras wat op de plaat staat maakt op sommige plaatsen een vitale indruk, dit was niet overal het geval."*
2005	drastic decrease around gas island, compared	*"Het Groot zeegras is rond het gas-eiland in bedekking en in oppervlakte*

[3] this was also observed by the German monitoring of Adolph et al. (2003): "neben ausgesprochen vitalen Bereichen [of *Zostera marina*] fanden sich auch solche, die vollkommen von braunen Kieselalgen überzogen waren".

Year	Observations and remarks	Citations from original text in Dutch
	to 2004; plants are smaller, but look vital (no photo in report)	*drastisch afgenomen t.o.v. 2004. Bovendien leken alle planten kleiner, over het algemeen minder ontwikkeld dan voorgaande jaren. Datzelfde gold voor de velden wat centraler op de plaat; kleinere planten, verder uit elkaar liggend, en beduidend minder in oppervlakte. De planten zagen er kwalitatief wel zeer goed uit."*
2006	partial monitoring, only south part; therefore difficult to compare but decreasing trend. Low cover only; plants are 30-40 cm and do not look vital. Voolhok similar to previous years; plants look more vital than on Hond-Paap and had max. length of 50 cm.  ***Zostera marina* at Voolhok, August 2006**	*"Op de Paap is alleen Groot zeegras waargenomen. De bedekking daarvan was zeer laag, variërend van 1 tot 5%. De planten hadden een maximale lengte van 30 tot 40 centimeter. De Groot zeegrasplanten zagen vergeleken met andere Groot zeegrasplanten elders niet vitaal uit. Volgens Jeroen Bergwerff was er sprake van een afname van Groot zeegras vergeleken met voorgaande jaren."* *"De situatie op de Paap anno 2006 valt niet goed te vergelijken met voorgaande jaren, omdat alleen het noordelijke deel is opgemeten. In dit deel valt op dat de aangetroffen velden alleen binnen de bedekkingsklasse 1 tot 5% vallen, terwijl in voorgaande jaren ook velden met hogere bedekkingsklasse aangetroffen zijn."* *"Op Voolhok is alleen Groot zeegras waargenomen. De bedekking varieerde van 1 tot 20%. Op Voolhok zijn twee zeegrasvelden onderscheiden. Dit komt overeen met de situatie van 2004 en 2005. De planten op Voolhok zagen er vitaler uit dan op de Paap en hadden een maximale lengte van rond de 50 centimeter."* *"Op Voolhok zijn in 2006 net als in 2005 en 2004 twee Groot zeegrasvelden aanwezig, één van 1 tot 5% en één van 6 tot 20%. Het veld met de laagste bedekking is korter geworden. Het veld met de bedekking van 6 tot 20% heeft zich wel uitgebreid."*
2007	shift in the position of the seagrass-meadow; vitality of the plants is variable. The decline of common eelgrass seems to be ongoing. (no photo in report)	*"Het groot zeegras bleek tijdens het veldbezoek in zeer lage dichtheden aanwezig te zijn. De velden blijken ten opzichte van 2006 lokaal verschoven te zijn. De bedekking ligt rond de 0-1%. De vitaliteit van de planten is zeer wisselend. Er zijn delen waar planten 1 meter lang zijn, terwijl de planten op andere locaties niet veel groter dan 30-40 cm worden. De afname van groot zeegras op de Paap lijkt zodoende nog niet gestopt."* *"De planten op Voolhok zagen er vitaler uit dan op de Paap en hadden een maximale lengte van rond de 50 centimeter."*
2008	only very low cover of seagrass plants on Hond-Paap, lower densities than in 2006.  **Higher cover at Voolhok, August 2008**	*"Overal werden slechts zeer lage dichtheden van Groot zeegras aangetroffen, steeds losse planten of groepjes tot zo'n vijf exemplaren en maximaal 1 meter lang. Het in 2006 aan de oostkant vastgestelde vlak met wat hogere dichtheden bleek niet meer zo dicht te zijn. Halverwege de raai liggen enkele mosselbanken, langs geulen wat andere schelpenbanken en hier en daar komen losse exemplaren Japanse oester voor."*
2009	only very low cover of Common eelgrass on Hond-Paap; 3 tufts of Dwarf eelgrass were found. At Voolhok increase in cover and one tuft of Dwarf eelgrass, too.  ***Zostera noltii* and *Zostera marina* plant (right) co-occurring at Voolhok, July 2009**	*"Op de meeste plaatsen werden slechts zeer lage dichtheden Groot zeegras aangetroffen, losse planten of groepjes tot zo'n vijf exemplaren. Ook werden er drie pollen Klein zeegras gevonden."* *Voolhok: "Het 5-20% vlak is flink uitgebreid en er zijn nu ook monsterpunten met 15 en 20%!" "Bas vond een pol klein zeegras (foto)".*
2010	No seagrass found on Hond, and very sparse on Paap (18 Ha). Voolhok: 9.2 Ha.	*"Op de Hond werd in het geheel geen Groot zeegras aangetroffen, op de Paap zeer spaarzaam."*

Year	Observations and remarks	Citations from original text in Dutch
	 ***Zostera marina* plant; Paap, August 2010**	
2011	Paap reduced compared to 2010; only 0.04 ha remaining. Cover reduced, scarce presence; Voolhok also decreasing and disturbance by lugworm digging	*Paap: "Groot zeegras werd zeer spaarzaam aangetroffen en lijkt een achteruitgang te vertonen ten opzichte van 2010."* *Voolhok: "Groot zeegras lijkt achteruit te zijn gegaan. Op het moment van karteren waren pierenstekers aan het graven, die ook in het zeegras-veld voor verstoring zorgden."*

In 2002, about 2500 *Zostera marina* plants were collected from the Hond-Paap meadow, to serve as donor material for a seagrass transplantation experiment on Balgzand. The plants at higher elevation were fully exposed during low tide, but looked green and vital and appeared to carry more seeds than plants at lower sites (pers. comm. D. Hilbers). In a sample of 352 plants, each shoot had on average 12,6 ears and 43% of them contained seed, with a mean of 1.44 seed per ear (Van Pelt et al. 2003).

Erftemeijer & Wijsman (2004) also observed qualitative plant parameters, such as plant density, plant length, width of leaves, biomass of plants, reproduction of *Zostera* plants at 6 permanent quadrats (PQ), 3 in the North and 3 in the South of Hond-Paap in 2003, at monthly site visits during the growing season. First germination was observed in March, but this was frozen to death at the beginning of April. At the end of April/beginning of May, plenty of new hatchlings were observed. At the southern plots, 23% of the plants grew from perennial rhizomes; all other plants in the 6 PQs had germinated from seed. The largest biomass of the plants was formed by the vegetative and flowering shoots; rhizomes and roots generally contributed less to the plant biomass (however, varying between 12-61%). There were significant differences in growth parameters between plants in the northern and southern PQs since the start of the growing season; these were probably related to the duration of exposure (65% in northern vs. 60% in southern PQs) or sediment composition (southern less silty than northern PQs). However, these qualitative measurements were unique and can not be referred to other years for comparison.

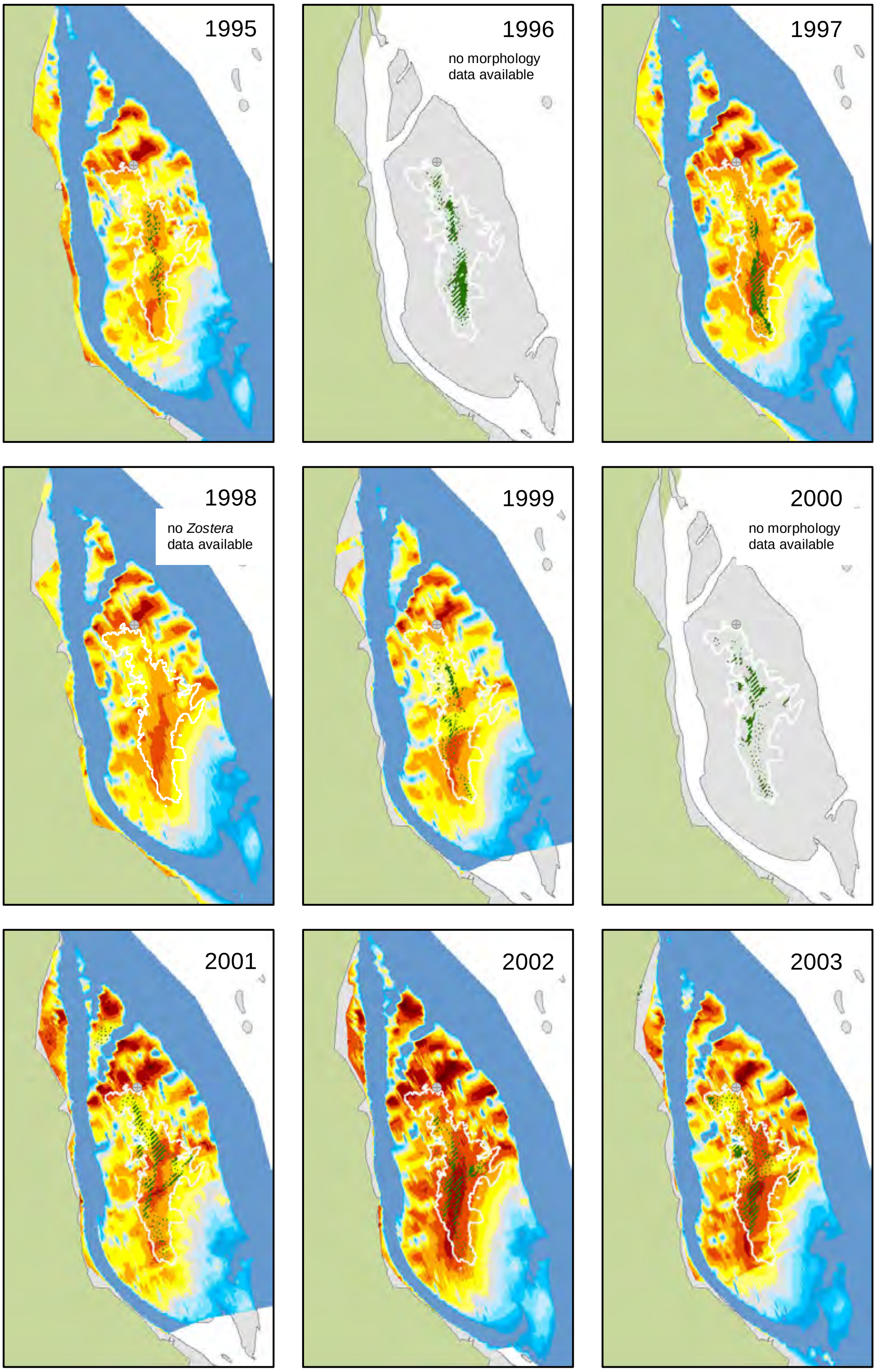
5.3 TIDAL FLAT ELEVATION AND MORPHOLOGICAL DEVELOPMENT OF HOND-PAAP

A sequence of GIS-maps illustrates the development of the seagrass bed in relation to the morphological developments of Hond-Paap (Figure 15).

The tidal flat Hond-Paap (c. 2440 Ha) is characterised by an elevated, North-South oriented 'backbone', with a maximum elevation of NN/NAP +0,40 m, which is functioning as a tidal divide. The fringes of the tidal flats are intersected with systems of tidal gullies, which are most nicely represented in the morphological map of 2010. The northern tip has been quite variable over the years.

Between 1995 and 2010, the tidal channel between the tidal flat and the Dutch mainland, Bocht van Watum, narrowed. At the south-east of Hond-Paap, there seems to be an intrusion of the main tidal channel and shipping lane Oostfriesche Gaatje, which is eroding the southern tip. This is also the area where the Gaszinker pipeline had to be repaired in 2003, as a result of erosive curents.

The axis of the tidal flat was originally oriented N-S, but is tilting to NNE-SSW in recent years (Figure 15).



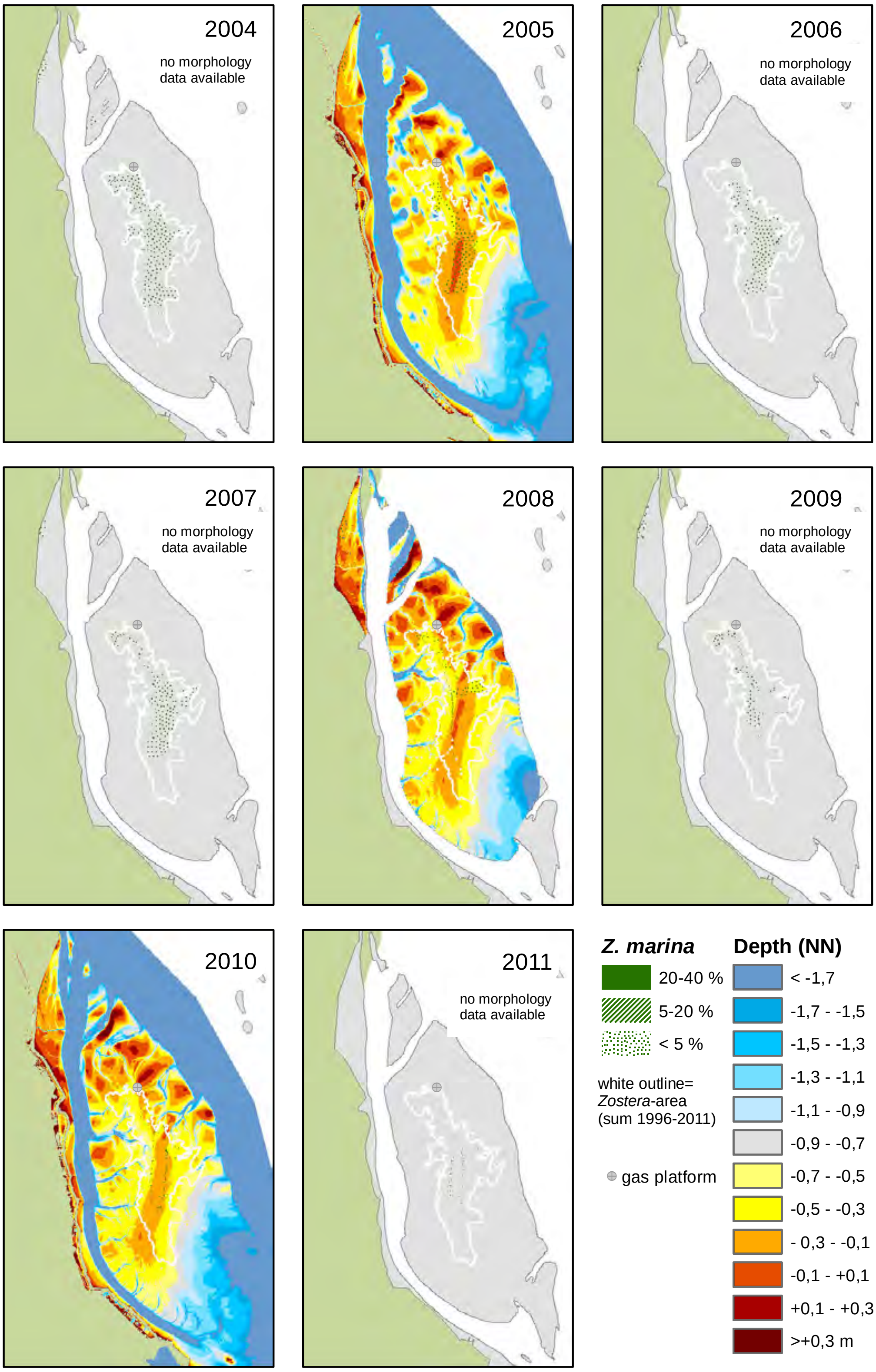


Figure 15. Spatial distribution (area and cover) of *Zostera marina* and tidal elevation (depth) on Hond-Paap and Voolhok in different years covering the period 1995-2011, projected on a morphological map (if available for that year). Data: RWS (*Z. marina*, elevation 2008), WSA (elevation); GIS: K. Kolbe, NLWKN.

