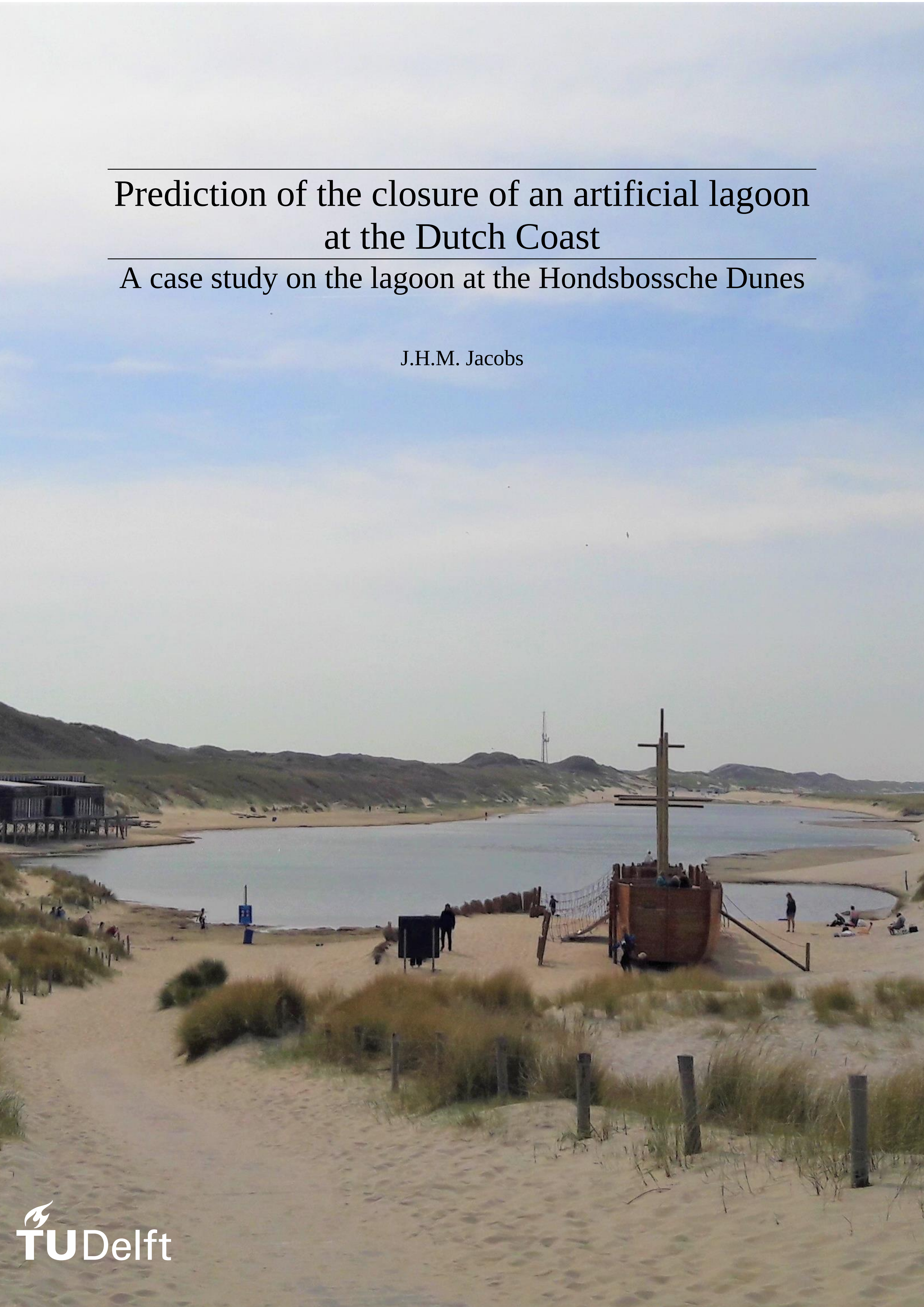
Prediction of the closure of an artificial lagoon at the Dutch Coast

A case study on the lagoon at the Hondsbossche Dunes

J.H.M. Jacobs



A smooth sea never made a skilled sailor.

-- Franklin D. Roosevelt

Cover image: Personal photograph of the author of the Lagoon at the Hondsbossche Dunes.

Prediction of the closure of an artificial lagoon at the Dutch Coast

A case study on the lagoon at the Hondsbossche Dunes

By

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Master of Science
in Civil Engineering

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November 2019

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Preface

This thesis report completes the final part of my Master of Civil Engineering at the Delft University of Technology in the track Hydraulic Engineering.

After a successful study in Civil Engineering at The Hague Universality of Applied Science I was eager to learn more about Hydraulic Engineering, and so I decided to get my master's degree. As Franklin D. Roosevelt one said: 'A smooth sea never made a skilled sailor'. And yes, it was a bumpy road, but I am proud that I accomplished it and can name myself a master's in civil engineering.

Growing up in the Netherlands and close to the sea the one thing you need to learn is how to swim. And so, my parents put me on swimming lessons at the age of four at a lifeguard association. One thing led to the other, and since the beginning of my teenage years you can find me on the beach for half of the year. Combine this with sailing weekly on lakes and an interest in technology and you got a young girl that is interested in anything technical that has to do with water. The choice to study Civil Engineering was therefore easily made. When I needed to pick a topic for my master thesis one thing was therefore clear: anything was good as long as it had a link with the coast and sand. This led to the thesis research you find in this report.

First, I would like to thank my thesis committee, starting with my daily supervisor Matthieu for guiding me in the interesting path I choose during my research. I had the feeling that I astonished you every time I came to see you. Stefan for offering me this topic, Julia for helping me getting clear what I was doing and where I wanted to go in my research, and Jill for the understanding that the topic that I choose is much more complicated than I thought.

I would like to thank my friends, starting with my Burgelijke Kuikens for encouraging me, with special thanks to Anke and Joreen for helping me to understand QGIS. My rowing team 34 for the sport in the beginning of my study and later on for all the tea we had instead of rowing. My friends at my lifeguard association for all the laughs and the action on the beach that gave me some distraction. All the students in the 'Hydraulic hokje' for the advice here and there and the breaks we had between our ongoing thesis research.

Finally, I would like to thank my parents and sisters for the support and love throughout my whole study and getting me back on my feet when I didn't see things so clear.

Joanneke Jacobs
November 2019

Abstract

To protect the coastal system, nourishment of the coast is nowadays being applied more frequently. Within these coastal systems new elements are often implemented to add value to the design without compromising on the function of the design of the nourishment. One of these possible purposes is the creation of an artificial lagoon. However, to be effectively applied a deeper understanding of the behaviour of these lagoons is required.

In 2015 the Hondsbosse Dunes (HD) were realized at the Dutch coast at the former "Hondsbosse en Pettermer Zeewering" near Camperduin, and an artificial lagoon was created for nature and recreation purposes within this design. The lagoon provides a boost for both the beach itself as well as the surrounding region. However, the lagoon's inlet is not stable and continuous maintenance is needed. The objective of this study is to explore the behaviour and longevity of this artificial lagoon, considering the frequency and moments of closure of the lagoon's inlet. This is achieved by assessing and studying offshore hydrodynamic conditions, satellite imagery, geographical measurements, dredging activity, and water level measurements inside the lagoon.

Whether the lagoon is stable or not depends on the inlet stability. Key factors that affect the inlet stability are the tidal prism and the annual littoral drift. The lagoon at the HD can be characterized as an intermittently closed estuary, which is a water body that become isolated from the open coast for a period of time. This system can be divided in a perched or a non-perched system. A perched system has a high berm that closes of the system, where a non-perched system does not necessarily have a berm but has a lack of channel surface area.

To get a better understanding on how local hydrodynamic conditions can cause the lagoon's closure, the hydrodynamic conditions and available data were analysed. The significant wave height for storm events and the total water level at the shore, which includes the tide, the surge and the runup, are considered for the hydrodynamic conditions. Geographical measurements, satellite imagery and dredging moments are used to achieve a better insight of the system. The lagoon surface area is examined above 2.03 m NAP, to establish the behaviour of the lagoon basin and its inlet in time.

The result of the data analysis performed in this thesis suggest that the lagoon surface area does not move spatially in time. However, due to the lack of bathymetric measurements the lagoon could not be studied in further detail. Closure of the system occurs due to its highly dynamic channel, which is supported by an analysis of the cross-sections of the channel area in combinations with satellite imagery.

A detailed view on the water level inside the lagoon and the exchange between the open coast resulted in four stages that were indicated visually:

1. Closed stage, resulting in a closed channel. The water level can only increase when the water level at the open coast overflows the berm. It leads to a stepwise increasement of the water level, referred to as a perched system.
2. Open stage. The channel is open and water exchange is possible with the open coast. The effect of the tide can be observed clearly in the water level of the lagoon.
3. Dredging stage. The water level decreases rapidly from a level above high tide at the open coast, to a value near or below high tide level. Afterwards water exchange with the open coast may occur, but this is not always the case.
4. Episodic event. The water level fluctuates, for which the cause cannot be stated beforehand. It depends among others on the type of system, hydrodynamic conditions and on the shape of the channel. The system is called non-perched when a high-water level overwashes the berm in the channel. It seems that the system is open, but water exchange does not occur and the water level in the lagoon increases.

Analysis of these stages indicates that the system is closed almost 70% of the time. The system is most often closed between October and April, when the channel is dredged again leading to an open system. An open system occurs after dredging in spring, where the results shows that the water level inside the lagoon follows the tide. The data indicate that the system is open for 10-17% of the time.

Storm events highly influence closure of the channel. Although storm events on the North Sea are indicated by a significant wave height larger than 400 cm, the results demonstrate that storm events with a significant wave height of 300 cm provoke closure of the channel. This is the result of the small catchment of the lagoon. These storm events increase in winter periods, whereas summer storms appear two to three times a year. The impression that storm events lead to closure of the channel is therefore confirmed.

The results show that the lagoon remains the same over a timespan of three years, which suggests that the frequency of closure and opening is not time dependent. This leads to different dredging strategies that are possible for the near future. To create an open lagoon all year round, dredging frequency needs to increase, as it is implied that storm events lead to closure. This increases the dredging costs. If the preference lies in low dredging costs, the system will be closed during certain periods of the year. Since the lagoon is created for recreation purposes closure during the winter season and dredging during the recreation season is proposed as a strategy. These findings correspond to the currently considered strategy for the HD.

The data suggest that artificial lagoons, like the investigated case at the Hondsbosse Dunes, never stay open or open without human intervention. This indicates that active management is needed to keep these lagoons open.

Contents

Nomenclature

Abbreviations

Abbreviation	Full Name
DTM	Digital Terrain Model
GIS	geographic information system
HAT	Highest Astronomical Tide
HD	Hondsbossche Dunes
ICOLL	Intermittently Closed/Open Lagoon
STI	Small Tidal Inlets
TOCE	Temporally Open/Closed Estuaries
ZSNH	ZSNH Combinatie Van Oord/Boskalis

List of symbols

Symbol	Description	[Units]
β_f	Foreshore slope	[-]
η_{NS}	Water level at the North Sea	[m]
η_{lagoon}	Water level inside the lagoon	[m]
η_{shore}	Total water level at the HD	[m]
A_c	Cross-section area of inlet	[m^2]
d	Depth in the mouth of the channel	[m]
H_0	Deep-water wave height	[m]
H_s	Significant wave height	[m]
HW	High water level	[m]
L_0	Deep water wavelength	[m]
LW	Low water level	[m]
M_{tot}	Total annual littoral drift	[m^3/year]
P	Tidal prism	[m^3]
r	Bruun ratio	[-]
$R_{2\%}$	Runup	[m]
T_{m02}	Wave period	[s]

1
Introduction

1.1 Problem description

Coastal zone management is an ongoing process in The Netherlands, especially in times of climate change. To prevent further structural erosion of parts of the coast, the Dutch government decided in 1990 to maintain the shoreline as it was measured at the time (Ministerie van Verkeer en Waterstaat, 1990). One of the measures taken to prevent coastal erosion is repetitive nourishment on the shoreface, beach and dunes. The intensive use of the hinterland behind the coastal defence required new safety standards to prepare for the future (HWBP, 2016) and continues to ask for a new approach in which dynamic coastal protection should be considered.

At the beginning of this decade the Dutch coast was reassessed, and multiple parts were identified as ‘weak links’. One of the weak links discovered during the assessment was the “Hondsbossche en Pettermer Zeewering”, a sea dike between Camperduin and Petten. To reinforce this part of the coast, the concept of *Building With Nature* was applied, which uses the forces of nature for hydraulic engineering purposes. A reinforcement was made with sand, resulting in the realisation of the Hondsbossche Dunes in 2015, hereafter referred to as HD.

Within the design of the HD several areas became available for nature and recreation along the coast. One of the new opportunities was the development of an artificial lagoon directly south of the HD (figure 1-1). Although local stakeholders mention that the lagoon has already provided a boost for the beach and the region, its inlet is not stable, and maintenance is needed. Both local entrepreneurs and the township want the lagoon to be maintained for at least five more years. To this end, a contract has been granted to ZSNH (Zwakke Schakels Noord-Holland), a collaborative alliance of Combinatie Van Oord/Boskalis, hereinafter referred to as ZSNH, until 2020. However, to be able to accurately plan the maintenance and to assess the financial implications, a deeper understanding of the stability of the inlet and the artificial lagoon itself over time are required.

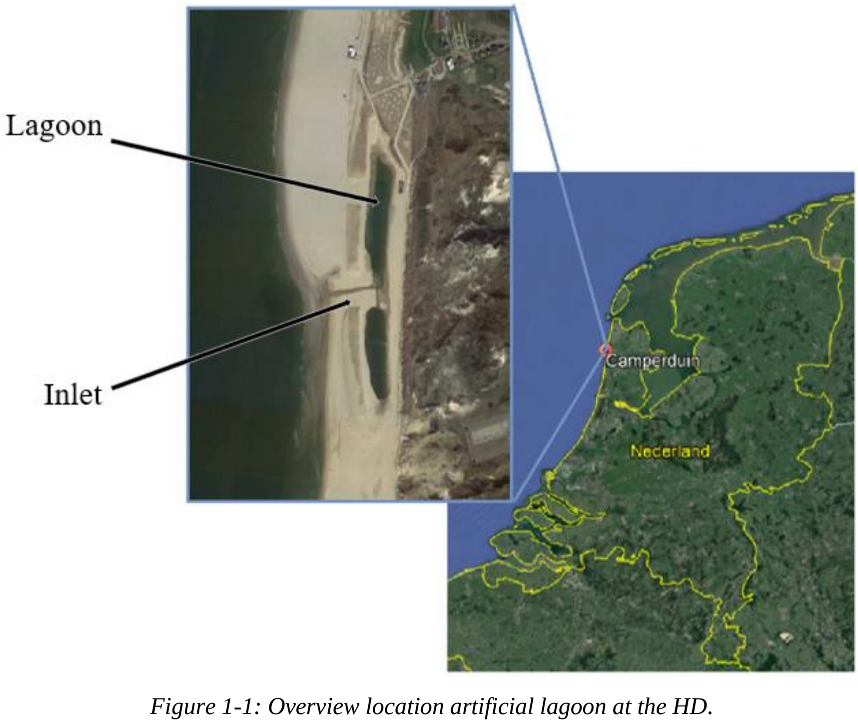


Figure 1-1: Overview location artificial lagoon at the HD.

1.1.1 Coastal lagoon

Lagoons are waterbodies that have restricted connections to the ocean and are a result of the drowning of coastal areas due to marine processes or the rising sea level during the Holocene. They are connected to the ocean by one or more inlets, separated from the ocean by barriers that are often orientated parallel to the coast. The lagoon is affected by tide, waves and river discharge (if present) (Kjerfve & Magill, 1989). Estuaries are waterbodies like a lagoon but are often deeper and a river is always present. Within the literature that will be reviewed for this research, the terms lagoon and estuaries are used interchangeably.