The ‘restricted area’, where seagrass once occurred during the period 1995-2010 (Figure 10b), is indicated with a white contour-line on the central axis of the tidal flat (Figure 15). It suggests that the spatial distribution of seagrass is narrowly linked to the tidal flat elevation. This relation was analysed in more detail.

Based on available data, Figure 16 represents a plot of Hond-Paap tidal flat area (Ha) against the elevation (dm-class, m to NN/NAP). The elevation of Hond Paap showed interannual fluctuations and reached its maximum elevation in 2002, up to NN/NAP +0.45 m (elevation dm-class). Since 2003, the elevation at which the largest area was present (the modus of the area distribution) decreased from NN/NAP -0.15 m to NN/NAP -0,45 m in 2010, indicating a maximum difference in elevation of 30 cm.

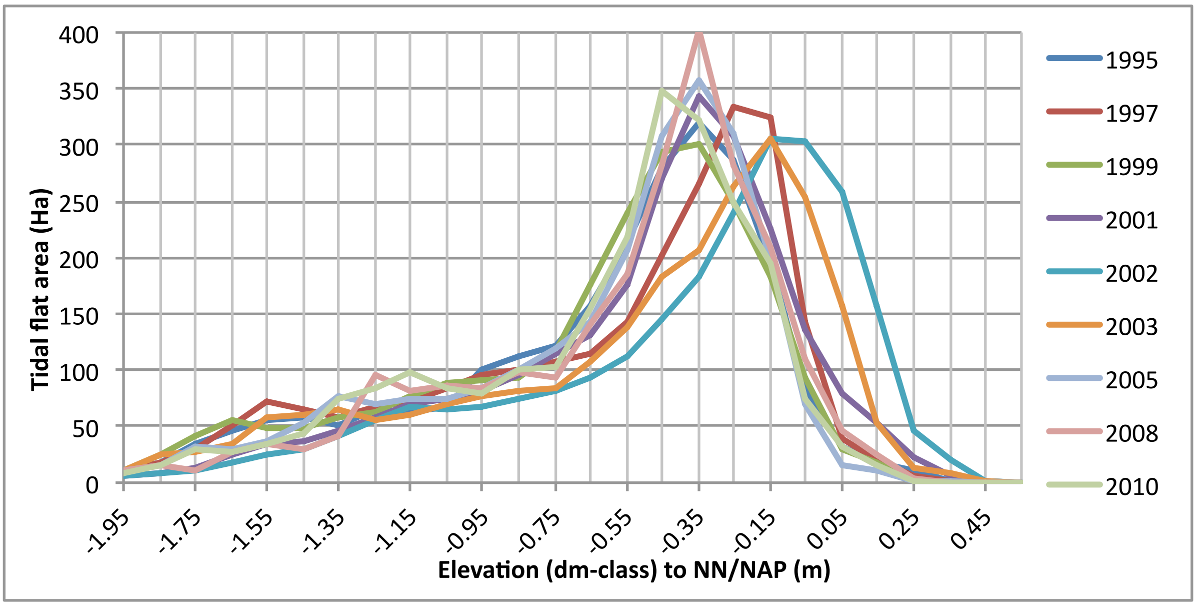


Figure 16. Area per elevation of Hond-Paap (contour Figure 10a) in 1995, 1997, 1999, 2001-2003, 2005, 2008, 2010. Data: NLWKN, RWS.

Similar plots were made of the ‘restricted’ area of potential seagrass occurrence on Hond-Paap (Figure 17) and the annual growth locations of *Zostera* (Figure 18). Both the elevation of the ‘restricted’ tidal area and of *Zostera* varied between NN/NAP -0.9 m and NN/NAP +0.3 m. The tidal flat elevation was shifted upward in 2002, with a modus of the elevation at NN/NAP +0.05 m. This is opposed to the modus of the elevation in 2010, which was at NN/NAP -0.45 m; a difference of 50 cm.

Among years, there were shifts in the elevation at which seagrass occurred, and generally the highest proportion of *Z. marina* occurred at an elevation of NN/NAP -0.15 m (Figure 18). In 2002 and 2003, the peak of seagrass distribution was at higher elevations than in other years, with a distribution mode at NAP +0.05 m. In these years, there was also more surface available at the higher elevations inside the ‘restricted’ area (compare Figure 17).

A plot of the seagrass area against the tidal flat area showed that the area of Zostera was linearly correlated to the tidal flat area at elevations between NAP -0.45 m and +0.35 m (R^2=0.66; Figure 19).

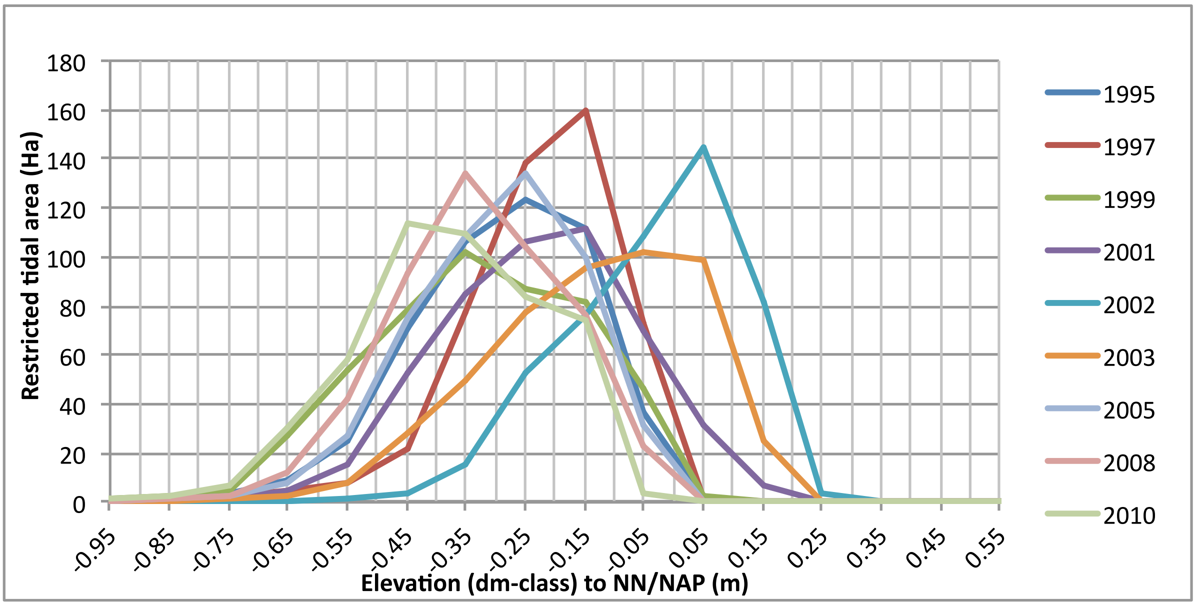


Figure 17. Elevation of the tidal flat Hond-Paap in several years. Restricted area of *Zostera* occurrence (contour Figure 10b). Data: NLWKN, RWS.

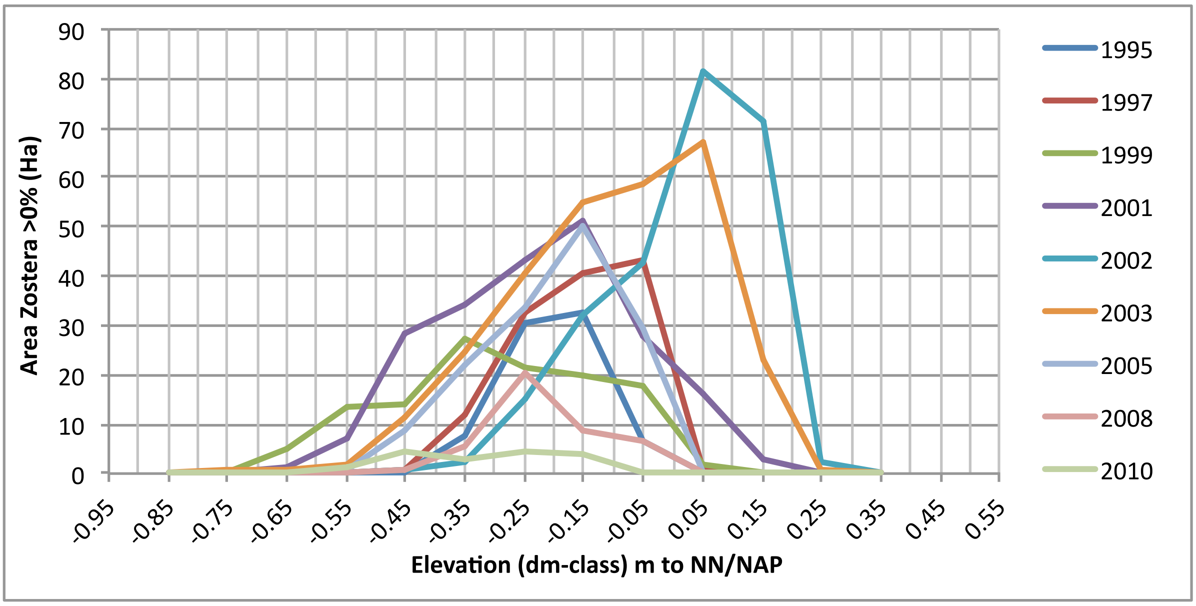


Figure 18. Elevation of growth locations on Hond-Paap of Zostera marina in 1995, 1997, 1999, 2001-2003, 2005, 2008, 2010. Data: RWS.

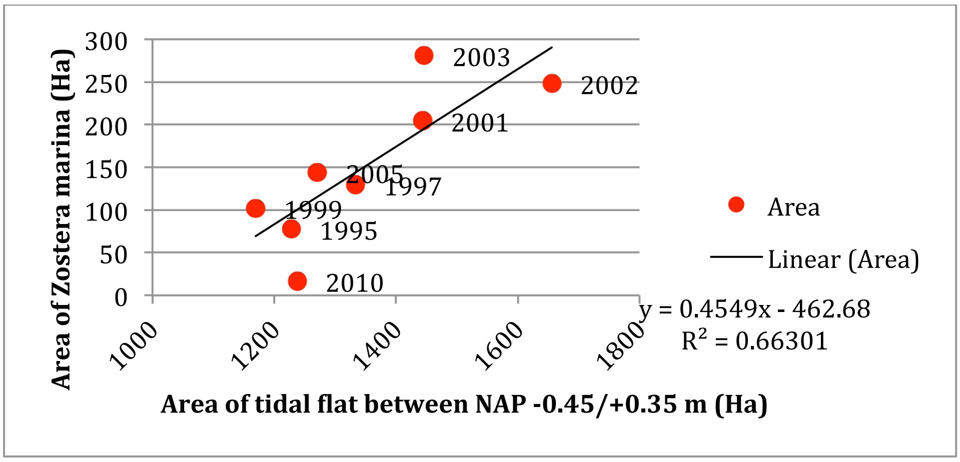


Figure 19. Relation between Zostera area and tidal flat area (elevation range NAP -0.45/+0.45 m) in different years.

Between 1999 and 2002, the peak of *Zostera* distribution more or less matched the elevation of the peak of available area (Figure 17, Figure 18). In other years, *Zostera* was distributed at higher elevations than at which most area was available. Details of the *Zostera* and tidal flat area distributions against elevation are shown in Figure 20. The upper elevation of seagrass occurrence on Hond-Paap seemed to be limited by the morphology; Figure 20 shows that seagrass in all years utilised the upper elevations available, whereas Figure 16 illustrates that elevations above NN/NAP+0.45 m were not available at all on the Hond-Paap tidal flat (1995-2010).

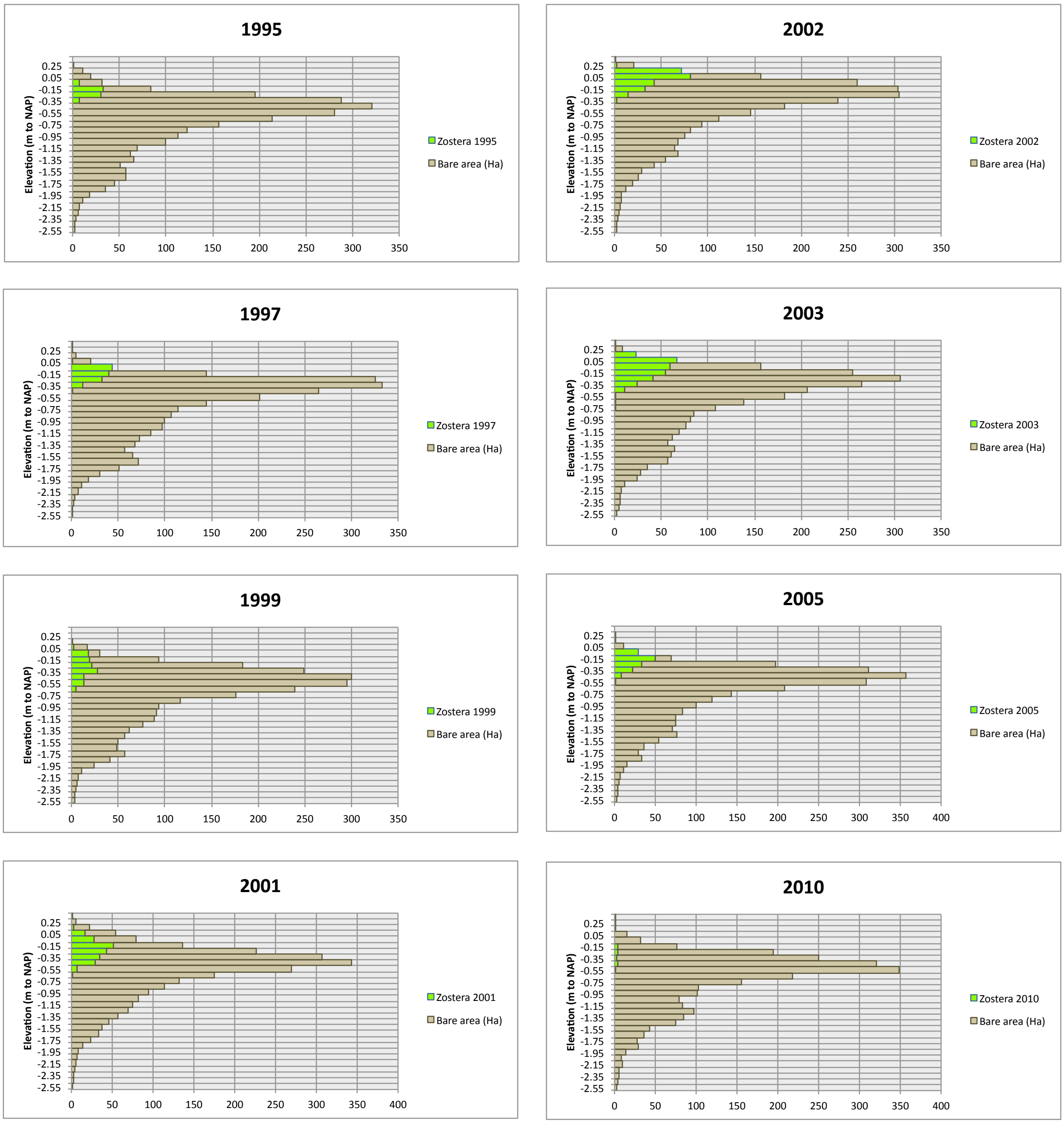


Figure 20. Distribution of area versus tidal elevation for a selecion of years (chronological: read left, top-down and then right, top-down). On the horizontal scale is the area (Ha) and on the vertical scale the elevation to NN/NAP (dm-classes); the figure shows the "area-elevation distribution" for bare tidal flat (olive) and *Z.marina* (light green).