The water volume in the lagoon depends on river inflow (if present), rainfall, evaporation, and ocean tides (Figure 1-2). According to Slinger (2016) closure of the lagoon occurs if the channel silts up, resulting in a non-tidally influenced water depth in the mouth channel (d) and so limited or no refreshing of the lagoon. These openings can be intermittently open and closed as is observed at the HD.

The volume of the lagoon's basin is a function of the surface area and the water depth of the lagoon. The volume of water that enters and leaves the basin between mean high tide (HW) and mean low tide (LW) is defined as tidal prism.

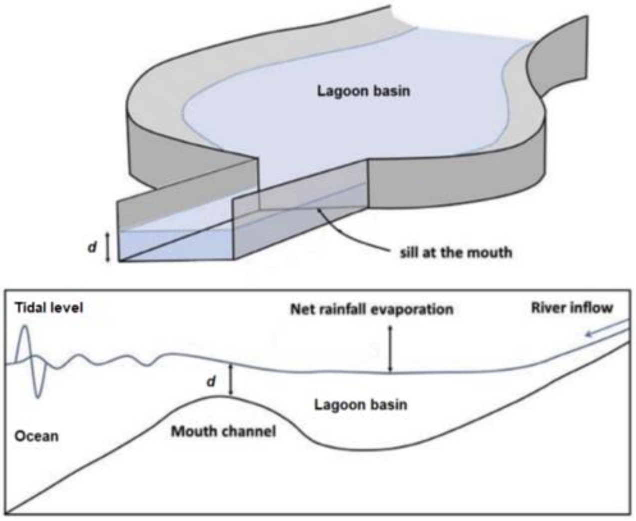


Figure 1-2: Overview of a lagoon with river inflow. (d) is the water level in the channel mouth. The lagoon basin changes in volume by net rainfall and evaporation, the tidal level that enters through the mouth channel and the river inflow (when present) (Slinger, 2016). Simplified by author.

1.2 Research objective

The objective of this study is to explore the behaviour and longevity of an artificial lagoon, specifically the frequency and moments of closure, based on observed data at the Hondsbossche Dunes. To address the objective, the following questions will be answered:

1. What was the behaviour of the lagoon in the recent years?
2. What are the hydrodynamic conditions that influence closure of the lagoon, and how often and when do they occur?
3. What implications does this knowledge hold for management in the near future?

1.3 Methodology

The scope of the research includes small estuaries in mixed tidal areas that intermittently closes. The research question will be answered by a data analysis combining with a literature review and a case study of the Hondsbossche Dunes. The literature review will give an understanding of the stability of an inlet, the classifications of an estuary and the processes that influence the inlet's behaviour.

The data that will be used for the case study consists of hydrodynamics such as: the wave conditions on the North Sea, the water level conditions on the North Sea, and the water level conditions in the lagoon. With this hydrodynamics the total surface elevation level at the shore at the channel will be estimated, which will give a better view on the influence that the water level at the open coast has on the water level inside the lagoon.

Extra available data that will be considered are geographical measurements, satellite imagery and dredging activities. From the literature review and the data, a dynamic hypothesis will be obtained for the study area.

A data analysis will be made for the surface area of the lagoon and its channel, considering geographical measurements. With the studied literature different stages will be set up for the development of the water level in the lagoon. These stages will be determined visually for the water level in the lagoon. Together with satellite imagery, dredging activities and storm events an overview will be made that give a better understanding of the frequency and moment of closure of the lagoon at the HD. It will allow to draw conclusions regarding the implications for management in the future.

1.4 Thesis outline

Chapter 2 presents a literature review that has a focus on small estuaries in mixed tidal areas that intermittently close. Chapter 3 present the case study of the artificial lagoon at the Hondsbossche Dunes. It outlines the design of the lagoon and the observed critical data. Chapter 4 provides the data analysis that is performed in this study. Chapter 5 discusses the results that are obtained, and Chapter 6 summarises the findings of the research and displays the recommendations for future management of the artificial lagoon.

2
Literature review

This chapter will provide an insight into relevant research for the study of the lagoon at the HD and has a focus on small estuaries in mixed tidal areas that intermittently close. It describes the stability of a tidal inlet, considering various empirical analyses and types of inlets, and describes the processes that influence these tidal inlets. Lastly, the behaviour of existing lagoons along the Dutch coast will be discussed.

2.1 Tidal inlet – stability

Tidal inlets consist of various elements, including the three main parts: an ebb-tidal delta, a flood-tidal delta, and an inlet channel. The ebb-tidal delta is located at the ocean-side of the inlet, while the flood-tidal inlet is located inside the bay. Between the deltas is the inlet channel (Figure 2-1). Over time, the tidal deltas change shape because shoals start to emerge: the ebb-tidal delta is fed by sediment that is deposited by the ebb flow leaving the inlet (creating an ebb-tidal shoal), and the flood-tidal delta grows owing to the sediment that is deposited by the flood flow entering the inlet (creating the flood-tidal shoal).

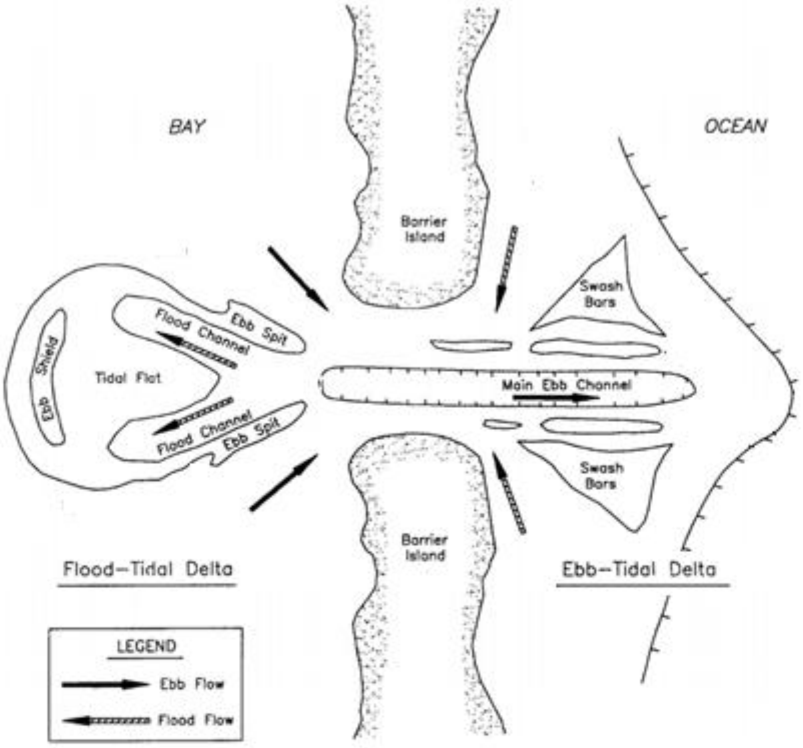


Figure 2-1: Morphological elements of tidal inlets. The inlet is located between the barrier islands. In the bay, left, the flood-tidal delta is located, whereas the ebb-tidal delta is located at the ocean, right (Boothroyd, 1985). Simplified by author.

2.1.1 Empirical analyses for stability tidal inlets

When the inlet is not stable, closure occurs due to changes in sediment transport and flow velocities. Several empirical analyses for the stability of the inlet have been proposed over the years. One of the most widely used methods is the relationship between the tidal prism and the inlet minimum cross-sectional area below mean sea level, the A-P relationship which is quantified by O'Brien (1931, 1969):

$$\mathrm{A_c} = \mathrm{aP^n} \tag{2-1}$$

Where A_c is the cross-sectional area of the inlet (m^2), P is the tidal prism (m^3), with P=A(HW-LW) for short basins, and a and n are empirical coefficients.

The Escoffier closure diagram (Escoffier, 1940) is another widely used method. This diagram plots the hydraulic stability curve for the maximum flow velocity in the inlet against the cross-section flow area (Figure 2-2). According to this diagram, the inlet is stable between point A and B and unstable for other conditions. When the entrance area increases past point B, the velocity decreases resulting in accretion in the entrance channel. The entrance channel will therefore become smaller, the maximum tidal velocity will increase, so the inlet moves eventually to stable point B. On the left of point A, the entrance area reduces, which gives a reduction of the tidal velocity and eventually leads to closure.

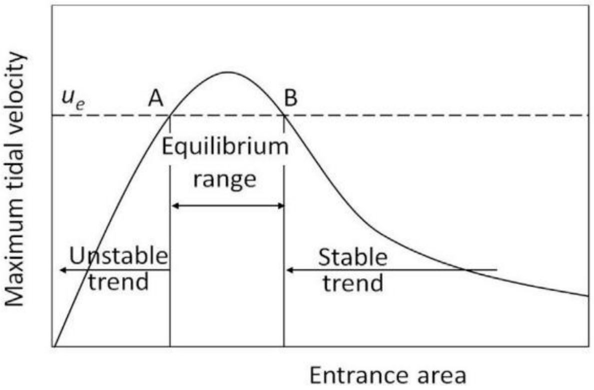


Figure 2-2: Escoffier diagram. The inlet is stable between point A and B. Right from B the inlet will return to the stable trend B, whereas left from A closure occurs due to the unstable trend. Replotted by (Hinwood & McLean, 2018)

The above methods only determine the inlet cross-sectional stability, not the locational stability. Bruun (1978) described both the cross-sectional as the locational inlet stability by including the longshore sediment supply. He proposed the following ratio for the inlet stability:

$$r = P/M_{tot} \tag{2-2}$$

With P the tidal prism (m^3) and M_{tot} the annual littoral drift (m^3/year), which is the longshore sediment transport along the coast. Bruun classified the ratio for the stability of the inlet as good, fair, poor or unstable (table 2-1).

Table 2-1: Inlet stability conditions by Bruun

r=P/M_{tot}	Inlet stability condition
>150	*Good*- Inlets are mainly tide-dominated and reasonably stable. Good flushing and little or no ocean bar forming.
100-150	*Fair*- Inlets are a mix of bar-by-passing and flow-by-passing. Entrance has low ocean bars. Mixed energy climate of tide and waves.
50-100	*Fair to poor*- Inlet is mainly bar-by-bar passing and unstable. Entrance is wider with higher ocean bars.
20-50	*Poor*- Inlet becomes unstable with non-overflow channels. Inlet is mainly wave-dominated, resulting in a wide entrance and shallow ocean bars.
<20	*Unstable*- Entrance becomes unstable. No permanent inlet, but rather overflow channels. Inlet might close by deposition of sediment in channel during a storm event. Small ebb current velocities will not be high enough to maintain and open inlet during storm events.

In Chapter 3 this formula will be applied to the situation at the HD to draw conclusions on its stability.

2.2 Estuary classification

Estuaries can be described by three main types, tide-dominated, wave-dominated and intermittently closed. The development of the inlet is different for each estuary.

2.2.1 Hydrodynamic classification

Inlets at the coast are affected by the tide and waves, and it is important to know which of these parameters dominates because they lead to different behaviour of inlets. The tidal range is divided into different ranges, microtidal (range <2 m), mesotidal (2-4 m) and macrotidal (>4 m). The wave height is divided in low, medium or high wave energy. Depending on the average tidal range and the average wave height a hydrodynamical classification exists, for which the inlets behave differently (Figure 2-3). The three main classifications are described below.

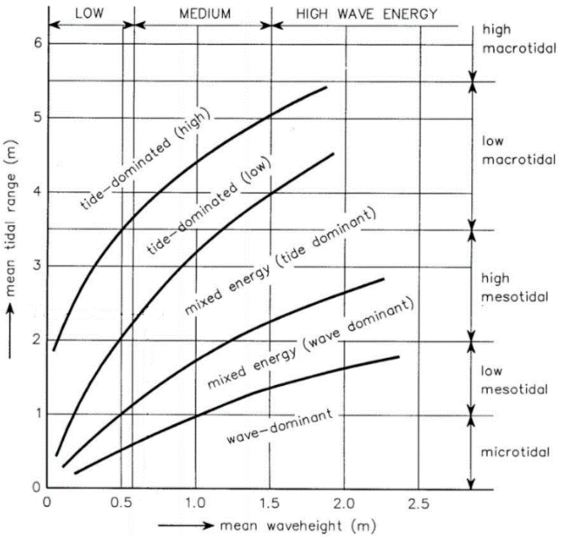


Figure 2-3: Hydrodynamical classification. The mean tidal range (vertical axis), divides into micro- meso- and macrotidal ranges. The mean wave height (horizontal axis), classifies as a low- medium- or high wave energy. The combination between the tidal range and the mean wave height result in a hydrodynamical classification (Bosboom & Stive, 2015).

In Chapter 3 this diagram will be applied to the situation at the HD to draw conclusions on its hydrodynamical classification.

2.2.2 Tide-dominated estuaries

Estuaries that are considered tide-dominant typically have large inlets and tidal ranges similar to the open ocean. For higher tidal ranges they are typified by funnel-shaped estuaries (Figure 2-4). However, tide-dominated estuaries are also present in microtidal areas where tides are locally more important than waves. (Cooper, 2001; Roy et al., 2001).

2.2.3 Wave-dominated estuaries

Wave-dominated estuaries have inlets that are influenced by the wave-deposited beach sand and the flood-tidal deltas that are smaller than in tide-dominated estuaries (Figure 2-4). The tidal range in the estuary is about 5-10% of the tidal range in the ocean and the tidal current is negligible. The sediment transport is driven by the local wind waves and the wind-induced water movements. They are strongly influenced by river discharge if a river is present (Cooper, 2001; Roy et al., 2001).

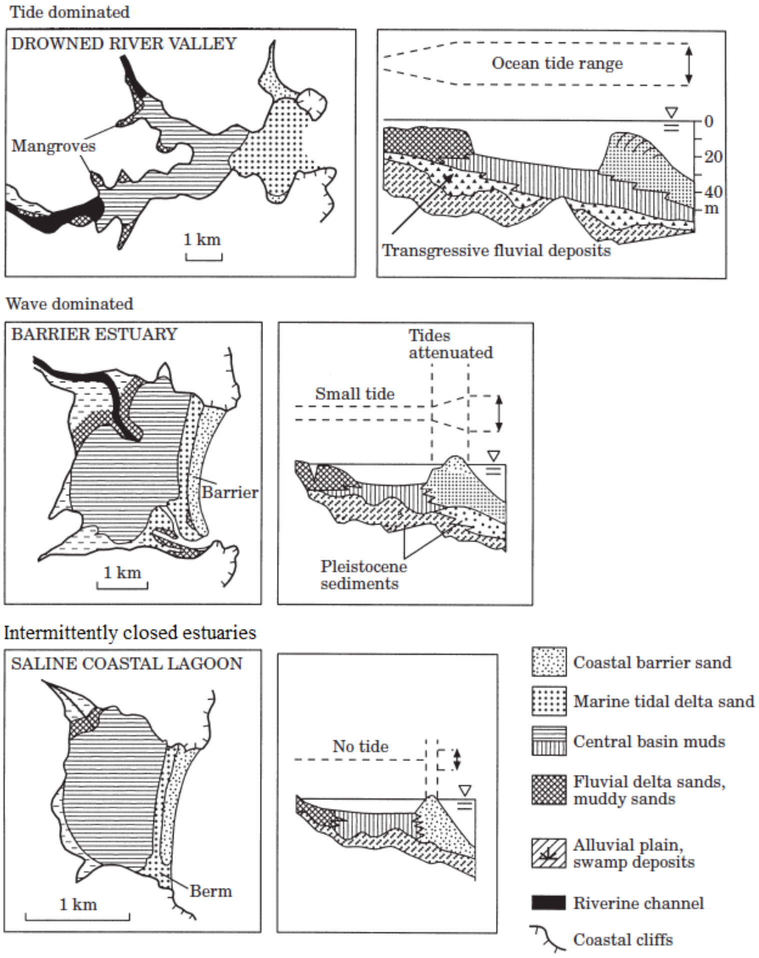


Figure 2-4: Three main estuary types described in top view and cross-section. Top: tide-dominated estuary. The tidal range is large, and the estuary is funnel shaped. Middle: wave-dominated estuary. The tidal range is small, it has a barrier between the ocean and the estuary and the river (when present) strongly influence the estuary. Bottom: Intermittently closed estuaries. There is no tidal range, a berm is located between the ocean and the estuary, and the estuary has a small catchment. Modified from (Roy et al., 2001)

2.2.4 Intermittently closed estuaries

Intermittently closed estuaries are coastal water bodies that become isolated from the sea for a period of time (Figure 2-4). These estuaries are identified differently in the world: Intermittently Closed/Open Lagoon (ICOLL) in Australia, and Temporally Open/Closed Estuaries (TOCE) in South Africa. They have a small catchment and a small river discharge when a river is present. The inlet can be blocked by beach sand for a longer period of time and has no tide in the estuary at such times. Breaching can occur by storm waves, raised water level in the estuary, heavy rainfall, or manmade breaching (Roy et al., 2001; Slinger, 2016; Slinger, Taljaard, & Largier, 2017).

These ICOLLs or TOCEs are divided into perched and non-perched systems. Perched systems have a high berm that closes off the system (Figure 2-5). The water level in the system is higher than the high tide. Breaching of the berm results in almost complete drainage of the system and scouring of the channel. Increases of the water level may occur by freshwater inflow, barrier overwashing, and rainfall. Decreases of the water level can occur by evaporation, seepage, and evapotranspiration by fringing vegetation (Cooper, 2001).

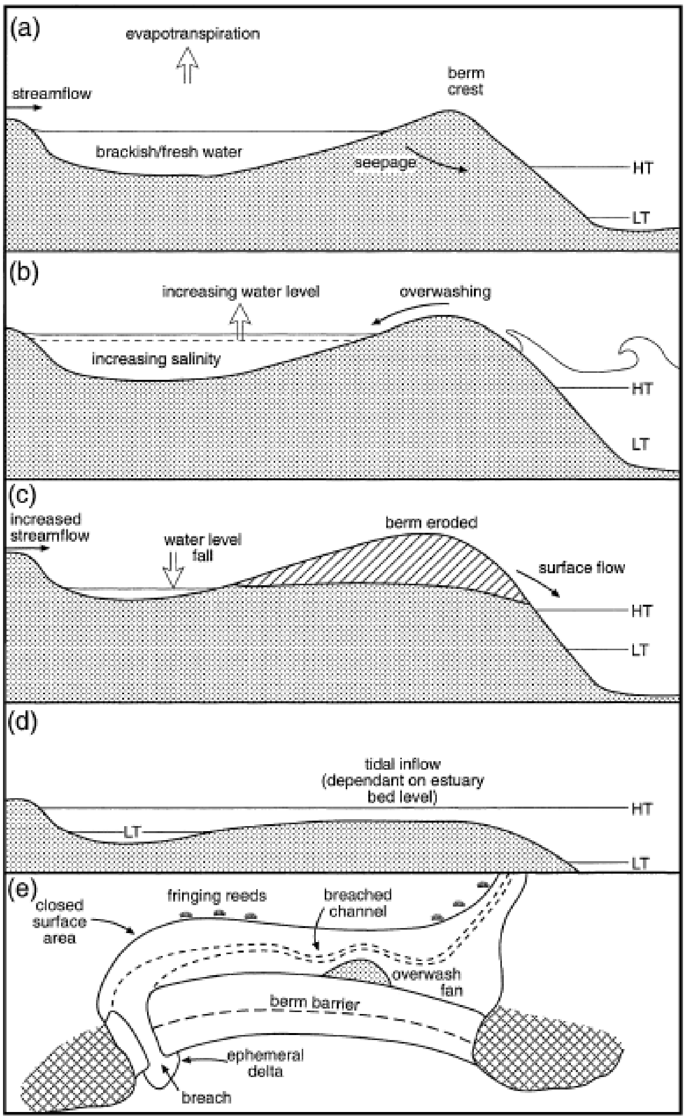


Figure 2-5: Cross-section of perched systems. (a) under balance conditions where the stream inflow is matched by evapotranspiration and seepage. (b) Overwashing, may increase the water level. (c) Streamflow, may foster breaching. (d) Breaching lead to a decrease in water level and result in tidal inflow. (e) Plan view with difference in water area for open and closed conditions. After Cooper (2001).

Non-perched systems do not necessarily have a berm that closes off the system, however they have a lack of channel surface area (Figure 2-6). The water level is close to or at high tide water level. The system overwashes more frequently (Cooper, 2001).

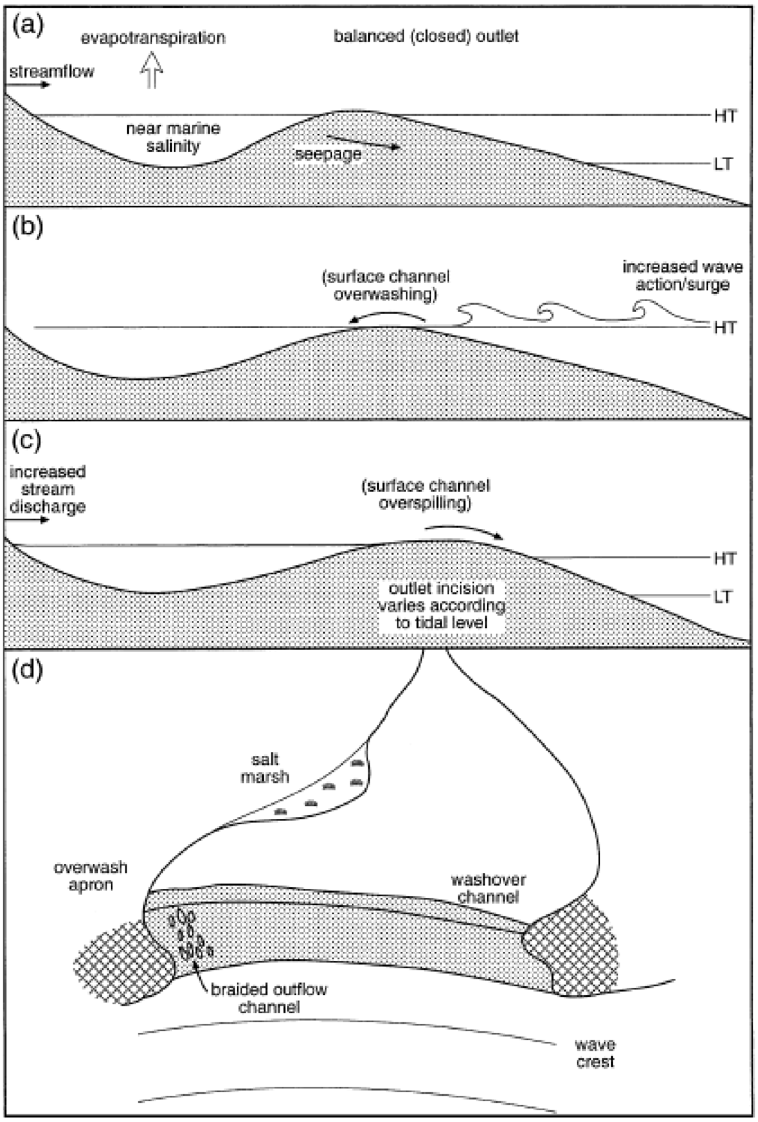


Figure 2-6: Cross-section of non-perched systems. (a) under balance conditions where the stream inflow is matched by evapotranspiration and seepage. (b) Overwashing under high wave energy, increasing the water level. (c) Streamflow may lead to overspilling of the surface channel and breaching. The depth of the channel is low since the water level in the estuary is close to sea level. (d) Plan view with difference in surface water area for open and closed conditions. After Cooper (2001).

2.3 Tidal inlets – processes

Closure of the inlet depends on the sediment transport along the coast. The behaviour of closure varies for long- and cross-shore transport.

2.3.1 Mechanism of closure of Small Tidal Inlets

Relatively small lagoons that are connected to the ocean are referred to as Small Tidal Inlets (STI), and are characterised by a surface area smaller than 50 km^2, a width of less than 500 m, and a maximum depth of 10 m. In these STI's little to no tidal flats or ebb tidal deltas are present. Duong et. al. (2016) distinguish three types of STI's:

- Type 1: permanently open, locationally stable inlets
- Type 2: permanently open, alongshore migration inlets
- Type 3: seasonally/intermittently open, locationally stable inlets

Closure of an STI type 3 is described by many different hypotheses, which are organized in two mechanisms by Ranasinghe et al. (1999). Closure of the inlet occurs due to longshore sediment transport (mechanism 1), or because of onshore migration of sandbars (mechanism 2). This is illustrated in Figure 2-7.

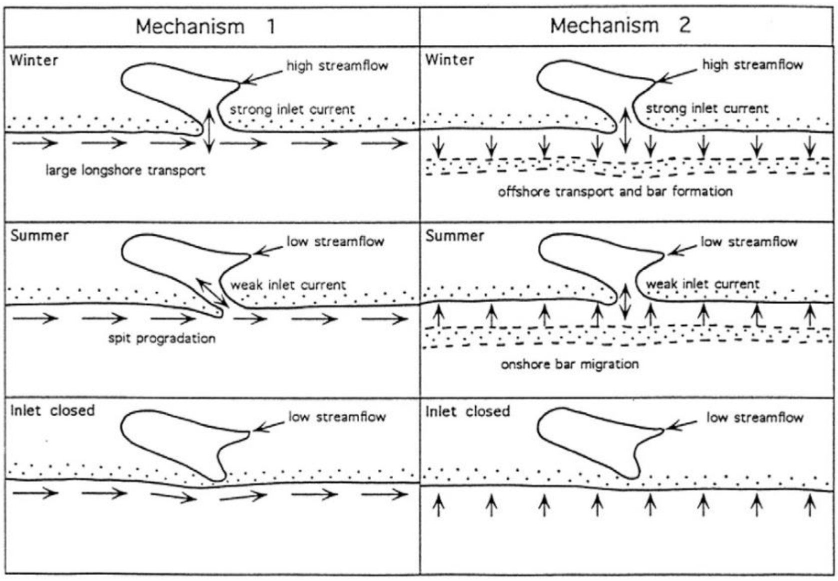


Figure 2-7: Inlet closure by longshore and cross-shore processes. Mechanism 1 describes closure by longshore sediment transport, which create a spit. Mechanism 2 describes closure by cross-shore sediment transport, as a result of onshore bar migration (Ranasinghe et al., 1999).

Mechanism 1 describes the interaction between the inlet current and the longshore current. The inlet current interrupts the longshore current and sediment transport, resulting in a shoal at the updrift side of the inlet. This shoal will develop depending on the longshore sediment transport. The supply of the sediment to the updrift shoal result in growth of the shoal which eventually forms a spit across the inlet entrance. When the inlet current is strong enough it will remove sediment that is deposited in the inlet entrance, preventing propagation of the spit. It results in two bars on either side of the channel. However, when the inlet current is weak spit forming will continue leading to closure of the inlet.

Mechanism 2 can only dominate when the inlet currents are small (< 1m/s) and describes the interaction between the weak inlet current and onshore sediment transport due to swell wave conditions. The longshore current and longshore sediment transport rates are small. Under stormy conditions the sand erodes from the beach and is transported offshore, resulting in a longshore bar at breaker position. When long-period swell waves dominate, sediment from the bar is transported onshore. For high ebb-flow conditions the system remains open, when the ebb-flow conditions are low it results in closure of the inlet.

2.3.2 Total water level on sandy beaches

The water level at the shore influences the water level inside the lagoon. Higher waves can penetrate further into the lagoon, increasing the water level inside the lagoon, whereas small waves may not reach the inlet. This result in fluctuations in the water level inside the lagoon.

Different processes affect the water surface elevation at the shore, which results in a total water levels that is different from the still-water level offshore (Figure 2-8). The total water level at the shore consists of the measured tide, the surge, which is the elevation of the water surface due to atmospheric pressure, and the runup ($R_{2\%}$):

$$\text{Total water level} = \eta_{total} = \text{Tide} + \text{Surge} + \mathrm{R}_{2\%} \quad (2\text{-}3)$$

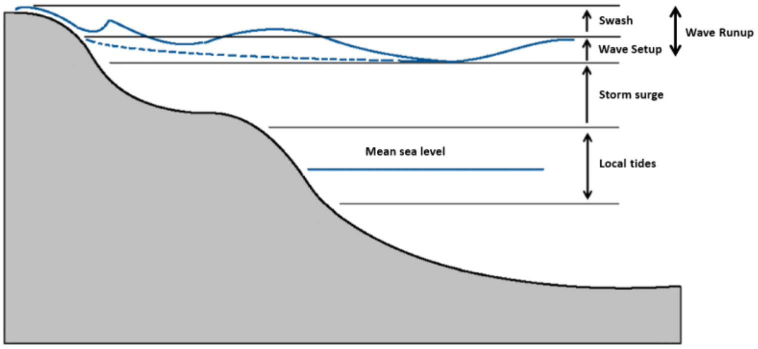


Figure 2-8: Total water level at the shore, including the local tides, storm surge, wave setup and wave runup (McLean, George, Ierodiaconou, Kirkwood, & Arnould, 2018). Adjusted by author.

The runup is defined as the maximum water level elevation on the beach and depends on the maximum wave setup, the time-averaged water level elevation at the shoreline, and the swash, which is the water layer that washes up the shore after wave breaking. Stockdon et al. (2006) proposed a general expression for the 2% exceedance wave runup, which represent the runup that exceeds 2% of the time:

$$R_{2\%} = 1.1\left(0.35\beta_f(H_0L_0)^{1/2} + \frac{\left[H_0L_0\left(0.563\beta_f{}^2+0.004\right)\right]^{1/2}}{2}\right) \tag{2-4}$$

Where β_f is the foreshore slope, H_0 the deep-water wave height and L_0 the deep-water wavelength.

2.4 Existing lagoons at the Dutch coast

Several STI's are located along the Dutch coast. The development of these STI's over time are outlined below, to give a better view how the lagoon studied for this research may behave over time.

2.4.1 The Slufter, Texel

At Texel, one of the Wadden Sea islands in the north of the Netherlands, a large estuary is located in the dunes at the North Sea side of the island; The Slufter (Figure 2-9). It has a channel leading though the dunes, a salt-marsh and a large intertidal zone landwards of the coastal dunes. This resulted in a unique nature reserve. The Slufter also works as a primary flood defence.

The dynamic coast leads to spit forming at the inlet, causing daily movement of the inlet, with a dominant movement in northern direction. The channel itself also changes daily, resulting in a larger channel length over time. Both elements result in siltation of the channel. Due to storms and high-water levels, closure will not happen fast. However, maintenance of the channel takes place to decrease the channel length to prevent erosion of the dunes surrounding the estuary (Durieux, 2003; Eysink, Hoekstra, & Hoozemans, 1992).