To estimate the sediment volumes that are responsible for the differences in elevation, the sediment budget (volume increase or decrease) was calculated (from GIS-data) between consecutive years of available data (Figure 21).

Between 1999-2002, c. 1.4 million m^3 sediment was gained in the restricted area on Hond-Paap. Between 2002-2003, 0.5 million m^3 sediment was lost again. Since 2005, the sediment loss stabilised. The area of seagrass (Ha) matched (with a time-lag of 0-1 yr) the increase and decrease of the cumulative sediment volumes (Figure 22).

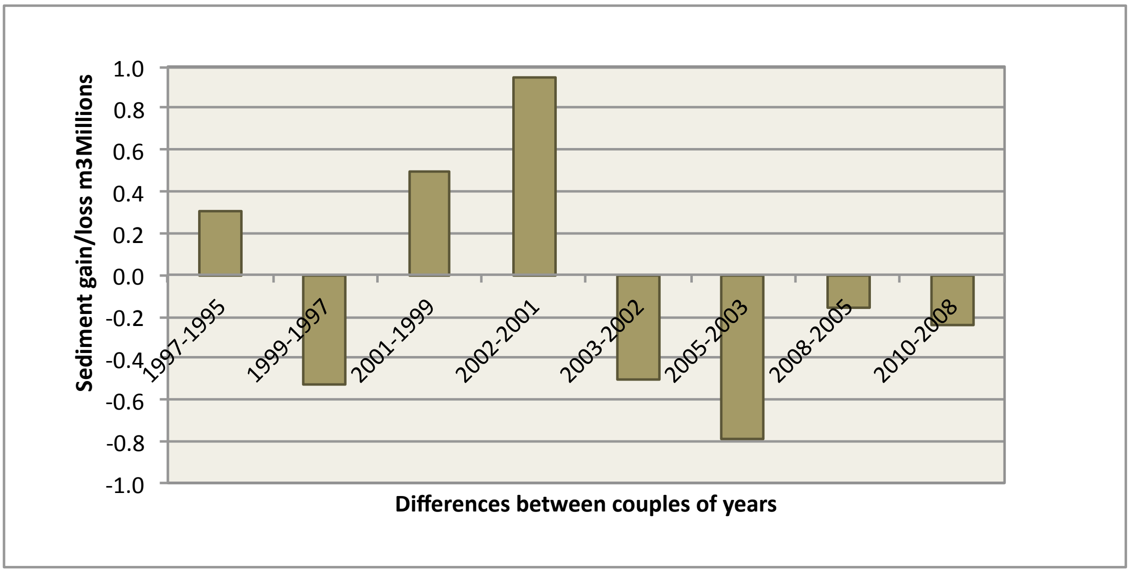


Figure 21. Sediment budget; differences between years of the sediment volume (m3) stored in the restricted seagrass area.

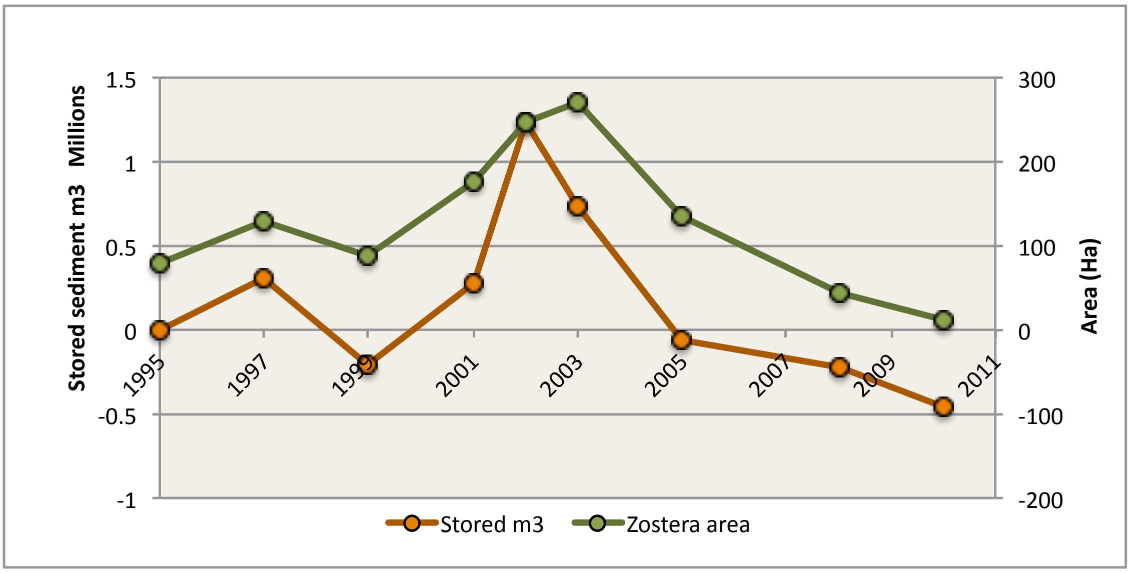


Figure 22. Combination plot of the cumulative sediment volume (Million m3; 1995 as starting point) and the area of *Zostera marina* on Hond-Paap.

5.4 Duration of exposure at low tide

From the combination of available elevation and actual water level measurements (www.waterbase.nl), the duration of exposure at low tide (%) was calculated and presented for each day of a month (for example July, representing the seagrass growing season) in Figure 23.

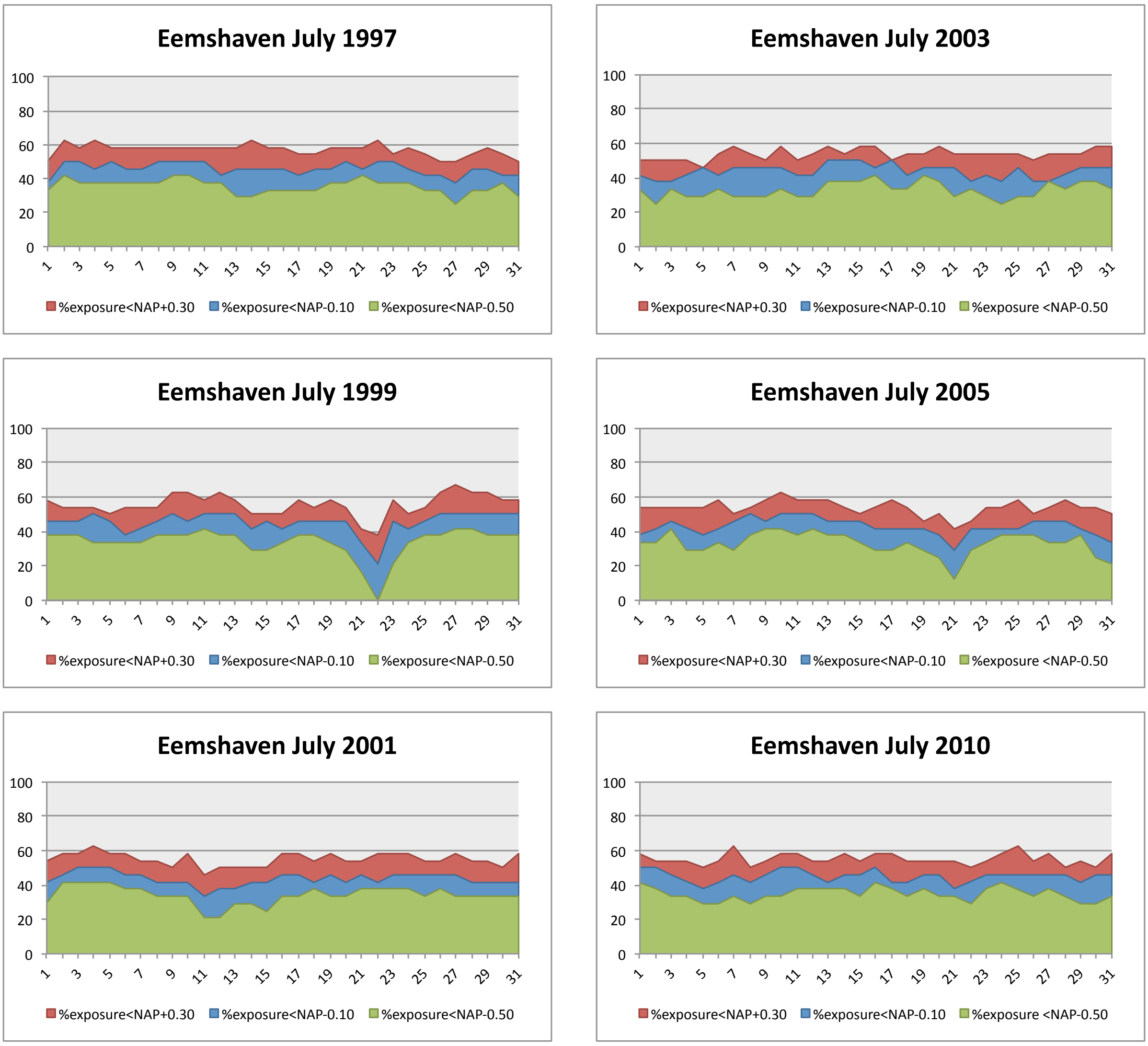


Figure 23. Exposure (% of the time, vertical axis) during low tide at different elevation levels: NAP +0.30 m (the highest elevation available on Hond-Paap; red color), NAP -0.10 m (corresponding to Mean Sea Level and the center of distribution of *Zostera marina*; blue) and NAP -0.50 m (the lower level at which seagrass was observed; green).

The tidal flat exposure at the upper level of the seagrass sites, NN/NAP =+0.30 m, ranges between c. 40 and 60% of the time. This is in close correspondance to the optimum exposure assumed in the growth potential map (40-65%; De Jong et al. 2005), and probably even would allow growth at a slightly higer elevation (but as we have seen in chapter 5.3, the Hond-Paap tidal flat area is not that highly elevated).

The Mean Sea Level (MSL; NN/NAP -0.10 m) is exposed between 30-50% of the time, which is already at the lower range of the seagrass demands, implicating that seagrass cannot grow much lower than at MSL. The elevation NN/NAP -0.50 m is exposed less than 40% of the time, which is below the seagrass range.

On occasions, e.g. on 22 July 1999, deviating (increased) waterlevels occurred wich resulted in a tidal cycle during which seagrass was not exposed at all during low tide. Permanent cover with water can lead to insufficient light for photosynthesis or too high hydrodynamics, damaging the plants.

On another occasion, e.g. 27 July of the same year, apparently the water levels were lowered which led to a longer than average exposure; but in this case the exposure (c. 65%) was still within the range that is tolerable for common eelgrass. Exposure during low tide for longer times can lead to desiccation of the plants.

Based on this example, it is obvious that seagrasses in the Ems estuary can only occur in a narrow elevation zone on Hond-Paap, a few decimeters around mean sea level.

5.5 Climate Indicators and Freshwater Discharge

No consistent response of the area and cover of common eelgrass was detected in relation to the climate indicators (Figure 24).

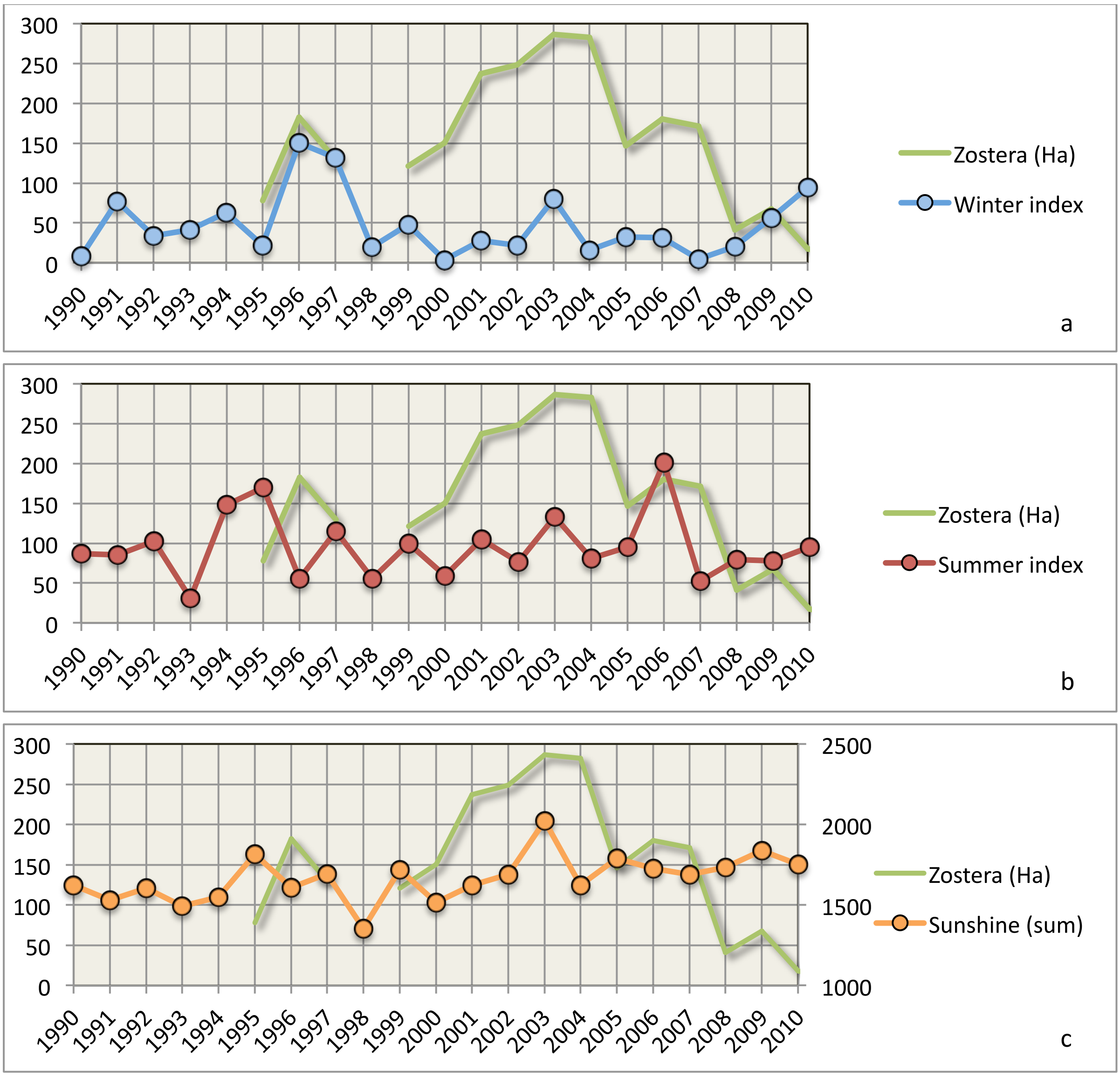


Figure 24. Climate indicators: a. Winter index (H; H<20: mild winter, 100<H<160: cold winter), b. Summer index, c. annual sum of Sunshine (h). Data: KNMI. For comparison, the *Zostera* area is plotted.