Figure 2-9: The Slufter at Texel

2.4.2 Het Zwin, border Belgium-The Netherlands

At the border of Belgium and The Netherlands an estuary is present, Het Zwin (Figure 2-10). It has a size of 1158 ha with an inlet of 250 m wide. The estuary inlet is not stable and silting of the channel occurs due to the twice-daily inflow of the tide. This is accelerated by sand nourishments at the Belgian beaches. The sill in the channel leads to sediment transport inland where it settles. Closures of the system is prevented by relocation of the channel, by dredging, and the creation of sand traps. (Eysink et al., 1992; Santbergen, 2004)

Figure 2-10: Het Zwin, between Belgium-The Netherlands

2.4.3 Sand Engine, Ter Heijde

In 2011 a mega-nourishment of 20 million m^3 was created near Ter Heijde: The Sand Engine. By spreading the sand by wind and waves, it feeds the adjacent coastline resulting in a new safety function for a lifetime of 20 years. Within the nourishment, a lagoon is present (Figure 2-11). The channel of this Sand Engine lagoon is not stable and migrates. Different from the previous two systems, this channel does not need to be dredged, but opens when high water levels exceed the crest of the spit of the lagoon. This results in an increase of the volume of the lagoon basin. Emptying of the lagoon occurs through the channel, where it scours the channel.

Figure 2-11: Sand Engine near Ter Heijde

De Vries et al. (2015) describe the tidal behaviour for the lagoon at the Sand Engine. For large inlets the tidal waves can propagate into the lagoon causing a tide that is observed both offshore and within the lagoon (Figure 2-12, top figure). However, when the inlet becomes smaller, the tidal range within the lagoon is damped. Outflow of the lagoon can only occur when the water level offshore is lower than the water level inside the lagoon and inflow only happens when the water level offshore is higher than the water level inside the lagoon. The high tide is only observed in the lagoon (Figure 2-12, middle figure). When the inlet becomes so small that almost no exchange of water is possible only small peaks are visible in the water level inside the lagoon (Figure 2-12, lowest figure).

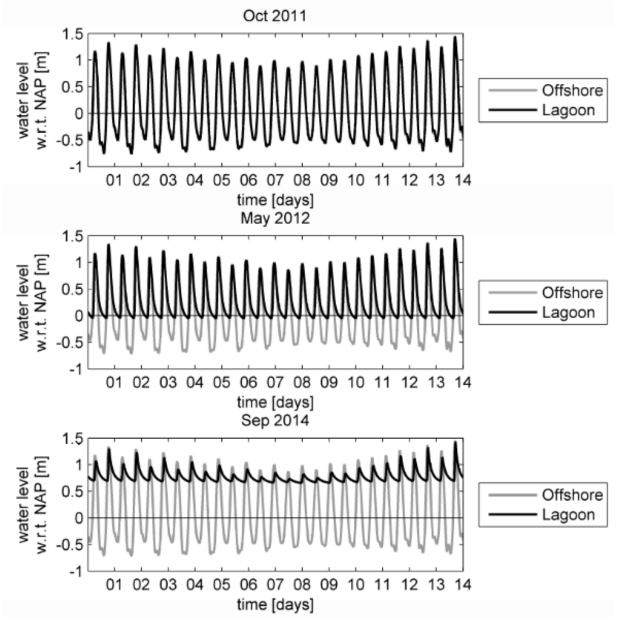


Figure 2-12: Modelled tides offshore and inside the lagoon for three different morphological situations over time at the Sand Motor. De Vries et al. (2015)

When the water level in the sea is high, it can overflow the threshold at the mouth, filling the lagoon. The lagoon starts to empty when the water level in the sea decreases below that of the lagoon, causing scouring of the inlet. This leads to a large mouth, and so the water level in the lagoon can again mirror that of the offshore water level.

2.5 Summary literature review

The literature review allows to give a first description of the behaviour of the lagoon at the HD. The literature shows that an inlet is stable or unstable, and the stability can be determined by empirical analyses such as Escoffier, O'Brien and Bruun, where Bruun includes the longshore sediment supply. A stable system has a connection with the sea, whereas an unstable system leads to closure.

The shape and process of closure depends on the hydrodynamic classifications. These are classified as wave-dominated, tide-dominated or intermittently closed estuaries. Intermittently closed estuaries are closed for a longer period and are referred to as ICOLLs or TOCEs. These ICOLLs or TOCEs can be defined as perched or non-perched systems, where a non-perched system has a lack of surface channel area leading to closure and a perched system has the presence of a berm that leads to closure.

Closure of the channel occurs by cross-shore or longshore sediment transport. Longshore sediment transport result in closure by spit forming. Cross-shore sediment transport leads to closure by onshore bar migration due to waves.

An overview of several lagoon systems along the Dutch coast shows that the systems are dynamic. Maintenance takes place to keep the channels open. If the system is fed by enough water due to overwashing, it can result in scouring of the channels leading to an open system.

The lagoon at the HD can be stable or unstable. Because it has a small catchment, it can be suggested that it will act as an intermittently closed system when it is unstable. The lagoon can therefore be perched or non-perched, depending if a berm develops which result in closure. Closure of the lagoon can be due to spit forming or onshore bar migration.

3

Case study

This chapter will give insight into the lagoon studied for this research. It contains an overview of the coastal system with the lagoon, its design, and describes the hydrodynamics that influence the lagoon. Additionally, details of the historical maintenance on the lagoon are outlined in this chapter.

3.1 Hondsbossche dunes

The lagoon studied in this research lies in the north of the Dutch coast between Petten and Camperduin, where the hinterland was protected by a sea dike the Hondsbossche & Pettermer sea defence (Figure 3-1). This sea dike was identified as one of the weak links of the coast and was reinforced using a mega nourishment, which resulted in the Hondsbossche Dunes in 2015 (Figure 3-2).

Figure 3-1:Hondsbossche & Pettermer sea defence until 2015. Adjusted by author.

Figure 3-2: Hondsbosse Dunes, including the lagoon. Completed 2015. Adjusted by author.

The orientation of the coast at the HD is 193° with respect to the north (de Jongh, 2017). The tide along the coast is semi-diurnal with an average tidal range of 1.5 m at the HD (Wijnberg, 2002). The mean wave height along the coast is 1.2 m and the mean wave period is 5 s (Wijnberg & Terwindt, 1995). The waves approach the coast mainly from southwest and north-northwest directions.

3.2 Design criteria of the lagoon

The lagoon is designed for recreation in the summer seasons, where families can enjoy calmer water than at the dynamic shore. It is located south of the HD, easily accessible from Camperduin and close to the present beach houses. A sheltered area is created by front dunes between the lagoon and the shore (Figure 3-3). The front dunes have two openings, one located in the north of the front dunes (i.e. north opening) and the other located in the middle of the front dunes (i.e. south opening). The entrance channel is located at the south opening. The remaining design criteria can be found in table 3-1.

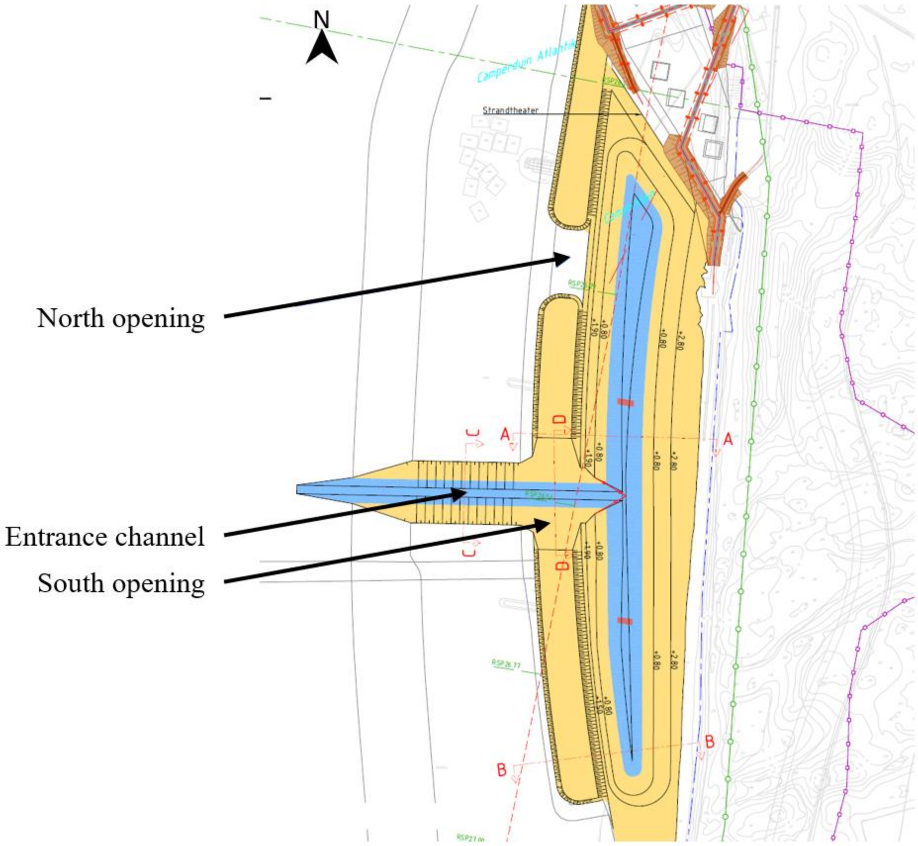


Figure 3-3: Lagoon design. It is located parallel to the coast and sheltered by font dunes. These front dunes have two openings, a north opening located in the north of the front dunes, and a south opening located in the middle of the front dunes. The entrance channel is located in the south opening, connecting the lagoon with the sea (ZSNH Combinatie Van Oord Boskalis, 2014). Adjusted by author.

Table 3-1: Design criteria lagoon HD (ZSNH Combinatie Van Oord Boskalis, 2014)

Design criteria	Value
Storage area lagoon	25,000 m2
Tidal prism	31,000 m3
Maximum bed level lagoon	-0.8 m NAP
Channel length	220 m
Channel width	10 m
Channel depth	0.55 m
Channel minimum cross-section	10 m2
Littoral drift at the channel is	0.33 M m3/y
Flow velocity at the entrance of the lagoon cannot exceed	0.5 m/s at HAT

3.2.1 Lagoon inlet stability

With the previously defined design conditions, the empirical analysis that are described in Section 2.1.1 can be performed. The formula of O'Brien (2-1) concludes that the minimum cross-sectional area of the lagoon (A_c) is 2 m^2 for the tidal prism (P) 31,000 m^3:

$A_c=6.56\cdot10^{-5}\cdot31{,}000=2\ m^2$.

The cross-section area is set on 10 m^2, so it can be stated that the system is not stable, and accretion will occur in the channel to meet the stability criteria.

The design ratio (r) set by Bruun (2-2) result in a ratio for the lagoon of 0.1, considering the total annual littoral drift (M_{tot}) of 0.33 Mm^3/y:

$r=31{,}000/0.33E^6=0.1$.

Table 2-1 shows that this results in an unstable inlet, and closure occur due to deposition of sediment in the channel. The system can only become stable, r = 100, if the tidal prism increases with a factor ten:

$P=100 \cdot 0.33E^6=33\ Mm^3$,

Or the littoral drift reduces, with at factor ten:

$M_{tot}=31{,}000/100=310\ m^3/y$.

Both analyses indicate that the system is not stable, and maintenance should take place to prevent closure on the long term.

3.3 Hydrodynamic data

The data used for the analysis of the hydrodynamics has been collected by Rijkswaterstaat (RWS, 2019), the Dutch national weather institute (KNMI, 2019), and the ZSNH (2019) between 04/09/2016-28/07/2019.

The data are collected at different stations with different frequencies (Figure 3-4 and table 3-2). Station Q1 is an offshore weather station. This station is chosen because of the short distance to the lagoon and the data availability for offshore conditions. The data of the significant wave height from this station is not complete, therefore data of the IJmuiden munitiestortplaats station is used to fill the gaps. This buoy is chosen because the distance to the lagoon is comparable to the distance between the Q1 platform and the lagoon. Station IJmuiden is chosen for the calculated tide because it has the best representation of the development of the tide and the surge near the coast and the lagoon.

Figure 3-4: Stations for data collection. Data is collected from the stations marked by solid circles. Wave conditions are collected from station Q1 and IJmuiden munitiestortplaats. Water level conditions result from IJmuiden station and the water level condition inside the lagoon from Lagoon station (RWS, 2019).

Table 3-2: overview used datasets

Dataset	Location	Frequency	Source
Wave condition North Sea	Q1 platform and IJmuiden munitiestortplaats	10 minutes	RWS
Water level condition North Sea	IJmuiden	10 minutes	RWS
Water level condition Lagoon	Inside Lagoon	10 minutes	ZSNH

3.3.1 Waves North Sea

The wave conditions can be characterizing in practice by the significant wave height (Hs), which is the mean of the highest one-third of waves. In general, it is used because it is closest to the wave height that can be estimated visually. The significant wave height varies between 0 and 9 m, with peaks that are clearly visual (Figure 3-5). Summer storms with a wave height larger than 3 m appear two to three times a year.

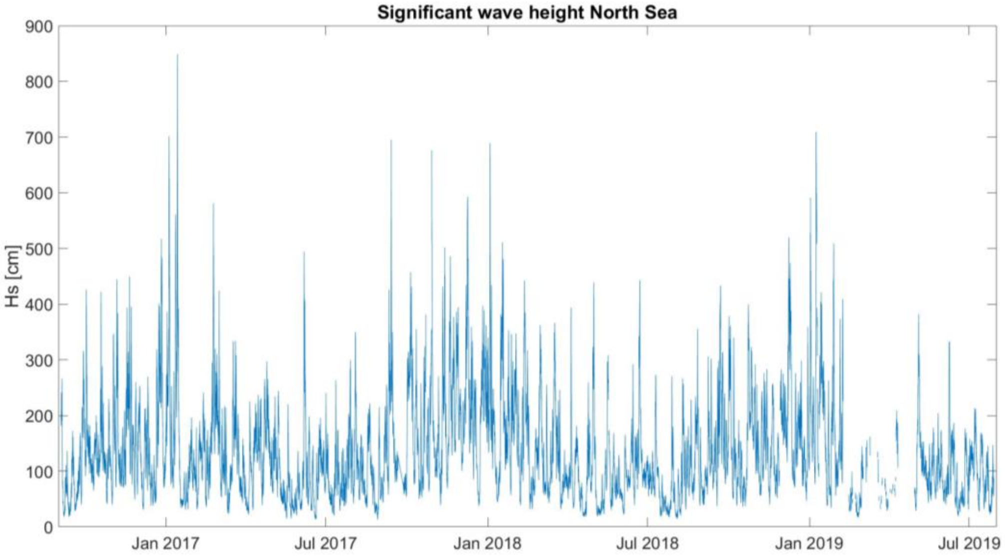


Figure 3-5: Significant wave height at the North Sea collected at station Q1 and IJmuiden munitiestortplaats.

3.3.2 Water levels North Sea

The water level observations include the tide and surge. Surge is the elevation of the water surface due to atmospheric low pressure and the effect of the wind on the North Sea basin. The water level fluctuates between -2 m and 3.5 m (Figure 3-6). The average daily difference between low- and high-water level is 1.5 m. The effect of the surge can be seen by peaks in the water level, with respect to the astronomical tide that lies between -0.75 m and 1.0 m.

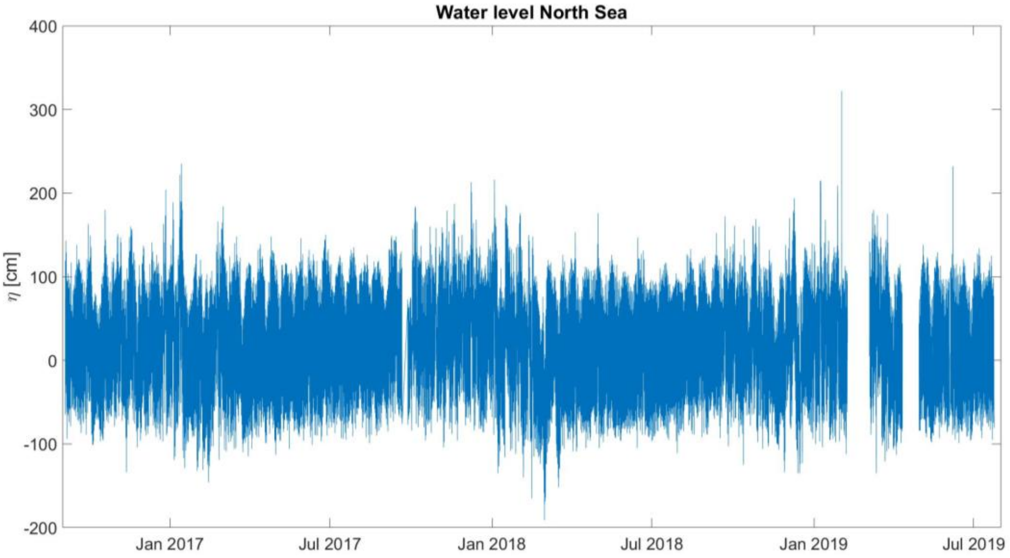


Figure 3-6: Water level at the North Sea, including the tide and surge from the North Sea. Collected at IJmuiden station.

3.3.3 Water level inside lagoon

A sensor is located inside the lagoon that has measured the water level (Figure 3-7) since 4-09-2016 (ZSNH 2019). The water level in the lagoon fluctuates between NAP +0.5 m and NAP +2.75 m. In the summer of 2017, 2018 and 2019 daily influences of the tide can be seen in the water level of the lagoon. The water level is higher during winter periods, and surface elevation peaks are clearly present in the graph. The rapid decrease in water level is the result after dredging. Fluctuations of a couple of centimetres in the water level may be linked to atmospheric pressure fluctuations.

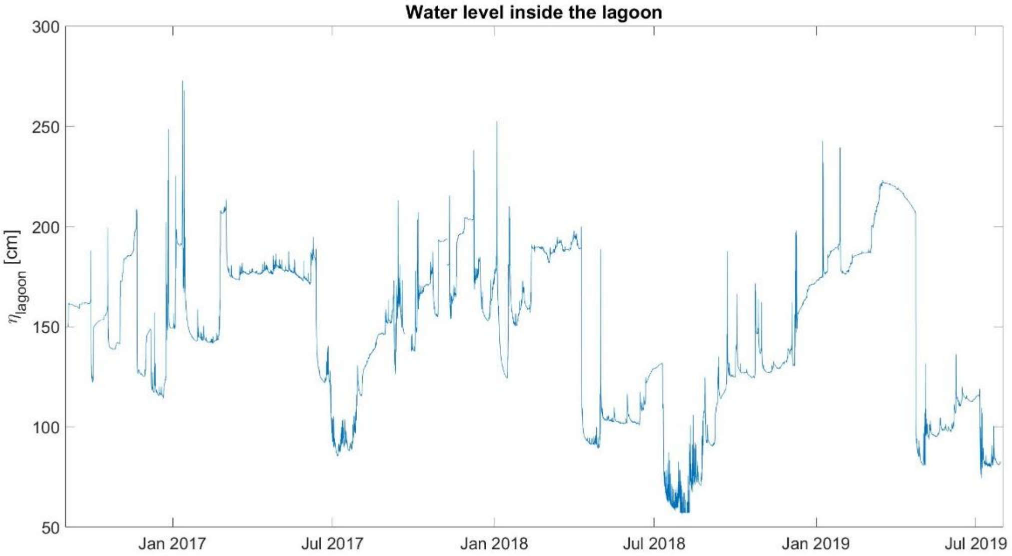


Figure 3-7: Surface elevation inside the lagoon. Daily influence of the tide is visible during summer periods. Water level increases between autumn and spring. Surface elevation peaks are clearly present. Rapid decreases in water level is the result of dredging.

3.3.4 Total surface elevation level at the HD

The surface elevation of the lagoon is affected by the estimated total water level at the shore. As already mentioned in Section 2.3.2, the total water level consists of the measured tide, the surge and the runup. With the use of equation (2-4) for the runup:

$$\text{Total water level}=\eta_{total}=\text{Tide}+\text{Surge}+R_{2\%}$$

The tide and the surge are available from the dataset (table 3-2), as is the significant wave height for the runup. The foreshore slope is calculated by a fit from the surface elevation above water level from GIS data (Section 3.4.1) near the south opening, where the channel is present, and results in a slope of 0.055 which is used for the runup. The wavelength is calculated with the formula for the wavelength for deep water conditions:

$$L_0=(9.81*T_{m02}^2/(2\pi))$$

Where, T_{m02} is the wave period.

The wave period is needed to estimate the runup, but has a limited record length, only being available for the year 2019. To generate the missing data the following linear regression was established between the significant wave height and the wavelength:

$$L_0=H_{m0}*0.013502+5.5$$

R2 gives an indication on the goodness of fit of the linear regression. The closer to 1, the better the data can be represented by a linear behaviour. The data is not representative of a linear behaviour the closer to 0. In this case the R2 coefficient resulted in 0.719 which suggests that it is a relatively good fit. The plot and correlation can be found in Appendix A.

The water level at the shore fluctuates between -0.75 m and 1.75 m, with peaks up to 4 m (Figure 3-8). Not all the data was present to calculate the total water level for the whole time period, which can be seen in the figure by the gaps. These gaps are not considered further in this research. The influence of the total water level on the surface elevation in the lagoon will be outlined in 4.3.1.

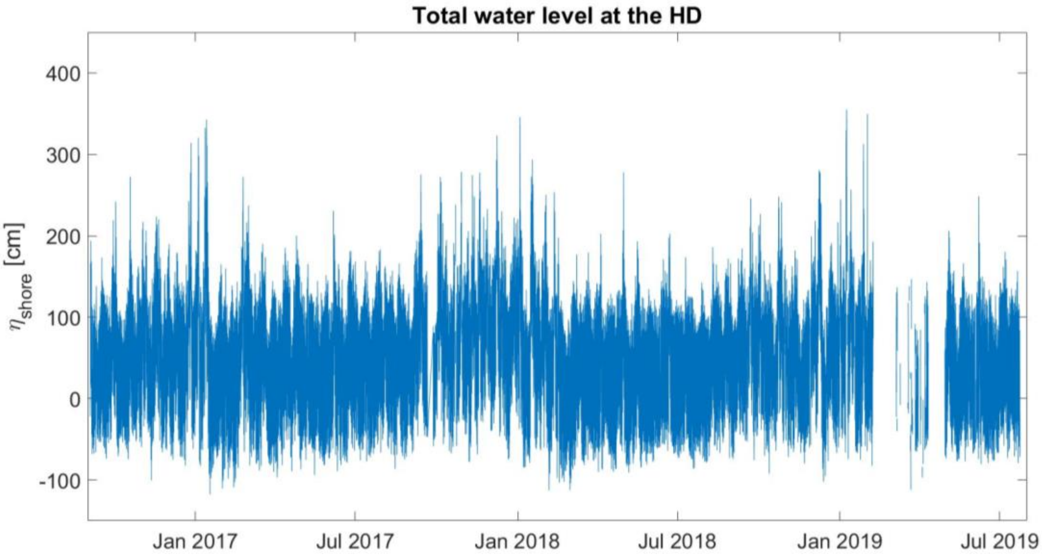


Figure 3-8: Total water level at the shore of the HD. Including tide, surge and runup.

3.4 Available data

In addition to the hydrodynamics data, topographic data and satellite imagery are available.

3.4.1 Geographical measurements

Rijkswaterstaat and *Ecoshape* have measured the topographic development of the HD and its lagoon since it was constructed. The monitoring is done by means of lidar measurements, and the data can be read using a Geographic Information System, hereafter referred to as GIS (QGIS). The data that is collected over the years is used in this study to be able to see the development of the lagoon and the channel at the HD.

Geographical data is available for 2015, 2016, 2017 and 2018 (table 3-3) and is collected in Digital Terrain Model (DTM) format. A DTM file represents the bare-earth reference (GISGeography, 2019), and does not consider man-made features, vegetation and water levels. The files are used to analyse the movement of the lagoon, its channel and the sediment volume changes in the study area. Spatial depictions of the data and cross sections are used to support this analysis.

Although the data does not represent specific events, such as open or closure of the lagoon, it can give insight into the development of the lagoon and channel, and to their respective variations throughout the year. For this study the software GIS is used to analyse the available data.

Table 3-3: Geographical data overview (RWS & Ecoshape, 2018).

Date	File type
24-05-2015	DTM
01-09-2016	DTM
05-12-2016	DTM
19-04-2017	DTM
11-08-2017	DTM
06-12-2017	DTM
19-03-2018	DTM

3.4.2 Satellite imagery

Satellite images provide a better insight on how the system develops over time. In this study different satellite products are used to capture the closure of the channel: Google Earth (spatial resolution 0.15-15 m), Sentinel-hub EO-Browser (spatial resolution 10-60 m), and Satellietdataportaal.nl V1 (spatial resolution 0.5-10 m). In the period between 4-9-2016 and 31-9-2019 154 satellite imagery were analysed to examine the changes in the system. For these 154 images the lagoon was visible on the satellite images, whereas other images are not considered due to clouds that hinder the view. While the channel was indicated as closed for 55 images, 99 images indicate an open channel (Figure 3-9, Figure 3-10, Figure 3-11).

As there are no daily satellite images available, the exact time of closure of the channel cannot be concluded. The images only indicate if the channel is open or closed for that specific date.

Figure 3-9: Satellite imagery from Google Earth. Left image shows an open channel, right shows a closed channel.

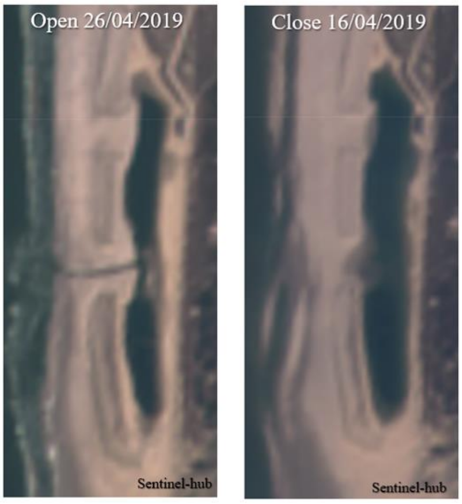


Figure 3-10: Satellite imagery from Sentinel-hub. Left image shows an open channel, right image shows a closed channel.

Figure 3-11: Satellite imagery from Sattelietdataportaal.nl. Left image shows an open channel, right image shows a closed channel.

The reader should note that it is sometimes difficult to visually determine an open or closed channel, as wet sand may appear as a connected channel. It is therefore possible that the satellite imagery suggests an open channel whereas the channel is closed.

3.5 Dredging of the channel to date

The maintenance strategy of the ZSNH for the channel is to dredge the channel before the start of the summer season, for support of the recreation season, at the beginning of April. In addition, dredging takes place when the water quality is below a safe threshold (table 3-4), which is monitored every two weeks during recreational season. The channel will be dredged until an elevation of 0.0 m NAP, to ensure daily refreshment of the lagoon. The dredged material will be deposited at the front dunes adjacent to the channel.

The ZSNH expects that the system will be unstable and that dredging of the channel will be needed two to three times a year.

Table 3-4: Channel dredging moments reasons, (ZSNH Van Oord Boskalis, 2016), (ZSNH Van Oord Boskalis, 2017),(ZSNH Van Oord Boskalis, 2018)

Date	Reason:
7-4-2016	Before summer season, to support recreation season
12&13-6-2017	Before summer season. Channel open whole winter, therefore dredging was later in year.
28&29-6-2017	Diminished water quality
9-4-2018	Before summer season, to support recreation season
10&11-7-2018	Unclear
30-7-2018	Diminished water quality
24-4-2019	Before summer season, to support recreation season
5-7-2019	Unclear

3.6 Dynamic Hypothesis

The description of the study area in combination with the literature review allows the formulation of a dynamic hypothesis. A dynamic hypothesis is a construction of a system story that reviews if the aspects that are found could be confirmed. The design and literature review suggest that it is not realistic to create a stable system, as is confirmed by the Bruun ratio. The lagoon is situated in a mixed wave-dominant environment on a low mesotidal range. The energetic conditions are therefore important for the closure of the channel, so the effect of storm events on the closure of the lagoon must be considered, which will be done by a data analysis.

4

Results data analysis

An analysis is performed to study the development of the surface area of the lagoon and its channel and is presented in the current chapter. The analysis is carried out by comparing the available geographical data at different points in time. Changes in the surface area are considered, because there is no information available for the bathymetry under the water surface. The dynamic hypothesis suggests that energetic conditions are important for closure of the channel and are therefore studied.

4.1 Development of the lagoon surface area

It is of interest to examine the behaviour of the lagoon over the years because it gives insight in the stability of the lagoon. Data on the surface area of the lagoon is gathered using geographical measurements. No conclusions could be drawn for the changes in volume of the lagoon over the years because the geographical measurements do not measure water areas. However, the geographical measurements can be used to analyse the surface area surrounding the lagoon.

Sediment fluctuations over time, between the measured days, and above the maximum water level in the lagoon are analysed. These are sediment changes over time between the measured days. An analysis is made above the maximum water level in the lagoon because it eliminates areas where no data is available, so where water is present. The maximum water level was measured at 2.03 m NAP. Comparing the sediment change with respect to the first measurement it shows how the surface area around the lagoon develops in time. Figure 4-1 presents the change, in meters, in sediment between 24/05/2015 and 18/03/2018. Appendix B outlines the sediment changes between 24/05/2015 and the data mentioned in table 3-3.

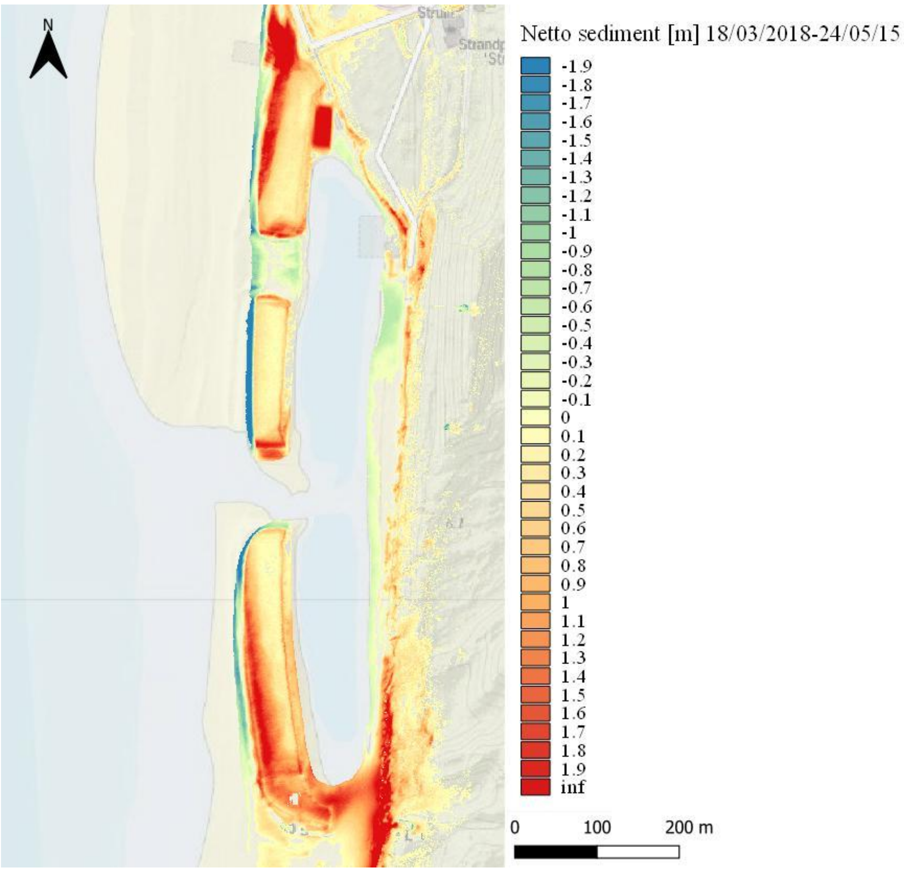


Figure 4-1: Sediment change lagoon area above 2 m NAP, between 24/05/2015-18/03/2018. Blue corresponds to erosion, red corresponds to accreting, yellow shows no changes.