The winters of 1996 (November 1995–March 1996) and 1997 (November 1996–March 1997) were classified as cold winters (Figure 24a), based on Hellmann number (100<H<160). During these winters, ice cover and thus ice scour will have occurred. This is partly confirmed by data from BSH (Bundesamt für Seeschifffahrt und Hydrographie), which indicate that 5 or more icedays occurred in the winters of 1991, 1994, 1996 (44 icedays), 1997 (33 icedays), 2003 and 2010. After the cold winter of 1996, the area of seagrass showed a decline; as no monitoring data of 1998 are available, the impact of the cold 1997 winter cannot be estimated. The winter of 2003 was of intermediate coldness. In 2004, the total area of seagrass was still unchanged, but the area with high cover (5-20%) had already decreased.

Mild winters (H<20) were those of 1995, 1998, 2000, 2002, 2004 and 2007; thus the period of seagrass increase (1999-2003) had a row of mild winters.

The Top-5 warmest summers during these years (Figure 24b) were those of 2006 (Summer index 201), 1995 (170), 1994 (148), 2003 (133) and 1997 (115). The year with the highest sum of sunshine hours (Figure 24c) was 2003 (2022 h), followed by 2009 (1838 h) and 1995 (1814 h).

The sum of annual precipitation (mm) at Delfzijl, representing for Hond-Paap, was exceptionally low (<600 mm) in 1996 (Figure 25a). Wet years, with annual precipitations of >900 mm, were 1998, 2001, 2002, 2004 and 2007.

The sum of annual discharge (m^3) at pumping station Spijksterpompen more or less followed the trends in precipitation of Delfzijl. The highest annual discharge at Spijksterpompen was in 2001 (39 million m^3) and the lowest discharge (16 million m^3) in 2005 (Figure 25b).

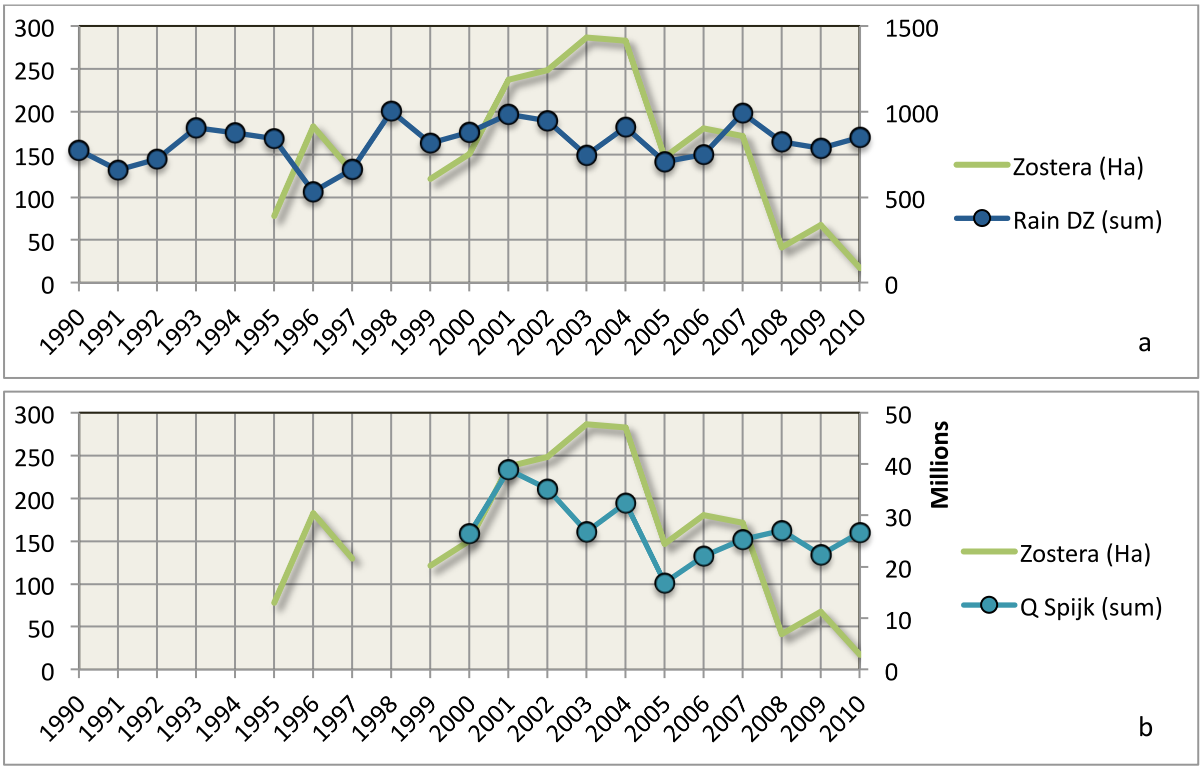
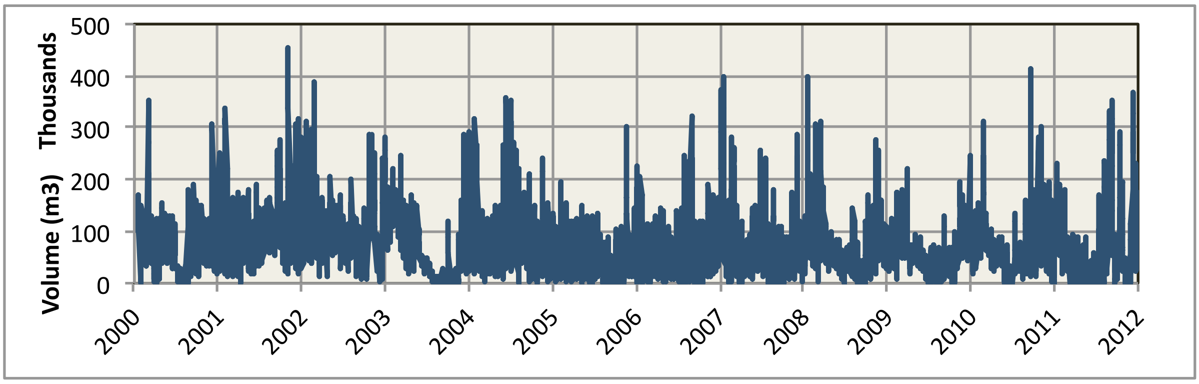


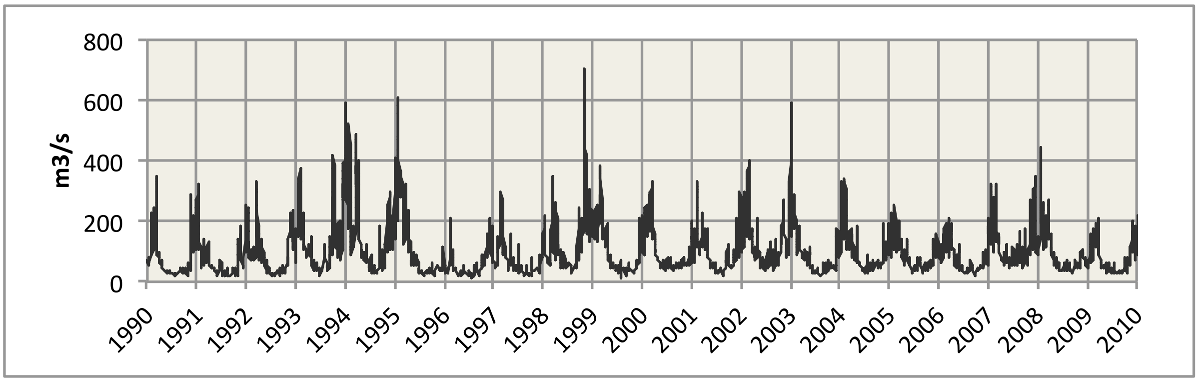
Figure 25. a. Annual precipitation (mm) at Delfzijl; b. Annual volume of freshwater discharge (million m^3) at Spijk (Gemaal Spijksterpompen); Data: KNMI (a), WS Noorderzijlvest (b).

Remarkable were a low discharged volume during the summer of 2003 and high discharge volumes during the summer of 2004 (Figure 26a).

The Ems river flow (Figure 26b) generally was the highest during winters, and in particular those of 1994/1995, 1995/1996, 1998/1999 and 2002/2003.



a.



b.

Figure 26 a. Daily volume of freshwater (thousand m³) at Spijk; b. daily average Ems flow at Herbrum (Q, m³/s); Data: WS Noorderzijlvest (a), BfG/WSV (b).

Heavy storms (> 10 Bft) occurred on the following dates in the period between 1994 and 2010: 1 April 1994, 3 March 1995, 4 January 1998, 3 December 1999, 28 May 2000, 29 October 2000, 26 February 2002, 9 March 2002, 27 October 2002 and 18 January 2007. Of these, only one (May 2000) took place during the Zostera growing season.

5.6 Abiotic parameters

Water temperature

On average, the water temperature (Eemshaven, nearby Hond-Paap) was <5°C between December 10th and March 17th (Figure 27), but the figure also illustrates the presence of considerable interannual variations in seasonal water temperatures. In some winters (e.g. 2006/2007 and 2007/2008), the water temperature hardly dropped below <5°C. In other years an initial temperature rise in early spring was followed by a cold spell (e.g. 2003, 2005 and 2006). Of seagrass observations in 2003 (Erftemeijer & Wijsman 2004) it is know that this can cause untimely germination and subsequent freezing of germs. The number of days with water temperature <5 °C was high in 2003, 2004, 2007 and 2010 (Figure 28). The average annual maximum temperature was c. 20°C, but temperatures >20°C (above the *Zostera* optimum) occurred during shorter or longer periods in individual years (Figure 27). This was particularly the case in 2002, 2003 and 2006 (Figure 28), but no unusual effects or mortalities of seagrass were reported during the monitorings. Water temperatures can furthermore be locally enhanced by the thermal discharge of the nearby Eemscentrale power station, but the maximum temperature of this discharge is restricted to c. 25°C by legal obligations.

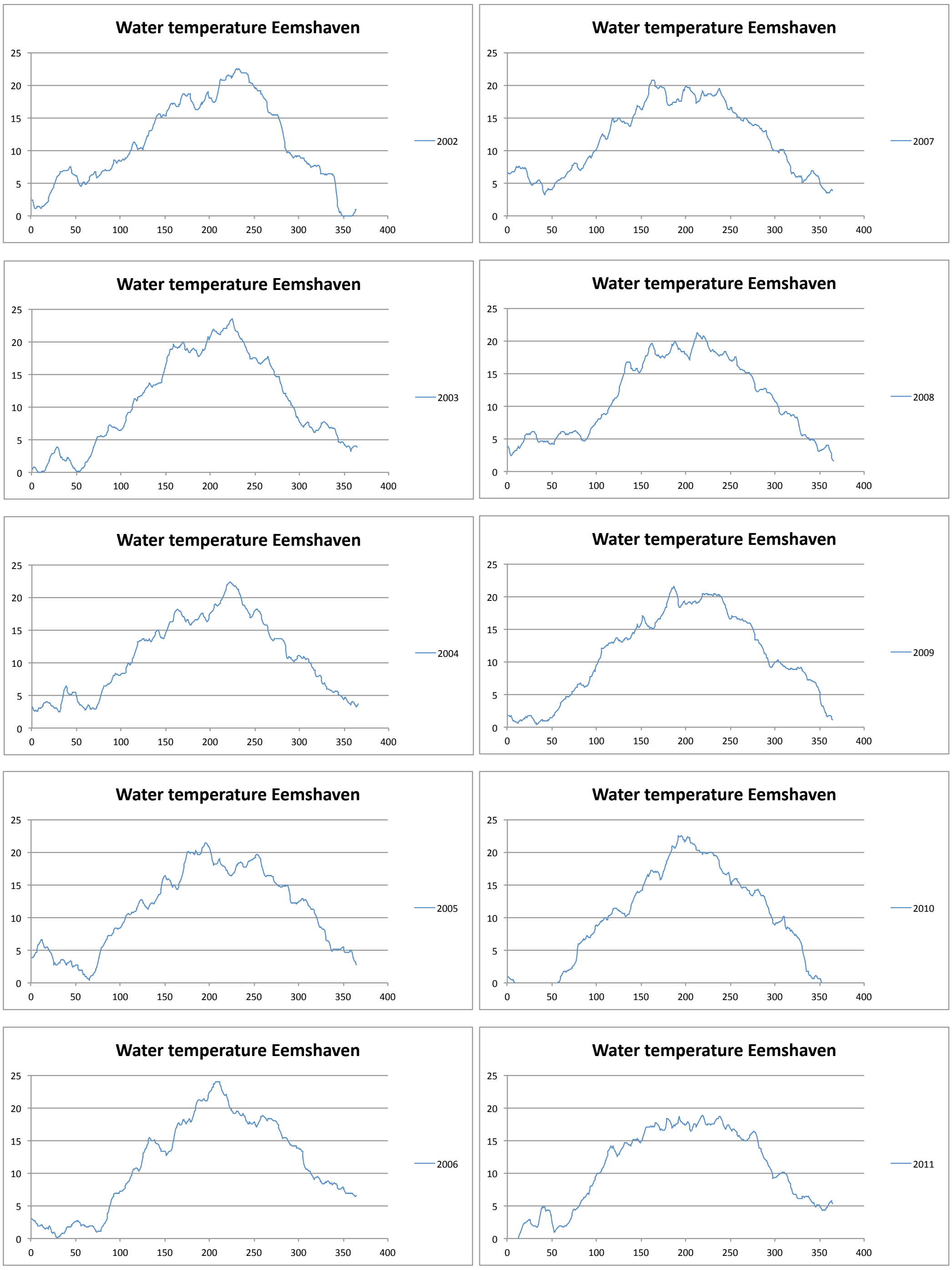


Figure 27. Daily water temperature (°C), measured at Eemshaven (2002-2011).

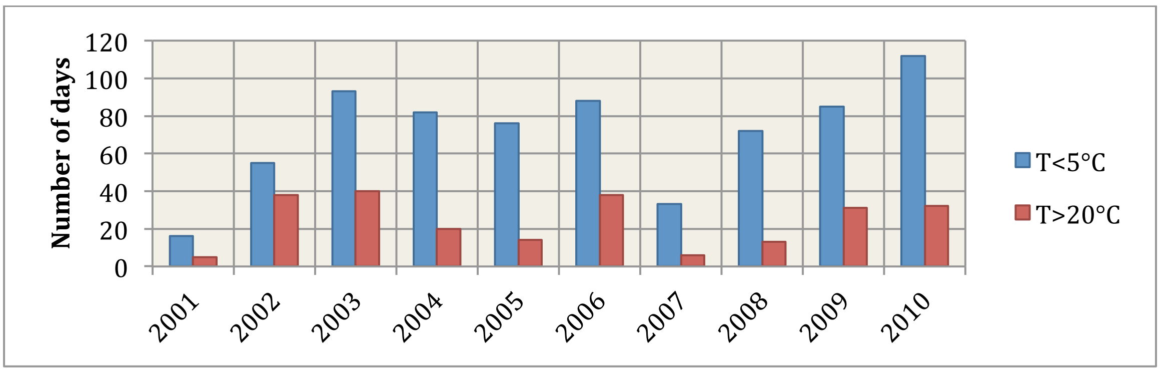


Figure 28. Nr of days with water temperature (Eemshaven) outside the optimum range for *Zostera marina* (T<5°C in blue or T>20°C in red bars). Source: RWS Waterbase.

Salinity

The average annual salinity varied between 18 PSU (2007) and 25 PSU (1997), and salinity shows seasonal variations (Figure 29, Table 6). During the seagrass growing season (Q2 and Q3), salinity was never below 20 PSU, but regularly >25 PSU, which is outside the optimum range for Zostera (16-25 PSU).

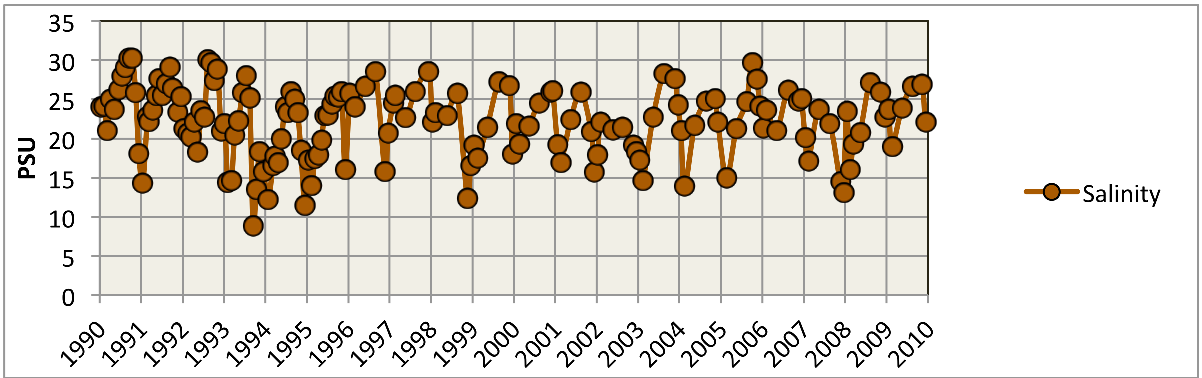


Figure 29. Salinity (PSU) during different seasons at Bocht van Watum Noord (1990 – 2010). (RWS Waterbase).

Table 6. Average salinity during different seasons (Q1-Q4) and annual average (AVG) of different years (1990-2009). Q1: Jan, Feb, Mar; Q2: Apr, May, Jun; Q3: Jul, Aug, Sep; Q4: Oct, Nov, Dec.

Quarter & Year	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Q1	23.1	19.8	20.7	17	15.5	16.2	24.9	25	22.7	18.4	20.6	18.1	20	15.9	17.4	15	22.5	18.6	19.6	21.4
Q2	25.0	25.6	21.3	22.8	20.3	20.2	26.7	22.7	22.9	21.5	21.6	22.4	21.1	22.8	21.7	21.3	21	23.7	20.8	23.9
Q3	29.1	27.2	27.5	20.7	24.8	24.3	28.6	26	25.8	27.2	24.5	25.9	21.4	28.3	24.8	24.7	26.2	22	27.2	26.7
Q4	24.7	25	25.8	15.9	17.8	22.4	18.2	28.6	14.4	22.4	26	18.3	18.8	25.9	23.6	27.2	24.9	13.8	24.3	24.5
AVG Salinity (PSU)	**25**	**24**	**24**	**19**	**20**	**21**	**24**	**25**	**20**	**22**	**23**	**20**	**20**	**22**	**21**	**24**	**24**	**18**	**22**	**24**

Low salinity (c. 15 PSU) during the hibernation season (Q1, January-March; light blue), which might favor seed germination, was observed in 1994, 2003 and 2005 (Figure 30). Only in 2003, this coincided with an increased and high area of common eelgrass.

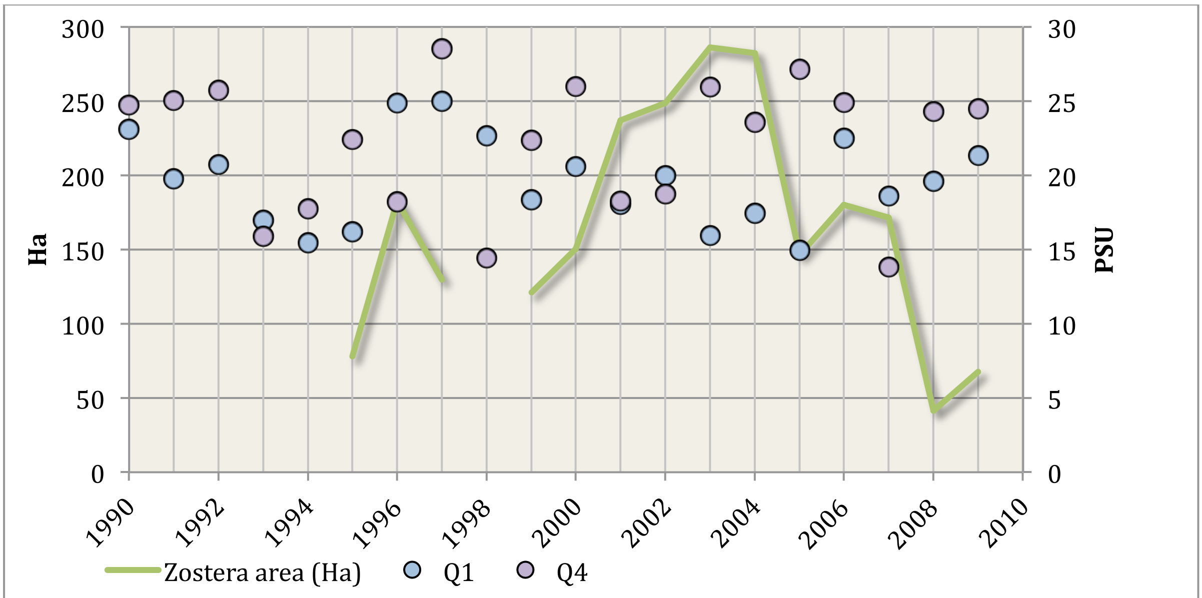


Figure 30. Average salinity during the hibernation season (Q1 of the same year and Q4 affecting next year *Zostera*). Salinity data Bocht van Watum Noord (RWS Waterbase).

Early in the growing season (Q2, April-June) average salinity was generally <25 PSU, and unfavourably high salinity (>25 PSU) occurred only in 1996. In the late growing season (Q3, July-September), favourable salinity (16-25 PSU) occurred in (1993), 1995, 2000, 2002 and 2007 (Figure 31). These years generally coincided with increased *Zostera* areas in the following year, except in 2007/2008.

Responses of common eelgrass to high salinity during the growing and flowering season can be: reduced growth, reduced seed production and increased susceptibility to *Labyrinthula*.

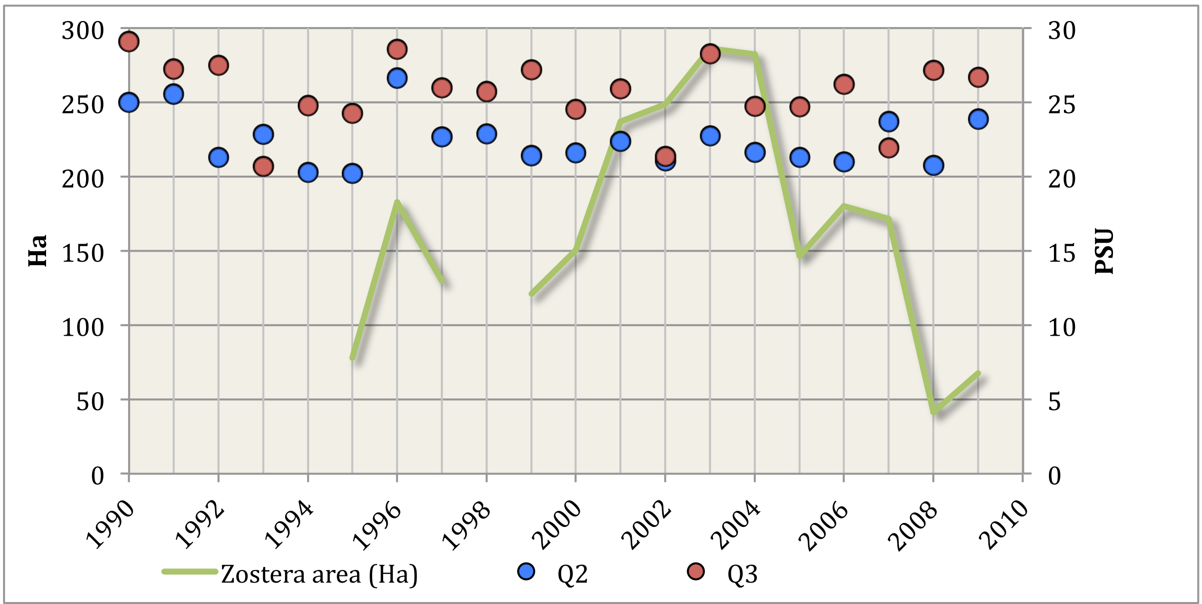


Figure 31. Average salinity during the growing (Q2) and flowering (Q3) season compared with the *Zostera* area. Salinity data Bocht van Watum Noord (RWS Waterbase).

Oxygen

The lowest oxygen concentrations at Bocht van Watum Noord (Figure 32) were just below 6 mg/l, and were measured in August 1996 and August 2003. On Hond-Paap, the intertidal seagrass plants are partly supplied with oxygen from the air during night low tides and will therefore be less vulnerable to reduced oxygen in the water column. However, at night high tides the situation may become more critical, especially during warm summers and at high sediment loads.

The oxygen measurements are not done frequently, so that episodes of oxygen deficiencies may go unnoticed but they meanwhile can have a negative impact on seagrass growth conditions on Hond-Paap.

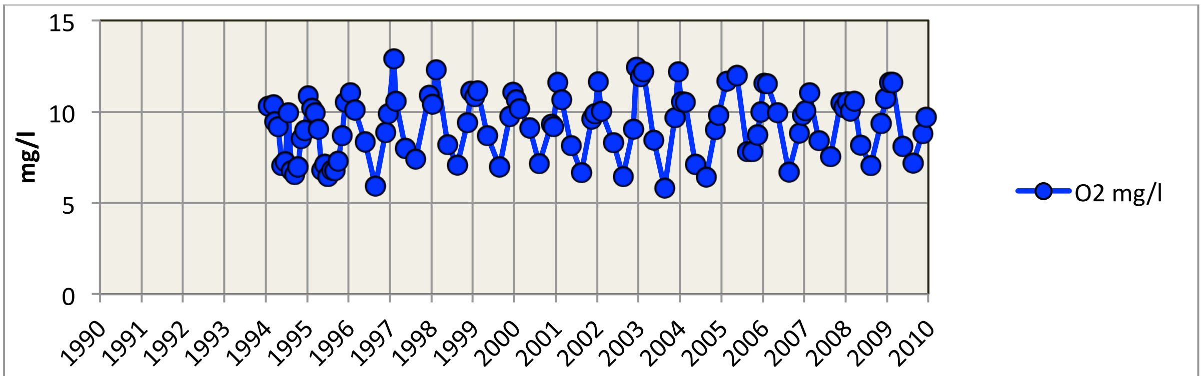


Figure 32. Oxygen measurements (mg/l) at Bocht van Watum Noord (1990 – 2010) (RWS Waterbase).

pH

Enhanced pH values (pH 9) can cause mortality of seagrass that is exposed to high ammonia concentrations (see chapter 3.2.3 for more explanation of this interaction).

The average pH was 8.0 (1990-2010). Between 1997 and 2003, the minimum pH values seem to be at a slightly higher level (c. pH 8) than in other years (Figure 33).

Higher pH-values (8.5<pH<9.0) were measured in May 1991 and May 2005. Although the number of pH-measurements is limited to a few per year, the data show that fairly high pH values may occur and maybe even more frequently than registered in the monitoring.

In relation to the occurrence of high pH values, the presence of the nearby, highly basic, Brunner Mond 'griesberg' may pose a risk if the material is released.

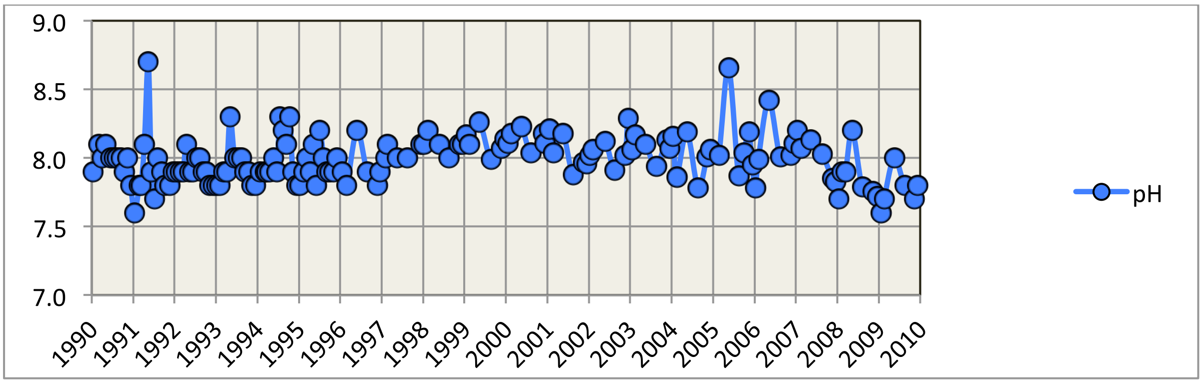


Figure 33. Measured pH values at Bocht van Watum Noord (1990 – 2010) (RWS Waterbase).

Suspended sediment

In view of the potential relation with seagrass, suspended sediment concentrations (SSC) are presented in Figure 34. Between 1990 and 2010 there was an increasing trend in SSC, which led to a doubling in seasonal SSC concentrations from c. 40 mg/l to c. 80 mg/l over the years. Exceptionally high SSC-concentrations of 180 mg/l were observed during the growing season of 1995 and 2006, and an extremely high winter concentration was measured in December 2006. A complex and detailed analysis of SSC-trends in the Ems-Dollard was recently reported by Vroomet al. (2012) and confirms a significant positive trend in SSC at station Bocht van Watum Noord, among other locations. High SSC may result in higher light extinction (see also next section), reducing the depth at which seagrasses can grow, but there are insufficient data available to substantiate this assumption.

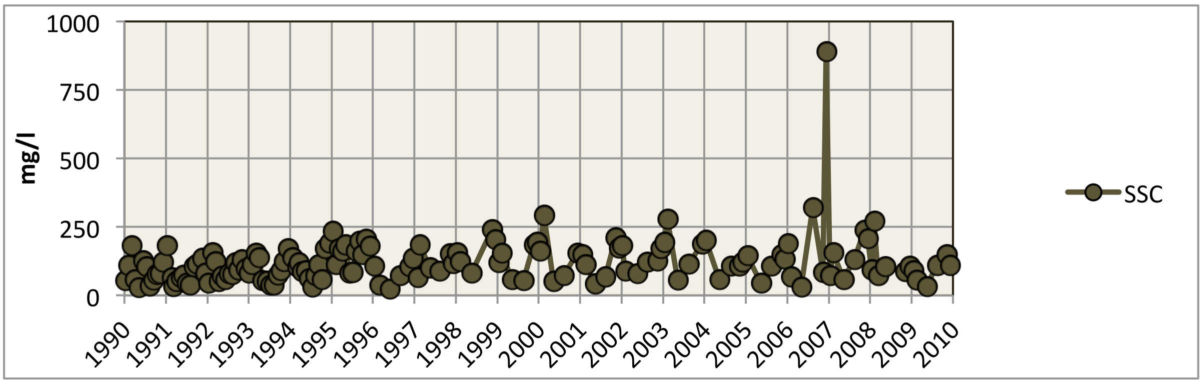


Figure 34. Suspended sediment concentrations (mg/l) at Bocht van Watum Noord (1990 – 2010) (RWS Waterbase).