The following can be seen from Figure 4-1:

- A light erosion is visible between 0.1-0.5 m on the east-side of the lagoon, with exception of the south where accretion of more than 2 m occurs.
- The overall south region shows accretion of more than 2 m.
- Erosion of more than 2 m occurs on the beach side of the front dunes, whereas accretion between 0.1 m up to more than 2 m occurs on the top of these dunes.
- The northern opening shows an overall erosion up to 0.5 m on both the west and the east side, whereas accretion of more than 2 m occurs at the adjacent dunes.
- The southern opening shows that the adjacent southern dune erodes, and the northern dune accretes and grows southwards. This last part can be linked to the dredged material that is deposited at the adjacent dunes (Section 3.5).

Overall no large changes in the surface area of the lagoon area measured, therefore it can be concluded that the surface area of the lagoon remains constant above 2.03 m NAP. A more detailed view of the development of the lagoon with the use of cross-sections for every 50 m can be found in Appendix C.

4.2 Development of the channel surface area

To study the development of the channel, the cross-section that goes from the adjacent dune at the north of the channel area to the dune at the south of the channel area is examined. The exact location of the cross-section and an overview of all the cross-sections for the available data can be found in Appendix D.

Figure 4-2 shows the cross-sections with no dredging between the topographic surveys. Therefore, it shows how the channel area develop over time. Two time ranges are shown 01/09/2016-05/12/2016 (yellow) and 11/08/2017-06/12/2017 (green), where the start of the time range is marked as a dashed line and the end of the time range is marked as a solid line.

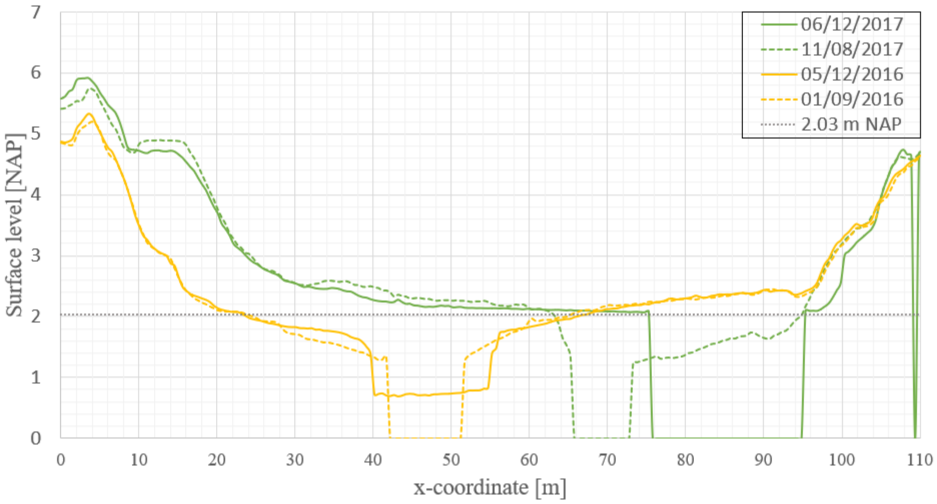


Figure 4-2: Cross-section of the channel. The left boundary is the northern dune, the right boundary is the south dune. Yellow corresponds to 2016, green to 2017. The horizontal dashed line is the maximum water level that was measured with the geographical data. Areas with water are indicated as 0,0 m NAP, resulting in straight channel bed.

Figure 4-2 shows that the surface next to the channel remains relatively constant for the time ranges, however, there are significant changes in the channel. Both channels become wider, and where the channel accretes in 2016, the channel changes location in 2017. For 2017 this location change is confirmed by the satellite imagery. The images that show the development of the channel to the south (Figure 4-4), whereas for 2016 satellite imagery does not give a better understanding of the changes (Figure 4-3). The development of the channel for both years could have multiple reasons, such as a storm events, drainage of the lagoon which causes scouring of the channel, or closure or opening of the channel by an event.

Figure 4-3: Development channel 09/2016-12/2016. The channel change to the south.

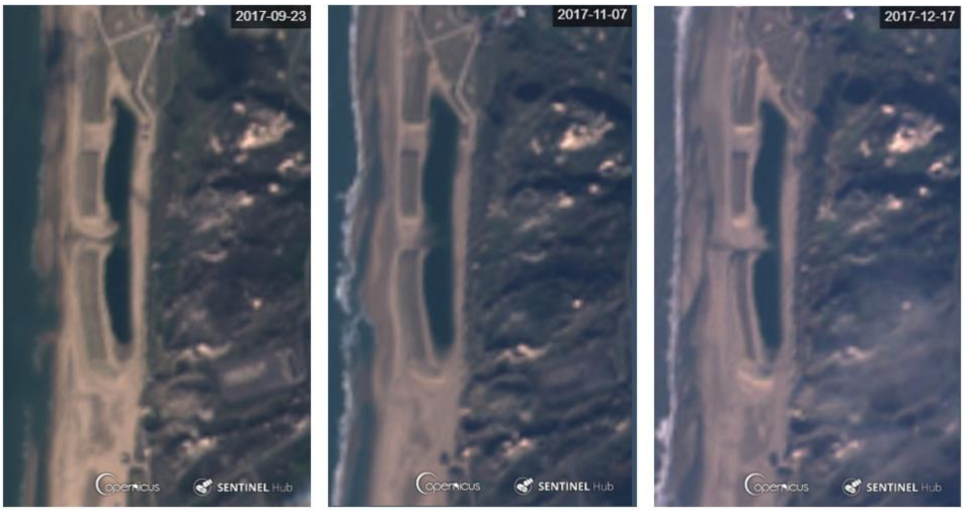


Figure 4-4: Development channel between 09/2017-12/2017. The channel change to the south.

The surface area for the channel remains constant between the measurements for one year. The channel becomes wider in time, where some channel stages silt up and others change location. More insight into the reasons behind the channel dynamics will come after Section 4.3.2.

4.3 Analysis of the lagoon’s closure behaviour through a study on the water level in the lagoon

The behaviour of the system was examined in detail by comparing and analysing the water level at different stages of the lagoon with the hydrodynamic conditions and satellite imagery.

4.3.1 Stages of water level in lagoon

The studied literature results in in four stages that are set up for the development of the water level in the lagoon: the dredging stage, open channel stage, episodic events and closed stage. These different stages for the water level in the lagoon are determined visually (Figure 4-5).

1. A dredging stage results in a rapidly decrease from a level above high tide at the open coast, to a value near or below high tide level. When the channel is dredged water exchange with the open coast may occur, however this is not always the case (top plot).
2. When the channel is open water exchange with the open coast is possible. The effect of the tide can be observed clearly in the water level of the lagoon, as described in Section 2.4.3 (2nd plot).
3. Episodic events indicate fluctuations in the water level for which the cause cannot be stated beforehand (3rd plot). It depends among others on the type of system, hydrodynamic conditions and on the shape of the channel. For close stages it can be referred to as a non-perched system (Section 2.2.4).
4. Lastly a closes stage results in a closed channel. In the closed stage, the water level can only increase when the water level at the open coast overflows the berm. This leads to a stepwise increasement of the water level (bottom plot), also referred to as a perched system (Section 2.2.4).

These stages are used to examine the water level in the lagoon.

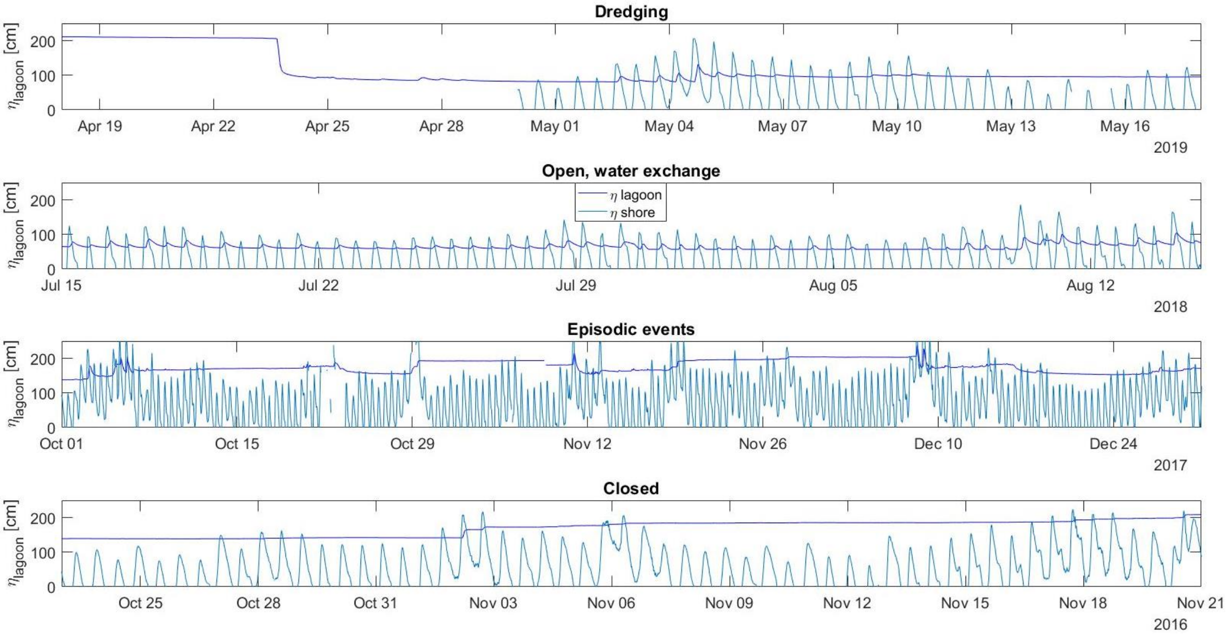


Figure 4-5: Stages of water level in the lagoon in combination with the water level at the shore of the HD. Top plot: dredging moment. 2nd plot: open channel water exchange. 3rd plot: episodic events, channel can close or open. lowest plot: closed channel.

4.3.2 Overview water level with all available data

A detailed insight of closure of the channel is achieved by studying satellite data, dredging moments, storm conditions, and the stages described previously.

Figure 4-6 shows the water level in the lagoon for different stages. Closure of the channel is indicated in red lines, and an open channel in blue lines. Green lines shown the dredging stage (when dredging works take place) and yellow lines mark the occurrence of an episodic event at the lagoon. Furthermore, satellite images are indicated at the x-axis, with green circles for a visually indicated open channel, and red crosses for a visually indicated closed channel. Dredging events are black vertical dashed-dotted lines and the grey dashed lines at the bottom of the figure indicates storm events with a Hs>300 cm.

This study uses storm events characterized with a Hs> 300 cm, corresponding with the episodic events in the lagoon. Although a Hs>400 cm is reasonable for storm events on the North Sea, it does not correspond to the episodic events inside the lagoon. This is because the lagoon is shallow and has a small water body, leading to lower storm events that have an effect on the water level inside the lagoon. Using the rule of thumb that a storm event is two times the average wave height (Holthuijsen, 2011), Hs=1.2 m (Section 3.1), leads to a wave height of 240 cm. This results in too many storm events which does not correspond to the episodic events seen in the water level inside the lagoon. A higher Hs>350 cm misses storm events that corresponds to the episodic events inside the lagoon. Therefore, storm events with a Hs>300cm are selected in this study. An overview of the other significant wave heights mentioned above can be found in Appendix E.

The channel is closed for most of the time (68% of the time on average) and is only open between the end of April and the beginning of September. This leads to an open channel for 10-17% of the time, with an average of 13% for the available time series.

Rapid changes in the water level are not only due to dredging but also due to storm events. A storm event can lead to a decrease of the water level, as seen in 2016, or an increase of the water level, like at the end of 2018. The storm events lead to silting or scouring of the channel, resulting in an increase or decrease of the water level respectively. These changes due to storm events are linked to episodic events in the water level timeseries. When the channel is open, storm events are not frequent. This suggests that storm events likely result in closure of the channel.

Although dredging should lead to an open channel, this was not the case in April 2018. The reason is unclear, but the effect of storm events can be excluded. A simple reason could be that the channel was not dredged deep enough. Furthermore, dredging will lead to a decrease of water level of 20 cm up to 120 cm. The small decrease in water level are linked to dredging due to water quality, the larger changes due to opening of the channel.

Most of the satellite images shows the same state as the results of the water level analysis. All the satellite images that were indicated as a closed channel showed a closed stage in the water level. For the images where the images suggest the channel to be open, the stage in the water level indicate an episodic event or a closed stage. A close stage indicated by the water level can never result in an open state by the satellite images. However, for episodic events the channel varies between open and closed stages so satellite images could vary in open or closed stages for the channel. It is, therefore, possible that a satellite image shows an open channel, which is the result of overwashing by an offshore high-water level, whereas the system is closed, so no water exchange occurs, and the water level in the lagoon will increase in time. This phenomenon is also referred to as non-perched (Section 2.2.4).