Light extinction

The light extinction was high (>6) in December 2003, January 2005, November and December 2007, January and December 2009. Low extinction values (<2, corresponding to Secchi values of c. 0.7 m), meaning relatively clear water, were observed in January 2003, May 2005 and May 2006 (Figure 35). Of these years, 2003 had the highest area of *Zostera* on Hond-Paap. No extinction data are available of 1995-2003, so the results are insufficient to be conclusive on the impact on seagrass in this estuary. The observed extinction range (1-9) corresponds to Secchi depths ranging between 1 m and 0.1 m (Van der Heide et al., 2006).

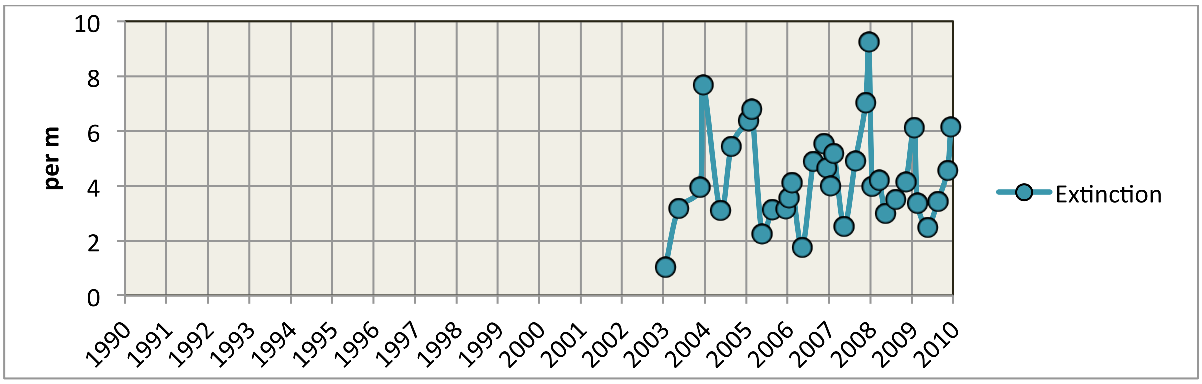


Figure 35. Light extinction (per m) at Bocht van Watum Noord (1990 – 2010) (RWS Waterbase)

Eutrophication indicators

The winter concentrations of Ammonium were on average 0.20 µg/l in the period 1990-2010 and fluctuated between 0.13 and 0.31 mg/l (Figure 36a). Concentrations were lower than average between 1998 and 2002, the period of rapid increase of the seagrass area, and also between 2004-2008. The concentrations of Nitrite fluctuated between 0.04-0.08 µg/l and were on average 0.05 mg/l (Figure 36b). In 1996/1997, 1997/1998, 1999 and 2001, the winter nitrite concentrations were above average.

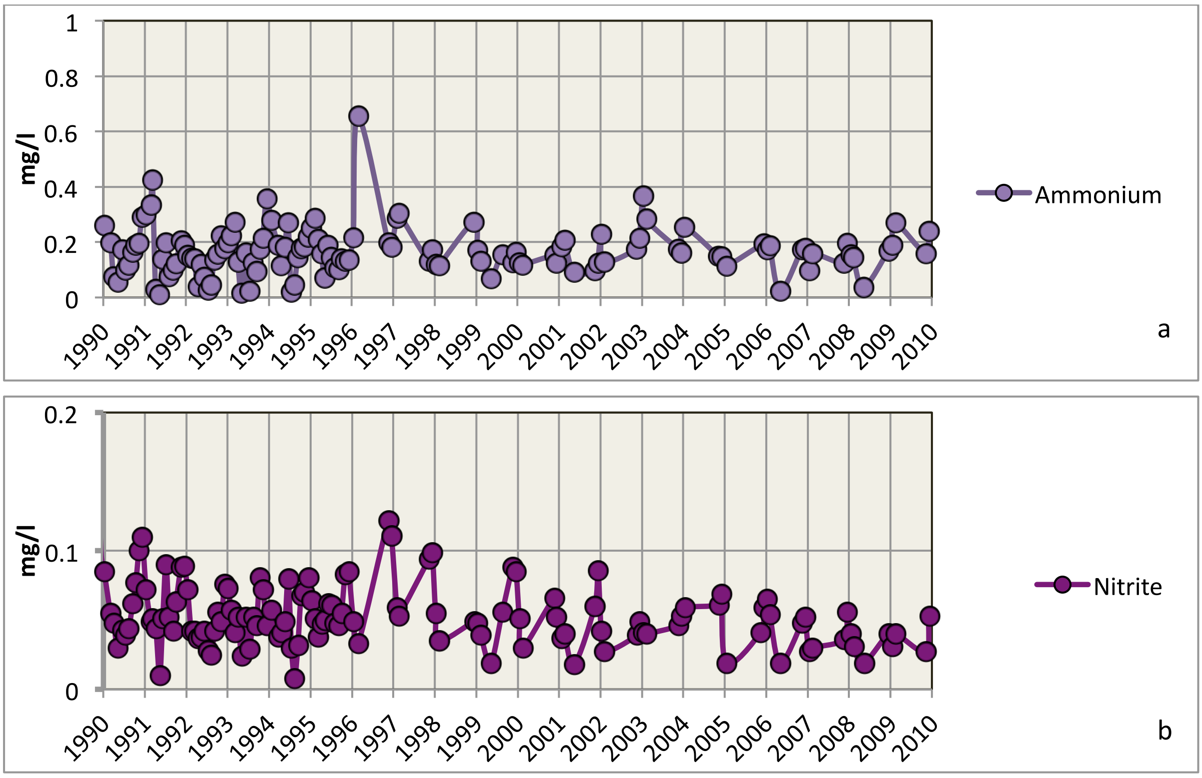


Figure 36. Eutrophication indicators, concentrations (mg/l) of a. Ammonium and b. Nitrite at Bocht van Watum Noord (1990-2010) (RWS Waterbase).

A combined plot of the *Zostera* area and winter ammonium concentrations indicates apparent parallel patterns of increase and decrease, with a minimal time-lag (Figure 37).

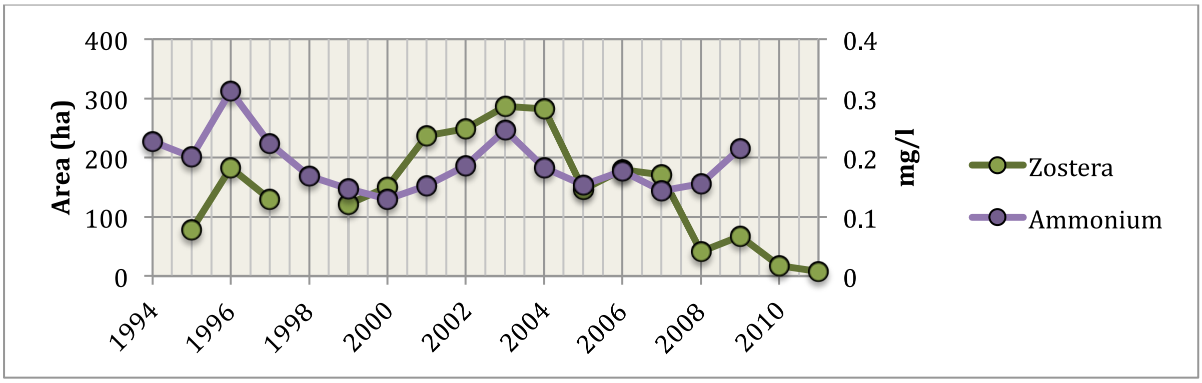


Figure 37. Combined plot of winter ammonium (mg/l) at Bocht van Watum Noord and *Zostera* area (Ha) Hond-Paap (1994 – 2010) (RWS Waterbase).

Herbicides

The concentrations of Irgarol, used as an antifouling agent, showed an increasing trend since 2003 (Figure 38a), the year that it was forbidden to apply TBT any longer as antifouling on vessels. In contrast, the concentrations of the herbicide atrazine showed a declining trend (Figure 38b). In Germany, atrazine is no longer produced and it is forbidden to apply this herbicide since 1992 (Umwelt Bundesamt: *„In Deutschland wird Atrazin nicht mehr produziert; seit 1992 besteht ein vollständiges Anwendungsverbot in Deutschland. Auch auf EU-Ebene ist Atrazin nicht als Wirkstoff zugelassen.“*). Atrazine was banned for application in crop protection in the EU by regulation nr. 2004/248/EG of 10 March 2004).

The total annual amount of herbicides sold to the agricultural sector gradually decreased over the years (Figure 39). While the sale of most substances decreased, the application of aminofosfonates increased since 1992 (Figure 39a). In recent years (since 1995) a strong increase in the use of glyfosate (Roundup), isoproturon and MCPA is observed (Figure 39b).

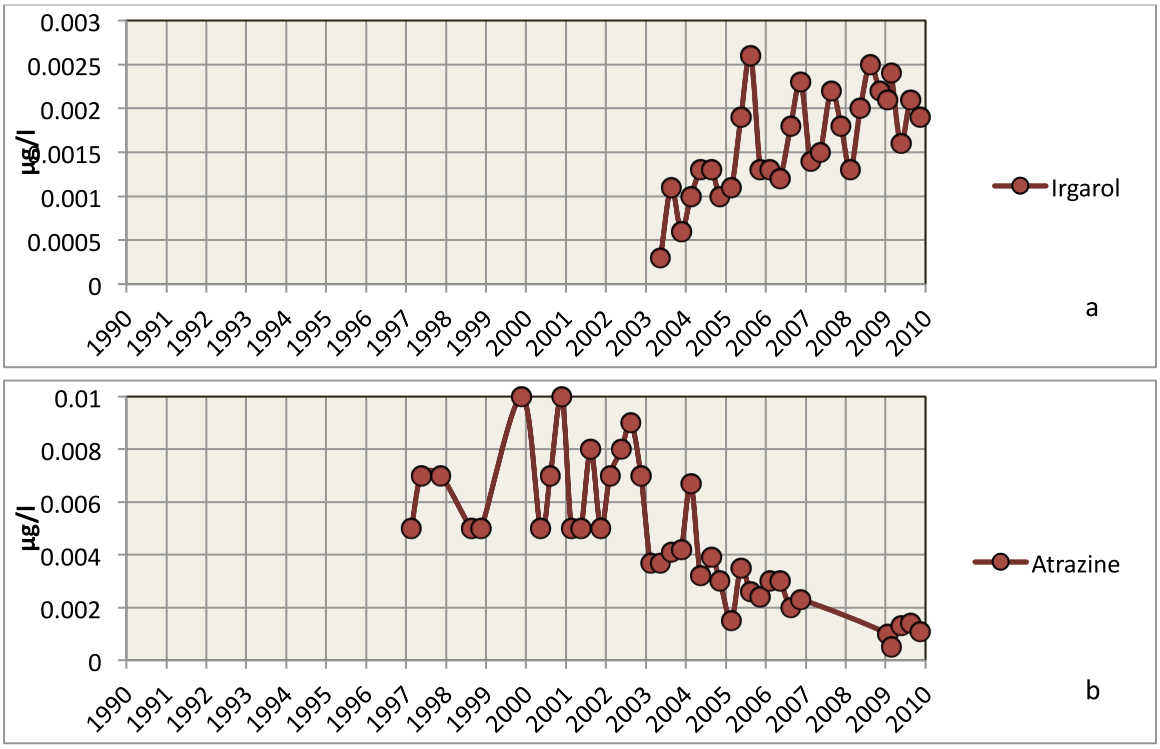
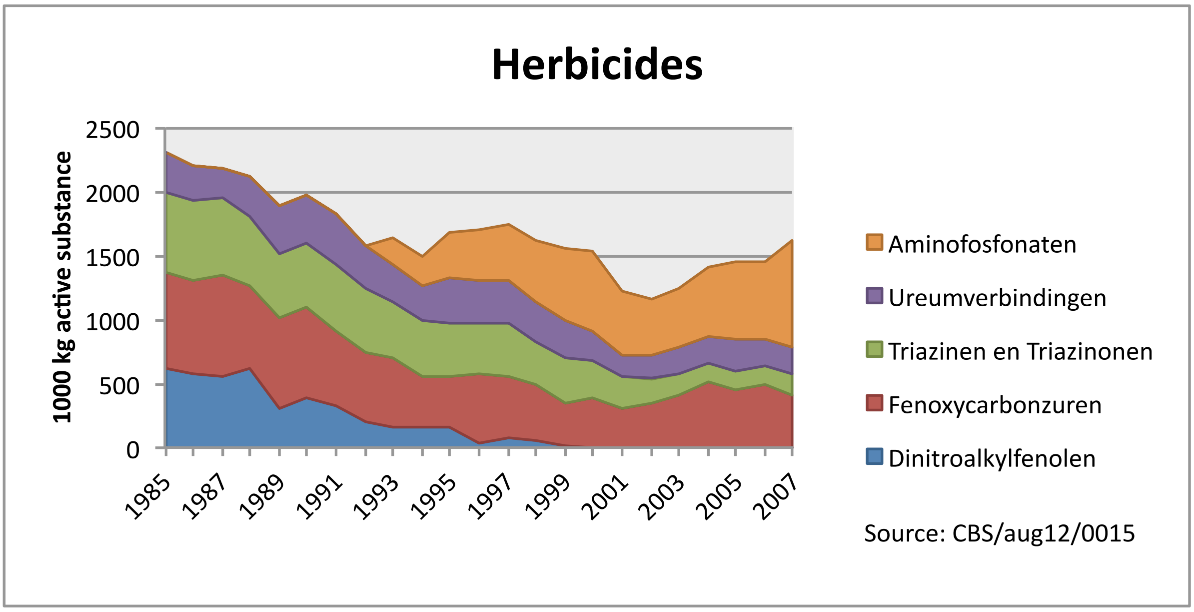
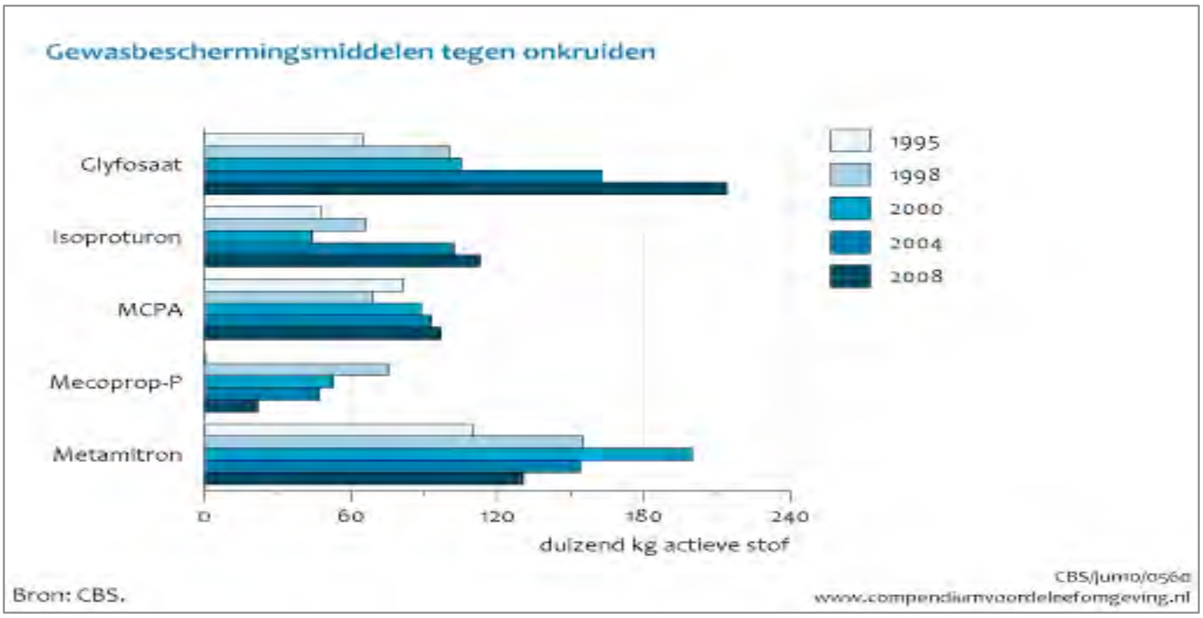


Figure 38. Herbicide concentrations (µg/l) of a. Irgarol and b. Atrazine at Bocht van Watum Noord (1990 – 2010) (RWS Waterbase).



a.



b.

Figure 39. Herbicides (kg active substance) a. Sales in the Netherlands and b. Use in the Dutch agricultural sector in different years. Data: CBS[4], published on www.compendiumvoordeleefomgeving.nl.

Dumping of dredged material

The dumping of dredged material in the Ems-Dollard Treaty area peaked around 1994 and 1995 at a volume of c. 13 million m^3 (Figure 40). In 1996, the dumping in the Ems estuary nearly halved but in the following years the volumes steadily increased again to reach a level of nearly 10 million m^3 in 1999. The volumes then fluctuated between 8-9 million m^3 until a next increase commenced in 2006 which led to volumes of 12 million m^3 in 2011 (Mulder 2011).

[4] Centraal Bureau voor de Statistiek

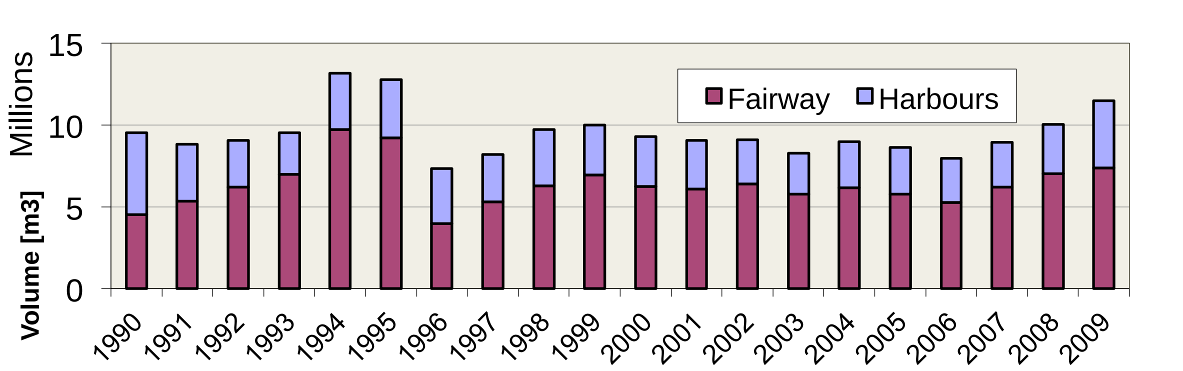
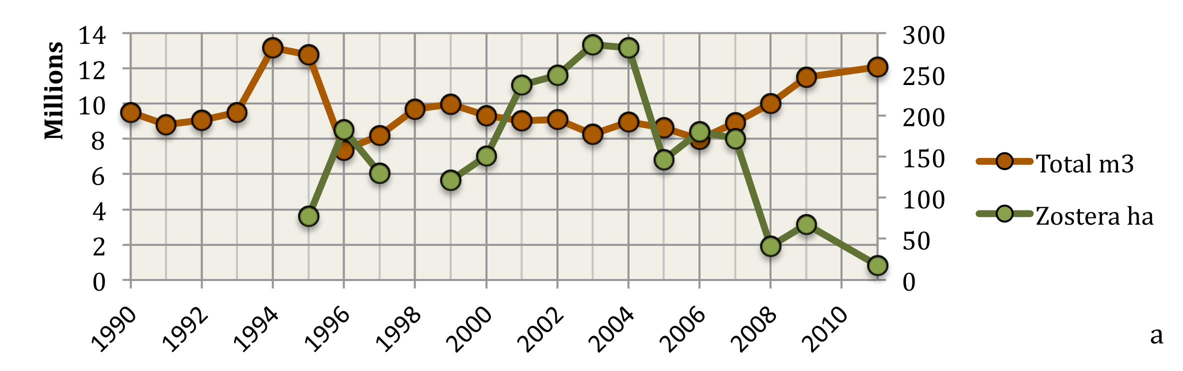


Figure 40. Dumpings (volume, m³) of dredged sediment in the Eems-Dollard estuary. Selection of years 1990-2010. Data: RWS, Herman Mulder.

The combined plot of the dumped volumes against the area of *Zostera* (Figure 41a) does not give a clear result. However, there appears to be a negative correlation between the dumped volume and the area of Zostera (R^2=0.45; Figure 41b). At dumped volumes >11 Mm^3, only *Zostera marina* areas of <80 Ha were observed.



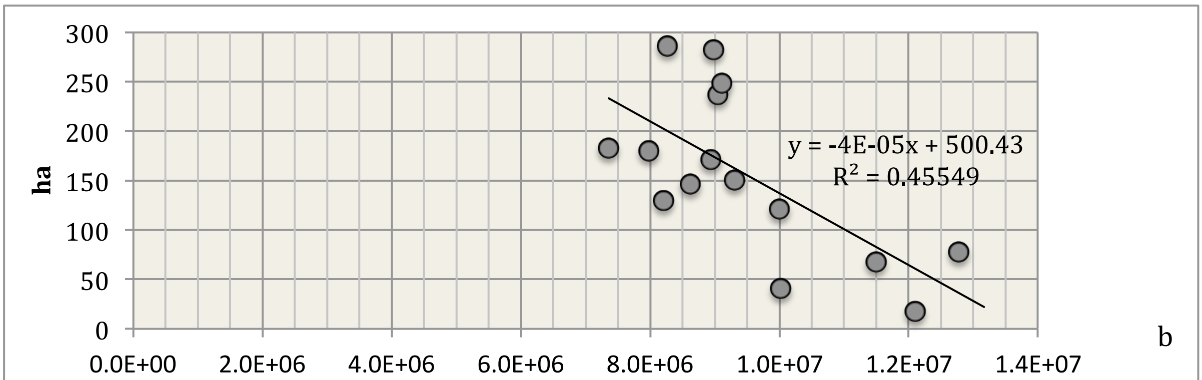


Figure 41 Dredged sediment (m³) in relation to the area of *Zostera marina* (ha) on Hond-Paap. a. Combined plot of *Zostera* area (ha) and volume dumped (m³), b. linear relation between *Zostera* area and dumped volume (R^2=0.45).

5.7 Biotic parameters

Labyrinthula

Given the prevailing water temperatures (sometimes >20 °C) and salinities (at times >30 PSU) and the reduced light conditions due to high SSC and increased turbidity, wasting disease caused by *Labyrinthula* cannot on forehand be excluded as a cause of decline of *Zostera marina* on Hond-Paap, but no evidence of its presence is available, simply because of lacking data.

Herbivores

The available bird counts on Hond-Paap, shown in Figure 42 and derived from De Boer et al. (in Erftemeijer & Wijsman 2004), do not suggest that herbivorous birds play a significant role in the reduction of the seagrass *Zostera marina*, at least not during the growing season. The most numerous birds were the mallard, common shellduck and widgeon. In the Ems estuary, *B. canadensis* and *A. acuta* are not observed. Heaviest waterfowl grazing of the observed bird species takes place during fall and winter, when the standing stock of *Zostera* is minimal.

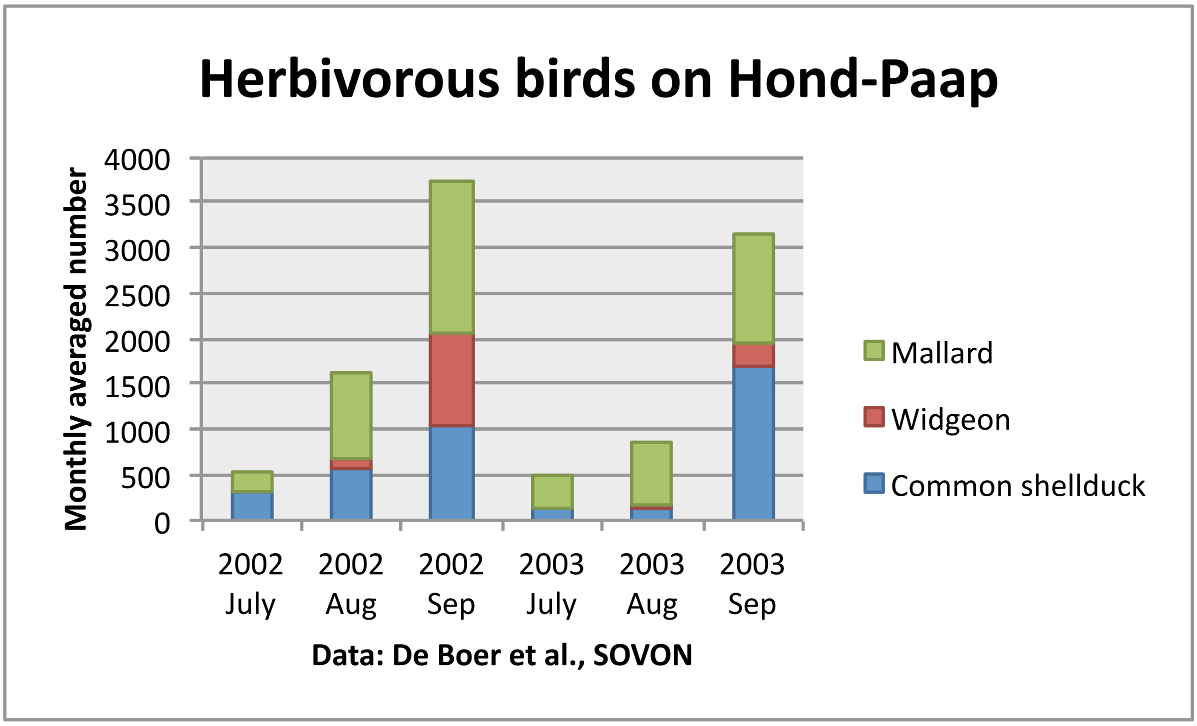


Figure 42. Herbivorous bird counts on Hond-Paap July-September 2002-2003 (Source: Erftemeijer&Wijsman 2004).

Mussel beds

The IMARES mussel monitoring data show that several mussel beds were present on Hond-Paap until 2001/2001 (blue colored area in Figure 43), which were more or less flanking the central ridge of the tidal flat. Since 2003, the mussels disappeared and were gradually replaced by the pacific oyster (*Crassostrea gigas*), creating mixed mussel/oyster beds (purple color). In 2010/2011, no mussels were found on Hond-Paap anymore, and oysters were encountered only on one spot in the southern part. However, it was recently discovered that this presumed oyster bed consisted of empty shell remains and was no longer alive (M. van Stralen, pers. comm.).

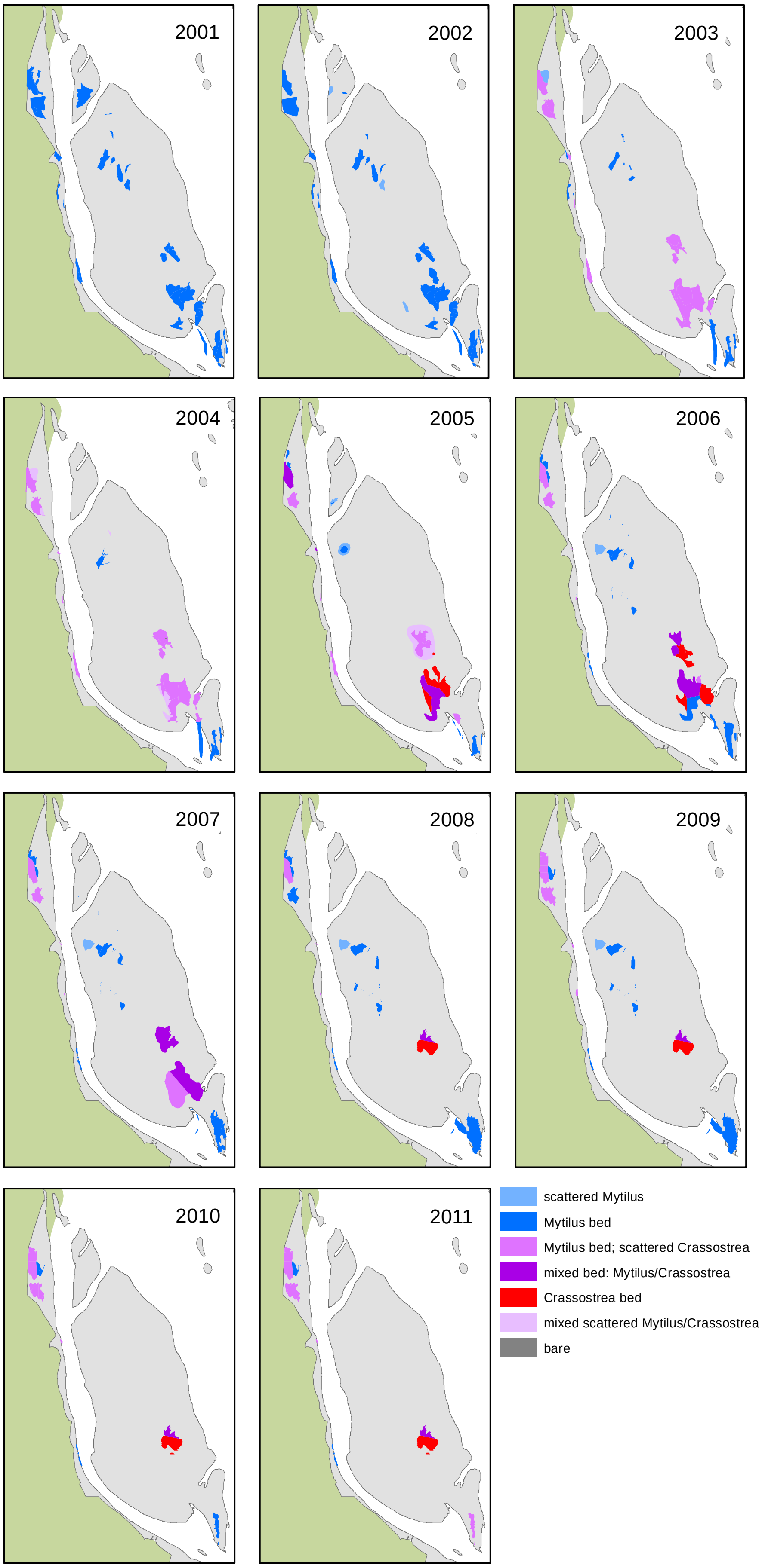


Figure 43. Mussel (*Mytilus edulis*) and oyster (*Crassostrea gigas*) beds on Hond-Paap. (Data: Karin Troost, IMARES).