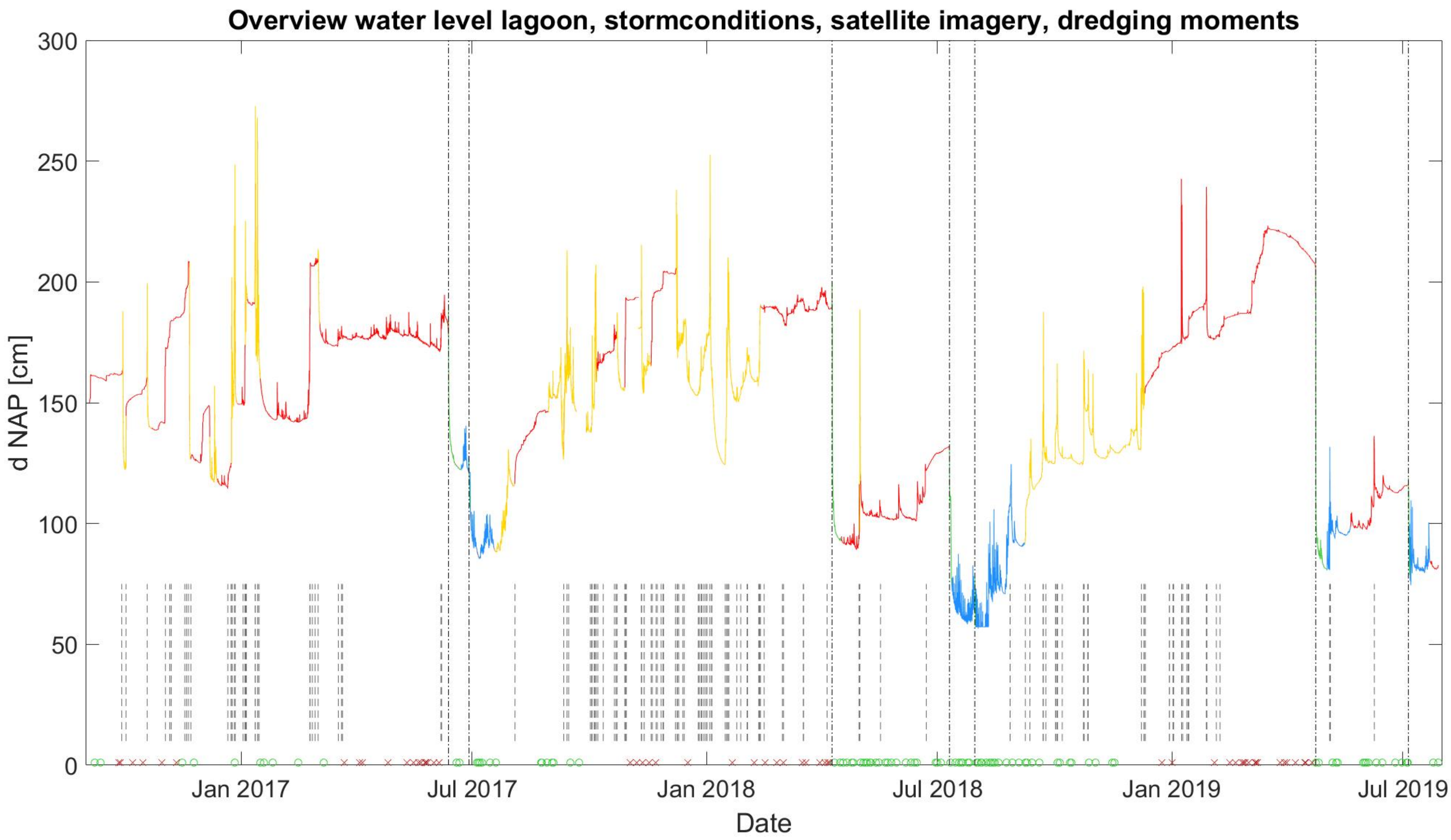


Figure 4-6: Overview of the water level in the lagoon including storm events, satellite imagery and dredging moments. Satellite images are indicated at the x-axis, with green circles for an open channel and red crosses for a closed channel. The grey dashed lines in the bottom of the figure indicates storm events with a Hs>300 cm. The black vertical dashed-dotted lines are dredging events. A dredged moment in the water level is indicated with green. Blue lines show an open channel where water exchange is possible. Episodic events are marked as yellow and a closed channel is indicated with red

Lastly, the cross-sections of the channel (Figure 4-2) are compared to Figure 4-6, to see what led to the change in and silting up of the channel. For 2016 the channel was mostly closed, this suggests that the channel is perched, and accretion occurs in the channel. In 2018 the time between measurements showed more episodic events than closed stages, which result in scouring and silting of the channel. This can be referred to as a non-perched system. The position of the channel can therefore be changed, because water chooses the path of least resistance.

4.3.3 Relation between storm events and episodic event in the water level

It is suggested that the episodic events correspond to storm events and is therefore further elaborated. Table 4-1 shows the storms for each significant wave height for each year. Not all the significant wave heights are counted as individual storms. It is considered that the influence of a storm can be seen in the significant wave height for two days, and therefore lead to less storms than showed in Figure 4-6 and Appendix E, that shows all the values above a chosen significant wave height as a storm event.

These storm events are compared to the change in water level inside the lagoon, where a water level peak of 10 cm or more is chosen. This led to 133 peaks in the time series. Which is more that the number of storms that are present for the lowest considered significant wave height. This is due to the influence of the tide and dredging activities and are therefore filtered out, resulting to 65 peaks in the water level due to storm events (Table 4-2).

Table 4-1: Amount of storm events for each year and for each chosen significant wave height. A storm event is considered for two days, in which the significant wave height occurs at least ones.

	Significant wave height			
Year	240	300	350	400
2016	15	10	7	6
2017	46	31	25	14
2018	50	27	17	10
2019	13	8	7	5
Total	124	76	56	35

Table 4-2:Amount peaks in the water level of the lagoon of 10 cm or more. The first row shows the total amount of peaks, row two displays the peaks due to dredging, row three due to the tide, row four shows the peaks that have an unknown reason and row five shows peaks within a storm event.

	2016	2017	2018	2019	Total
Peak >10 cm in the water level of the lagoon	16	46	57	14	133
Peaks due to dredging	0	2	4	2	8
Peaks due to the tide	2	8	29	7	46
Unknown reason for a peak	3	7	2	2	14
Peaks due to storms	11	29	22	3	65

It shows that changes in the water level, disregarding the tide and dredging activities, are indeed the result of storm events. The choice for a storm event with a Hs>300 is a good correspondence to the influence on the water level in the lagoon. A Hs>350 cm will be to conservative, whereas a Hs>240 cm will result too many storm events.

4.4 Summary data analysis

The development of the lagoon surface was analysed above the maximum water level in the lagoon using geographical measurements. The analysis showed that accretion occurs on the south of the lagoon and at the top and south of the front dunes. At the beach side of the front dunes erosion takes place. The front dunes will therefore become smaller and higher over time. Accretion of the front dunes at the southern opening is the result of deposition of the dredged material. The east side of the lagoon eroded mildly with a maximum of 0.5 m in three years. The northern opening also eroded mildly in the observed three years, with a maximum of 0.5 m of the bed. It shows that the surface area of the lagoon remains constant above the maximum water level.

The development the channel surface area, with the use of a cross-section showed how the channel developed naturally without the influence of dredging. The surface area remained constant, whereas the channel moved in time. For both channel stages the channel became wider, where one channel silted up and the other changed its location. With the use of the water level in the lagoon and satellite images these changes are linked to episodic events which transport sediment in or out the channel, leading to accretion in the channel.

Four stages of the water level in the lagoon were identified. A closed stage, where the water level in the lagoon increase stepwise due to the water level at the open coast that overflows the berm, is referred to as a perched system. The channel is open when water exchange is possible with open coast, the tide can be observed in the water level in the lagoon, resulting in two daily fluctuations in water level in the lagoon. A rapid decrease of water level can be linked to dredging moments, which is confirmed by using the documented dredging moments. Episodic events are the last stage, for which the reason cannot be stated beforehand.

These stages were applied to the water level measured in the lagoon and compared with dredging events, satellite images and storm event with a Hs>300 cm that corresponds with the episodic events in the lagoon. the data analysis showed that the channel is closed for 68% of the time, and open for 13% of the time, which only occur between the end of April and the beginning of September. The rapid changes in the water level occur due to dredging and episodic events. These episodic events are linked to storm events, that occur two to three times in summer periods and are more dominant in winter periods.

The data analysis showed that dredging does not always lead to an open channel, which could have a simple reason that the channel was not dredged deep enough. The large decrease in water level after dredging can be linked to opening of the channel, whereas the small decrease in water level is linked to dredging due to water quality.

The addition of the satellite imagery showed that a closed stage in the water level was confirmed by a closed channel in the satellite imagery. However, not all the satellite imagery that showed an open channel was confirmed by an open stage in the water level. This is because the catchment of the channel is so small that the satellite imagery indicates this as an open channel, whereas the data analysis of water level in the lagoon indicates a closed stage.

The overall conclusion for the system is that the lagoon does not move spatial in time. The channel becomes wider in time and silts up or changes location as result of episodic events. These episodic events will eventually lead to closure. Most of these episodic events are due to storm events, which suggest that closure of the channel occurs due to storm events. The channel will follow the stages dredged, open, non-perched, perched until dredging will take place again.

5

Discussion

The discussion elaborates on the outcome of the results of the data analysis, the implementation of the theory and the implications to management and design for the lagoon that are obtained for this study.

5.1 Uncertainty in the analysis

No large changes occur for the surface area of the lagoon above 2.03 m NAP. This suggests that the lagoon does not change spatially in time. Based on the available data, it cannot be concluded whether the bed of the lagoon changes in time and if so, how it would influence the volume of the lagoon basin.

Satellite imagery provides a general view on the state of the channel: whether it is open or closed. The assessment of the satellite imagery was done qualitatively. Thus, there is some uncertainty associated to the qualitatively assessment of the different stages of the channel. An example of such uncertainty may be that a satellite image can show an open channel, whereas in reality the catchment of the channel is so small that the results of the data analysis indicate it as closed when observing the water level inside the lagoon.

Four stages were visually obtained for the water level inside the lagoon and were based on the theory of a non-perched system, a perched system and the tidal behaviour in a lagoon. As these stages were indicated visually for the water level inside the lagoon, hence uncertainty arises.

The results of the analysis are sensitive to the choice of wave height to characterize a storm event in the North Sea. A storm event at the North Sea is assumed to produce wave heights higher than 400 cm. Nevertheless, this did not result into episodic events for the water level inside the lagoon because of the small catchment of the lagoon. Therefore, the waves above 300 cm were assumed to be representative for storm events in this thesis. It remains uncertain whether a different wave height would provide a more accurate representation of the storm events that directly affect the closure of the lagoon. Hence, the sensitivity of Hs could be explored further in later assessments if required.

5.2 Comparison of existing lagoon stability theories

Different empirical analyses were performed for the stability of inlets. The theories of Escoffier (1940) and O’Brien (1931, 1969) do not apply for the case of the studied lagoon as they do not consider the locational stability, but only consider the cross-sectional area of the inlet. A larger depth is needed for the channel and for the lagoon to apply these methods. Bruun’s theory (1978) can be applied for the lagoon, because it reflect on the relationship between the littoral drift and the tidal prims, instead of the cross-sectional area of the inlet.

The theory for Small Tidal Inlets (Duong et al., 2016) distinguish three types STI. The lagoon at the HD can be characterized as an intermittently open, locationally stable inlet, which is referred to as a type 3 STI. For these types, closure of the inlet occurs due to: spit forming (mechanism 1) by the longshore current, or due to onshore bar migration (mechanism 2) by wave conditions. The results support the relationship for wave conditions, where storm events lead to closure of the inlet, resulting in a type 3 mechanism 2 system for the lagoon.

Analysis of the development of several estuaries along the Dutch coast has shown that these systems are not stable due to the effect of storm events that generally lead to closure. Human interventions are required to keep these inlets open. The results for this study also support the fact that ongoing maintenance is needed to preserve the channel and the lagoon.

5.3 Implications for management and design of artificial lagoons (in nourishments)

The data analysis showed that the lagoon closes rapidly after channel opening events. Generally, closure occurs after 1 to 2 storm events, with exception of 2018 that has over 15 storm events before closure occur. This suggests that the lagoon will never stay open without human interventions. Consequently, active management for the channel is needed to remain an open lagoon. The surface area of the lagoon only slightly changed in the investigated years. Large changes in the frequency and speed of closure of the lagoon's inlet due to infilling of sediment are therefore not expected. Two main maintenance strategies are possible for the near future and these are discussed below.

1. If the preference lies in an open lagoon all year round, it will imply that dredging frequency needs to increase to weekly dredging or once every two weeks. The results of the analysis indicate dredging needs to occur more often in winter season due to the increase in the occurrence of storm events. Furthermore, good weather in the summer season also requires dredging to increase the water quality. In short, higher dredging frequencies are needed to maintain the lagoon open all year. This will lead in an increase in dredging costs.
2. If the preference lies in low dredging costs, this will automatically result in a closed system for a certain period of the year. Because the lagoon is designed for recreational purposes the system can be closed in winter season and dredging is only needed in summer season. This is equal to the currently considered dredging strategy.

Several options should be considered to reduce the frequency of closure, such as:

- Optimization of the timing of dredging works.
  It is not clear why the ZSNH dredge at a certain date, when the purpose of dredging is to open the channel. The moment when dredging woks are performed is of high interest because the water level offshore will influence the possibility of emptying the basin. It is recommended to dredge after high tide, but before low tide, so the basin has time to empty. This maximize scouring of the channel before the influence of the high tide. It is also recommended to dredge after a storm event. The water level inside the lagoon could be increased prior to the dredging event, which leads to a deeper scouring of the channel.
- Increase the channel cross-sectional area.
  By dredging the channel deeper, the cross-sectional channel area will increase, which postpones the closure of the channel. An equilibrium should be found between the increase of dredging cost per dredging event and the decrease in the required frequency of dredging works.
- Volume increase of the basin.
  Increasing the volume of the basin could be done by deepening the basin. Especially the shallow banks of the lagoon could give a big change in the volume. When the depth of these sections increases the intertidal surface area, the tidal prims increases which is beneficial for the stability of the system. It will also benefit the water quality and at the same time enable a decrease in the dredging frequency.
- Source of inflow in the lagoon.
  A source of inflow will increase the volume of the basin. This would lead to an increase of the refreshment of the lagoon basin. The consequences of such implementation are that the system will remain open for a longer period or can scour the channel when the volume in the lagoon basin becomes high. Several options are possible to obtain this. An extra inlet will increase the refreshment of the basin, whereas a water inflow, for example by a pipe, will increase the volume in the basin. Measuring the amount of water that is pumped in the basin and the moment of breaching will give a better insight in the volume and water level that is needed for natural breaching. If natural breaching gives the same results for the channel cross-sectional area as for dredging it is of interest which measurement will be most (cost) efficient.

6

Conclusions & Recommendations

This chapter presents the conclusions and recommendations based on the results of the data analysis and the discussion in the previous chapter.

The objective of this research was to explore the behaviour and longevity of the artificial lagoon at the Hondsbossche Dunes, specifically the frequency and moments of its closure. The following research questions were posed:

1. What was the behaviour of the lagoon in the recent years?
2. What are the hydrodynamic conditions that influence closure of the lagoon, and how often and when do they occur?
3. What implications does this knowledge hold for management in the near future?

6.1 Conclusions

6.1.1 What was the behaviour of the lagoon in the recent years?

The lagoon at the Hondsbosse Dunes is situated in a mixed wave-dominant environment on a low mesotidal range. The inlet is intermittently closed, which indicates that the design of the lagoon is unstable. The results of the data analysed in this thesis confirm this unstable character. Following literature values, the state of the lagoon could only become stable either if the tidal prism increases by a factor 10, or the littoral drift decreases by a factor 10. Both suggestions are not realistic in the landscape of the Hondsbosse Dunes and thus it is concluded that the system will remain unstable and maintenance is an ongoing process.

The lagoon surface area is examined above the maximum water level in the lagoon (2.03 m NAP). Above this isobath the lagoon surface area remains the same over time, whereas the (front) dunes change over time. It suggests that the lagoon surface area does not move spatially in time, and closure of the system occurs due to closure of the channel. This is supported by the cross-sections of the channel area and the satellite imagery; the analysis confirms that the channel is highly dynamic. The results of the analysis on the water level signal inside the lagoon suggest that the system does not fluctuate with the North Sea water level for almost 70% of the time.

6.1.2 What are the hydrodynamic conditions that influence closure of the lagoon, and how often and when do they occur?

Several hydrodynamic conditions were found that influence the closure of the lagoon: the significant wave height of storm events and the total water level at the shore, which includes the tide, the surge and the runup.

Four stages of the water level inside the lagoon were visually analysed:

1. Closed stage, resulting in a closed channel. The water level in the lagoon increases stepwise due to overflowing of the water level from the open coast, referred to as a perched system.
2. Open stage. The channel is open and water exchange is possible with the open coast. Fluctuations in the water level are visible and follow the tide at the open coast.

3. Dredging stage. The water level decreases rapidly from a level above high tide at the open coast, to a value near or below high tide level. Afterwards water exchange with the open coast may occur, but this is not always the case.
4. Episodic event. The water level fluctuates, of which the cause cannot be stated beforehand. It depends among others on the type of system, hydrodynamic conditions and/or on the shape of the channel. The system is called non-perched when a high-water level overwashes the berm of the channel. It seems that the system is open, but water exchange does not occur and the water level in the lagoon increases.

An overview of these stages in the water level inside the lagoon, combined with dredging moments, satellite data and storm events gave an indication on how the system behaves. The lagoon is most often closed between October and April and opens in April when the channel is dredged.