6 DISCUSSION AND CONCLUSIONS

By nature, the estuarine environment is highly dynamic on temporal and spatial scales, and poses high demands to the coping strategies of organisms living there. In addition to natural dynamics (water temperature, salinity, SSC, oxygen, pH), anthropogenic influences (changed morphology and hydrodynamics due to dredging activities, discharges of nutrients and herbicides, thermal discharges) are superimposed stressors. All acting against background variations in climate and weather conditions that can cause 'events' in the development of seagrassess (ice-scour, heat-stress, storm). The highly variable 'wax and wane' development of *Zostera marina* in the Ems estuary can be interpreted as a reflection of this cumulatively stressfull environment.

Annual strategy

One strategy of plants to cope with a stressfull environment is a shift from a perennial towards an annual strategy. Recent modeling work suggests that annual and perennial life histories of plants are epigenetically regulated in response to environment-specific selection affecting flowering, where high mortality would favor a summer annual phenotype (Satake 2010, cited in Zipperle 2012).

The decrease in seagrass area (since 2003) was preceded by a decrease in the cover of *Zostera marina* plants (since 1996). On hindcast, the decrease of the seagrass cover on Hond-Paap may have been an early indication of increasingly stressfull conditions for seagrass, causing the plant to invest more and more in generative reproduction and thus an annual lifestyle, rather than the vegetative expansion by rhizomes.

Unfortunately there are no documented qualitative observations from earlier or later years, but in 2003 Erftemeyer indeed noted that on the northern part of Hond Paap all seedlings had germinated from seed, whereas on the southern part of Paap 77% grew from seed and the other 23% shooted from the rhizome (Erftemeijer & Wijsman 2004). In this light, the finding of Erftemeijer & Wijsman (2004) of very high percentages of seedlings from seed and the highly variable spatial distribution between years sustains the hypothesis of an annual strategy in response to the prevailing stressfull conditions for *Zostera marina* on Hond-Paap. It is unknown if this is a true shift from perennial to annual, or if common eelgrass on Hond-Paap expressed an annual strategy from the start. The areas with high cover (>20%) may hint to a wider occurrence of perennial growth in former years. Although the annual strategy of common eelgrass was quite successful for several years, judged by the rapid increase of seagrass area between 2001 and 2003, a turning point was reached in 2002/2003. Hereafter, only low cover of seagrass remained and the seagrass area decreased steadily each year until 2012.

Tidal flat elevation

The spatial distribution on the tidal flat was closely related to the elevation of the central ridge of Hond-Paap. The highest elevations of the tidal flat were observed in 2002 and 2003, corresponding to a maximum area of seagrass in those years (c. 300 ha). Seagrass was found at elevations between NAP +0.30 and NAP-0.80 m, but the upper limit seemed not so much determined by the duration of exposure at low tide but more by the limited tidal flat area available at that elevation. If more area of higher elevation had been available at the central part of Hond-Paap, it is speculated that the area of seagrass would have expanded even more in those years.

Duration of exposure at low tide

The actual duration of exposure at low tides was found to range between 40-60%, generally corresponding to the assumed range in the potential growth map (De Jong et al. 2005). Between 1995-2010, the largest area of seagrass was observed at c. NAP -0.15 m, which more or less matches the local average mean sea level (MSL) of the recent decade (RWS unpublished data). Currently, there is hardly any tidal flat area available at elevations above NAP -0.05 m, and the largest area is available at elevations of NAP -0.3 m – corresponding to exposures of <40% of the time; thus outside (below) the optimum range for seagrasses!

Sedimentation and erosion

In connection with the increasing elevation in these years, the sediment volume inside the potential seagrass area on the tidal flat ("restricted area") gained approximately 1.5 million m^3 of sediment between 1999 and 2002. The cause of this rapid sedimentation is unknown; more detailed data of the dumping sites K5, K6 and K7 can perhaps shed more light on this matter. At least one structural change was the introduction of the air-set to dredge the Delfzijl harbour since 2001, which reduced the dumped sediments (at ebb tides) in Bocht van Watum from formerly 2.5 million m^3 to currently only 0.1-0.3 million m^3 per year (pers. comm. Sjaak de Boer, Groningen Seaports). The erosion of the Hond-Paap between 2002 and 2005 was equally rapid and of almost the same size as the previous increase (1999-2001), and further changes between 2005 and 2010 were minor. Supporting our observation, Cleveringa (2008) calculated a substantial sediment loss (20 Million m^3) between 2002-2005 for "area 3" (Oostfriesche Gaatje). This loss is not easily explained, and may be related to the precisions of the elevation and accuracy of position measurements of RWS. The season of measurement is also of influence, because sediments that are accumulated during summer can be flushed away by the turbulence caused by storm events during winter.

Seagrass can cope with a sediment deposition of 2-13 cm/yr (Vermaat et al. 1997) and sediment trapping can even lead to increased germination rates. However, seagrass cannot cope with erosion, probably related to the shallow roots and relatively low below-ground biomass of the species. On the west coast of the USA, it is suggested that erosion rates of 0.5 mm day^{-1} and burial rates of 0.3 mm day^{-1} are limits for *Z. marina* survival (cited in: Van Katwijk 2000). Erosion can also negatively impact the seed bank on which the seagrass population is dependent for its survival. Despite erosion being an important process, affecting seagrass occurrence, species-specific values are poorly documented (De Boer 2007). Indirectly, erosion can lead to lower elevations of the tidal flat and to increased hydrodynamic exposure.

Anoxic sediments and diatom blooms

According to the field reports, anoxic sediments were there in the warm late summers of 2002 and 2003, but in these years, there was no mentioning of mass mortality and there are documented observations of seed production in these two years (Van Pelt et al., 2003 and Erftemeijer & Wijsman 2004). Nevertheless, the annual strategy depending on seed production and survival, is risky and results in a variable seagrass outcome. Consecutive years of unfavourable conditions are capable of depleting the seedbank (Plus et al. 2003). And because no substantial other seagrass populations are nearby, apart from the 'satellite location' Voolhok, a locally destroyed seedbank will not easily be replenished by import from elsewhere. The abundant presence of diatom blooms was remarkable, too. This was observed by both Groeneweg 2002 and Adolph et al (2003) but it is unknown if diatom blooms are beneficial or harmful for eelgrass.

Events

Other "events" coincided with the turning point of the seagrass population in 2003: in 2001 and 2002, the Hond-Paap seagrass population was used as a donor population for experimental restoration of seagrass in the western Wadden Sea (Balgzand), for which hundreds of seagrass shoots were collected by hand (Van Pelt et al. 2003). No detrimental effects of this was observed in 2002 (Groeneweg 2002). And in 2003, substantial works were undertaken to reconstruct the gas-pipe crossing Hond-Paap. At the time, there were no indications of negative impact of these events (Erftemeijer & Wijsman 2004). However, there was no follow-up monitoring for delayed effects.

Climatic extremes

The heat wave of August 2003, with observed diatom blooms and anoxic sediments, may have had negative impact on the seagrass of Hond-Paap. Although climatic extremes are a natural phenomenon and act on a wider scale in the Wadden Sea, they may have contributed to stressful conditions for *Zostera marina*, especially in addition to the coinciding stressful events which were discussed in the previous section.

Abiotic factors

Unfavourable abiotic conditions can have contributed to the negative *Zostera* developments. The suspended sediment concentrations show an increasing trend in Bocht van Watum (Vroom et al., 2012) and may have increased the light limitation. Salinity values were sometimes higher (25-30 PSU) than the optimum range. High salinity hampers leaf formation and shoot growth and at salinity of 22 psu seagrass plants perfomed better than at 32 psu in experimental tests (Kamermans et al. 1999). In experiments, plants from the Eems showed reduced vitality indicators at salinities of 26 and 30 PSU (Van Katwijk et al. 1999).

Most monitoring data of abiotic parameters give snap-shots of the conditions during the year, and the frequency is far too low to observe episodic events that can kill seagrass very quickly (oxygen depletion). Furthermore, there is a lack of knowledge and monitoring of the processes that occur in the sediment (pore water) at the site where seagrass grows. Of special relevance are sulfide and ammonium concentrations in the sediment pore water, in combination with oxygen concentrations and pH.

Eutrophication

The high ammonium loads (winter) seem not to hamper the development of seegrass in the following summer. In fact, the seagrass area and preceding winter ammonium show a parallel trend. Seagrass morphology and growth are strongly linked to available nutrient resources. Short (1983) reported a strong correlation between sediment N and eelgrass leaf morphology. Probably, the amount of ammonium during the preceding winter indicates a scope for growth of primary producers such as seagrass.

Biotic factors

The role of *Labyrinthula* is one of the knowledge gaps. Abiotic conditions at times may have favoured *Labyrinthula* at the expense of *Zostera*. *Labyrinthula* can not on forehand be excluded as a cause of decline, but data are lacking to substantiate this suspicion.

Herbivores are not believed to play an important role in the population dynamics of *Zostera marina* in the Ems estuary.

It is remarkable that mussel beds showed a parallel decline since 2002, and have become scarce. It is unknown if there is a common factor responsible for the decline.

Herbicides

There is no information on herbicides on the scale of the Ems estuary for the relevant time-period (1990-2010). Therefore no conclusions can be drawn on this topic, but the scarce literature indicates that herbicides pose a potential risk for seagrasses and that the effects are complicated by the interaction of substances and the different impact on different stages of *Zostera marina*.

Knowledge gaps

A better understanding is needed of the the development in the elevation of the tidal flat in relation to the changes in the nearby (shipping) channels as a consequence of the continuous and progressive dredging and dumping of dredged materials. The rapid filling up of the Bocht van Watum may have had an impact, too: if the channel is shallower, more water must find its way over the surface of the tidal flat which may cause increased current velocity and erosion. It was outside the scope of the present study to include an analysis of the hydrodynamic situation, but it would be worthwile to simulate the changed flow patterns as a consequence of the changes in morphology by model studies.

In addition, this area is slowly sinking by gas exploitation; however, the considerable sediment transports in the estuary are thought to largely compensate for this subsidence (Cleveringa 2008).

Evaluation of 'Kansenkaart'

Of the 'Kansenkaart' 2005, only the parameter 'duration of exposure at low tide' could be evaluated against the observations. The observed elevation at which *Zostera marina* was found corresponded with an exposure duration of c. 40-60% of the time, which is in good agreement with the assumptions made for the habitat suitability map (40-65%), which applies to both common and dwarf eelgrass in the Wadden Sea. The wave exposure and current velocities were not examined in the present study and cannot be evaluated. The ammonium load (as NH_4-flux $mol.m^{-2}.d^{-1}$ in 'Kansenkaart 2005') is not comparable to the examined parameter NH_4/NO_2 winter concentrations in water ($mg.l^{-1}$) and this parameter can therefore not be evaluated. Salinities were at times above the optimum range of *Zostera marina*; the interaction of salinity with nutrients could not be evaluated in the present examination.

Recommendations

It is recommended to undertake more intensive monitoring to follow up on the development of the remaining surviving plants. Monitoring of qualitative indicators of plant health (ratio of above-/below-ground biomass, plant lenght, number of spathes, seed production estimates), and of *in situ* conditions in the sediment (pore water) (sulfide, ammonium, oxygen) and water column (oxygen saturation, light, current velocity, temperature, salinity) can give better explanations of a seagrass populaton decrease by early warning and enhanced detection of hampered growth conditions. Given the annual strategy of *Zostera marina*, early indication of the seed survival (additional monitoring in late spring) may be of added value. The present monitoring, by walking transects on the tidal flat, is rather limited and inaccurate. In the Netherlands, the frequency of monitoring was unfortunately reduced to once every 3 years which is insufficient given the observed rapid (annual) changes in seagrass cover and area. Fieldwork reports indicate that the transects were not always measured completely, due to adverse weather or tide conditions.

It is recommended to tune the monitoring of RWS and NLWKN, or to join efforts to increase the frequency and/or quality of the seagrass monitoring in this area. The most recent morphological map of 2010 indicates a tilt of the axis from N-S to NE-SW of the tidal flat ridge where the seagrass was concentrated. The monitoring transect may therefore need adaptation to the changed situation. Temporal and spatial coverage of seagrass monitoring could be improved and could be supported by low-altitude camera-observations. In this way, the fate of the last remains of a former common eelgrass population on the Hond-Paap tidal flat in the Ems estuary can be documented.

7 SUMMARY

The seagrass (*Zostera marina)* population on Hond-Paap, with its predominantly annual strategy, is stressed by a combination of anthropogenic impacts on top of dynamic and sometimes unfavourable climatic and abiotic conditions and is highly dependent on successful seed production in summer and germination in the following spring. Erosion and mortality of seeds and mortality of seedlings contribute to the recruitment success or failure. A failing seed production in two consecutive years can cause a rapid population decline, which is a likely scenario that occurred around 2003.

In this study, several abiotic and biotic parameters were examined in varying detail and the (merely inconclusive) findings in relation to eelgrass trends are summarised below.

Climate indicators: ice scour and heat waves have occurred on occasions and may have contributed to the decline.

Abiotic parameters: monitoring data of salinity, pH, oxygen, SSC were measured at too low frequencies, therefore the (highly relevant) exceptional values may have gone unnoticed. Water temperature measurements were frequent, but did not cover the entire period of seagrass wax and wane. The monitoring locations were not optimised to represent the conditions at the seagrass site. None of the abiotic parameters were measured in the sediment (pore water), and there is no information on sulfide at all.

Herbicides: monitoring data and knowledge of the impact on *Zostera marina* are insufficient.

Dumping of dredged sediments: these data are recorded by the authorities but were unavailable for the present analysis. Volumes dumped at the sites K5, K6, K7, Bocht van Watum and Mond van de Dollard are needed (at least of the period 1990-present).

Biotic parameters: monitoring data are insufficient on herbivores and *Labyrinthula*. Efforts could be made to demonstrate *Labyrinthula* presence in seagrass on Hond-Paap.

Elevation: the tidal flat elevation was measured frequently by Germany, and the accuracy is improving over the years; an annual frequency is required and the measurements should be done in comparable seasons between years.

Changes in the tidal flat morphology, a.o. lowered elevations and an apparently eroding tendency, are mainly held responsible for the rapid decline of seagrass *Zostera marina* on the Hond-Paap in the Ems estuary. The underlying causes of this are not clear.

The increasing trend in SSC, contributing to an increasing light extinction, may further have limited the water depth at which *Zostera marina* can grow. The range of suitable elevation for seagrass growth is thus squeezed both from both (upper and lower) sides.

At the presumed eroding situation, resulting in a lowered tidal flat elevation, and under the prevailing limiting light conditions, there is currently very little potential for recovery of common eelgras on Hond-Paap. Transplantation of *Zostera marina* seeds or plants from elsewhere will not be succesfull if this hypothesis is correct.

Further studies of the underlying causes of the observed morphological changes on Hond-Paap, of the hydrodynamic changes and of the impact of the ongoing dredging activity and channel deepenings may help to understand if there still is a potential for the growth of Common seagrass on the tidal flat of Hond-Paap in the Ems estuary.

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