An open system starts after dredging works in spring are performed. It this season, the results of the data analysis show that the water level inside the lagoon follows the tide offshore. This fact implies that the inlet of the lagoon is open. On the contrary, closure of the lagoon occurs and the water level inside the lagoon cannot follow the tide offshore anymore. The analysed data indicate that the system is open for 10-17% of the time.

The system is highly influenced by storm events and most storms lead to the closure of the channel. Although a storm event on the North Sea officially requires a significant wave height larger than 400 cm, the results demonstrate that high energy wave conditions with a significant wave height of 300 cm can provoke the closure of the lagoon. These storm events are prevalent in winter periods, whereas in summer these storms occur two to three times a year.

6.1.3 What implications does this knowledge hold for management in the near future?

The results of the data analysis performed in this thesis suggest that the lagoon will never stay open or open without human interventions. Consequently, active management is needed to preserve the lagoon. Two main dredging strategies were considered:

1. The dredging frequency needs to increase to achieve a lagoon that is open all year round. The results of the analysis imply that storm events are the main reason for closure, and because the intensity of storm events increases in winter season, the dredging frequency needs to increase in this period of the year as well. This strategy leads to an increase in dredging costs.
2. When the preference lies in low dredging costs, it is possible the lagoon will be closed for a period of the year. Since the lagoon is designed for recreational purposes, the lagoon could be open in summer season and closed during winter season. This requires the same dredging strategy as is currently considered by ZSNH.

Several other options were considered that could reduce the frequency of closure, such as a source of inflow in the lagoon, an increase of the channel cross-sectional area, the moment when dredging takes place or the increase of volume in the basin.

6.2 Recommendations for future research

For future research the following is recommended:

- Optimize the dimension of the channel for dredging cost optimization.
  Certain dimensions of the channel might be able to delay the closure of the channel. An option to study this influence would be to perform field experiments. In these experiments, the channel could be dredged for different depths and/or widths to obtain more information on the overall system which can lead to an optimized design of the channel. However, these experiments might be time-consuming. Thus, an alternative proposed here is to build a physical or numerical model that caters different dimensions for the channel. It is strongly suggested to set up a model that considers the local hydrodynamic conditions and considers the variations in the flow throughout the channel. Although a model that includes sediment transport and morphological changes is more realistic, it is theoretically and computationally challenging. Therefore, it would only be recommended after completion of a numerical model for the hydrodynamics.

- Optimize the dimensions of the lagoon's basin for dredging cost optimization.
  It would be interesting to investigate whether certain dimensions of the lagoon's basin could lead to a decrease in the frequency of dredging works. An increase in the lagoon's basin volume could increase the tidal prism and therefore increase the stability of the system. It could also increase the water quality. Consequently, it could decrease the dredging frequency and thus reduces the dredging cost. A consideration should be made between field experiments, a physical model or a numerical model.
- Study natural breaching as an alternative to dredging activities in the lagoon to keep the channel open.
  Natural breaching of the channel will decrease dredging costs. A field measurement can be done where water is pumped into the basin until breaching occurs. Measuring the volume of the basin and the dimensions of the channel before and after breaching will give a better insight in whether natural breaching is a good alternative for dredging and so reduce the dredging costs.
- Obtain information on the dredged sediment volume.
  It is recommended to request the sediment volumes and the dimensions of the dredged channel from the ZSNH for each dredging moment. These volumes are deposited at the south opening, which can give a better view on the increase in the surface area due to the deposition of the dredged volumes. It will also give a better prospect on the dredging costs.
- Study and determine the runup in more detail to decrease uncertainties of the water levels at the shore.
  One of the uncertainties associated with the runup calculation in this study is the foreshore slope that is obtained from the geographical measurements and is averaged in time. The foreshore slope is dynamic in time, resulting in a more dynamic runup. A detailed calculation of the runup can result in a more accurate water level at the shore, that would describe more accurately the water level inside the lagoon.

Bibliography

Boothroyd, J. C. (1985). Tidal inlets and tidal basins. In *Davis, R. A. (ed.) Coastal sedimentary Environmennts.* (pp. 445–532). New York.

Bosboom, J., & Stive, M. (2015). *Coastal Dynamics I, lectures notes CIE4305*. Delft: VSSD.

Bruun, P. (1978). Stability of Tidal Inlets: Theory and Engineering, *23 (Develo*.

Cooper, J. A. . (2001). Geomorphological variability among microtidal estuaries from the wave-dominated South African coast. *Geomorphology*, *40*(1–2), 99–122. https://doi.org/10.1016/S0169-555X(01)00039-3

de Jongh, L. (2017). *Initial morphological evolution of a mega nourishment*.

de Vries, S., Radermacher, M., de Schipper, M. A., & Stive, M. J. F. (2015). Tidal dynamics in the Sand Motor lagoon. *E-Proceedings of the 36th IAHR World Congress*, 1–6.

Duong, T. M., Ranasinghe, R., Walstra, D., & Roelvink, D. (2016). Assessing climate change impacts on the stability of small tidal inlet systems: Why and how? *Earth-Science Reviews*. https://doi.org/10.1016/j.earscirev.2015.12.001

Durieux, M. (2003). De stabiliteit van de Slufter op Texel, 91.

Escoffier, F. F. (1940). The stability of tidal inlets. *Shore and Beach*, *8*(4), 114–115. Retrieved from https://apps.dtic.mil/dtic/tr/fulltext/u2/1001653.pdf

Eysink, W. D., Hoekstra, A., & Hoozemans, F. M. J. (1992). Nederlandse slufters: verkennende inventarisatie naar abiotische parameters : *TU Delft Repository Hydraulic Engineering Reports*, 92. Retrieved from http://repository.tudelft.nl/view/hydro/uuid%3Aca3d744a-8263-4fdd-9cf1-9153b0a78b53/

GISGeography. (2019). DEM, DSM & DTM Differences - A Look at Elevation Models in GIS - GIS Geography. Retrieved May 30, 2019, from https://gisgeography.com/dem-dsm-dtm-differences/

Google Earth. (n.d.). Retrieved July 31, 2019, from https://www.google.nl/intl/nl/earth/

Hinwood, J. B., & McLean, E. J. (2018). Tidal inlets and estuaries: Comparison of Bruun, Escoffier, O'Brien and attractors. *Coastal Engineering*, *133*, 92–105. https://doi.org/10.1016/j.coastaleng.2017.12.008

Holthuijsen, L. H. (2011). Waves in Oceanic and Coastal Waters. *Contemporary Physics*, *52*(1), 75–75. https://doi.org/10.1080/00107514.2010.529511

HWBP. (2016). Vragen rondom Implementatie Nieuwe Normering. Retrieved from www.hoogwaterbeschermingsprogramma.nl/Documenten+openbaar/default.aspx

Kjerfve, B., & Magill, K. . (1989). Geographic and hydrodynamic characteristics of shallow coastal lagoons. *Marine Geology*, *88*(3–4), 187–199. https://doi.org/10.1016/0025-3227(89)90097-2

KNMI. (2019). KNMI - Daggegevens van Noordzee stations. Retrieved May 30, 2019, from https://www.knmi.nl/nederland-nu/klimatologie/daggegevens_Noordzee

McLean, L. J., George, S., Ierodiaconou, D., Kirkwood, R. J., & Arnould, J. P. Y. (2018). Impact of rising sea levels on Australian fur seals. *PeerJ*, *6*, e5786. https://doi.org/10.7717/peerj.5786

Ministerie van Verkeer en Waterstaat. (1990). Kustverdediging na 1990.

O'Brien, M. P. (1931). Estuary tidal prisms related to entrance areas. *Civil Engineering*. Retrieved from https://ci.nii.ac.jp/naid/10016529954/

O’Brien, M. P. (1969). Equilibrium flow areas of inlets on sandy coasts. *J. Waterways and Harbors, Ww1, P43-52*. Retrieved from https://repository.tudelft.nl/islandora/object/uuid:3fbe479f-e8d2-4a99-aa2a-86de4bf917ea

QGIS. (n.d.). QGIS 3.6.1. Geographic Information System that read lidar measurements.

Ranasinghe, R., Pattiaratchi, C., & Masselink, G. (1999). A morphodynamic model to simulate the seasonal closure of tidal inlets. *Coastal Engineering*, *37*(1), 1–36. https://doi.org/10.1016/S0378-3839(99)00008-3

Roy, P. ., Williams, R. ., Jones, A. ., Yassini, I., Gibbs, P. ., Coates, B., … Nichol, S. (2001). Structure and Function of South-east Australian Estuaries. *Estuarine, Coastal and Shelf Science*, *53*(3), 351–384. https://doi.org/10.1006/ecss.2001.0796

RWS. (2019). Waterinfo: actuele, verwachte en historische meetgegevens over de rijkswateren. Retrieved from http://waterinfo.rws.nl/#!/nav/expert/

RWS, & Ecoshape. (2018). Lidar measurments of the Hondsbossche Dunes. Retrieved from Hoogheemraadschap Noorderkwartier.

Santbergen, L. L. P. A. (2004). 3rd European Conference on River Restoration RIVERRESTORATION 2004 The international ZWIN project : an example of European cooperation ? *North*, (May), 17–21.

Satellietdataportaal.nl V1. (n.d.). Retrieved July 31, 2019, from https://www.satellietdataportaal.nl/

Sentinel-hub EO-Browser. (n.d.). Retrieved July 31, 2019, from https://apps.sentinel-hub.com/eo-browser/

Slinger, J. H. (2016). Hydro-morphological modelling of small, wave-dominated estuaries. *Estuarine, Coastal and Shelf Science*, *198*, 583–596. https://doi.org/10.1016/j.ecss.2016.10.038

Slinger, J. H., Taljaard, S., & Largier, J. L. (2017). Modes of water renewal and flushing in a small intermittently closed estuary. *Estuarine, Coastal and Shelf Science*, *196*, 346–359. https://doi.org/10.1016/j.ecss.2017.07.002

Stockdon, H. F., Holman, R. A., Howd, P. A., & Sallenger, A. H. (2006). Empirical parameterization of setup, swash, and runup. *Coastal Engineering*, *53*(7), 573–588. https://doi.org/10.1016/J.COASTALENG.2005.12.005

Wijnberg, K. M. (2002). Environmental controls on decadal morphologic behaviour of the Holland coast. *Marine Geology*, *189*(3–4), 227–247. https://doi.org/10.1016/S0025-3227(02)00480-2

Wijnberg, K. M., & Terwindt, J. H. J. (1995). Extracting decadal morphological behaviour from high-resolution, long-term bathymetric surveys along the Holland coast using eigenfunction analysis. *Marine Geology*, *126*(1–4), 301–330. https://doi.org/10.1016/0025-3227(95)00084-C

ZSNH. (2019). Water level measurments inside the lagoon at the Hondsbossche dunes. Retrieved from collaborative alliance of Combinatie Van Oord/Boskalis.

ZSNH Combinatie Van Oord Boskalis. (2014). *Ontwerpnota template*.

ZSNH Van Oord Boskalis. (2016). *ZSNH-KF-O-2016-07.1 Getijdengeul Strandlagune Camperduin*.

ZSNH Van Oord Boskalis. (2017). *ZSNH-KF-O-2017-07 Getijdengeul Strandlagune Camperduin*.

ZSNH Van Oord Boskalis. (2018). *ZSNH-KF-O-2018-07 Getijdegeul strandlagune Camperduin*.

A

The significant wave height correlated to the wavelength

The figures show the correlation and the correlation coefficient, R2, between Hs and L0.

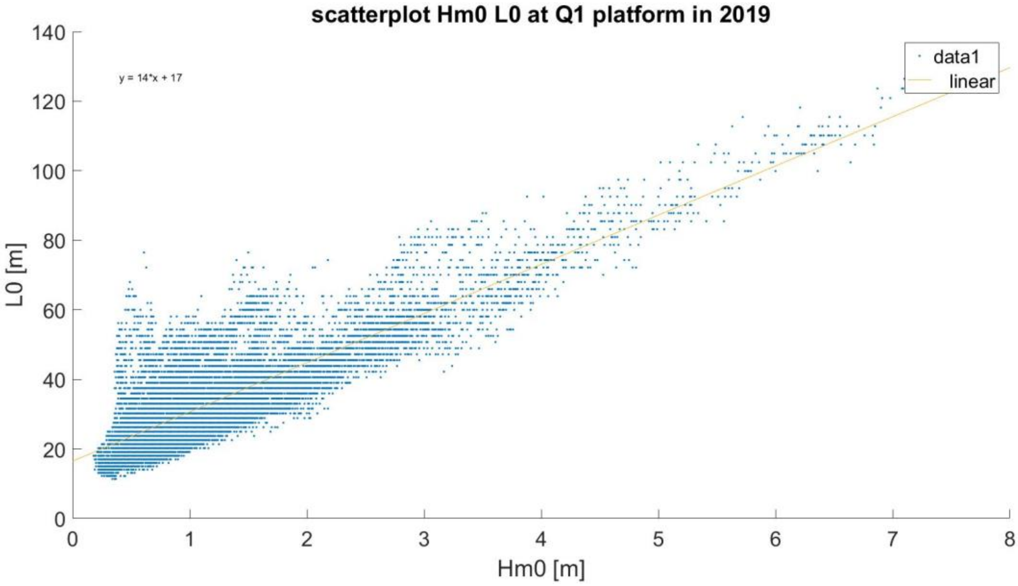
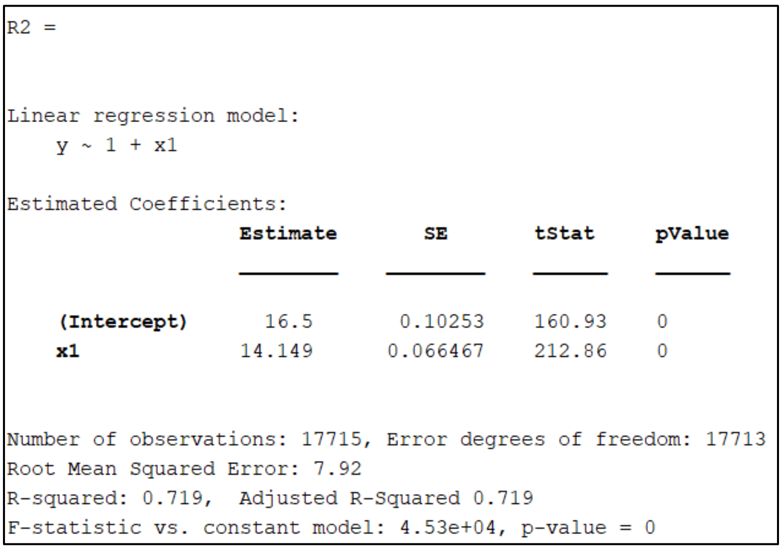


Figure 0-1: scatterplot Hm0, L0 at Q1 platform. Data is only available from 2019. The Linear regression is established at $L_0=H_{m0}*0.013502+5.5$



```
R2 =


Linear regression model:
    y ~ 1 + x1

Estimated Coefficients:
                   Estimate      SE       tStat     pValue
                   ________    ________   ______    ______


    (Intercept)      16.5       0.10253   160.93      0
    x1             14.149      0.066467   212.86      0


Number of observations: 17715, Error degrees of freedom: 17713
Root Mean Squared Error: 7.92
R-squared: 0.719,  Adjusted R-Squared 0.719
F-statistic vs. constant model: 4.53e+04, p-value = 0
```

Figure 0-2: R2 correlation coefficient, that lies between 0 and 1. The correlation coefficient between Hs and L0 is 0.719, suggesting a relatively good fit.

B

Sediment changes lagoon surface area

Sediment changes of the lagoon surface area above 2 m NAP, gathered using geographical measurements.

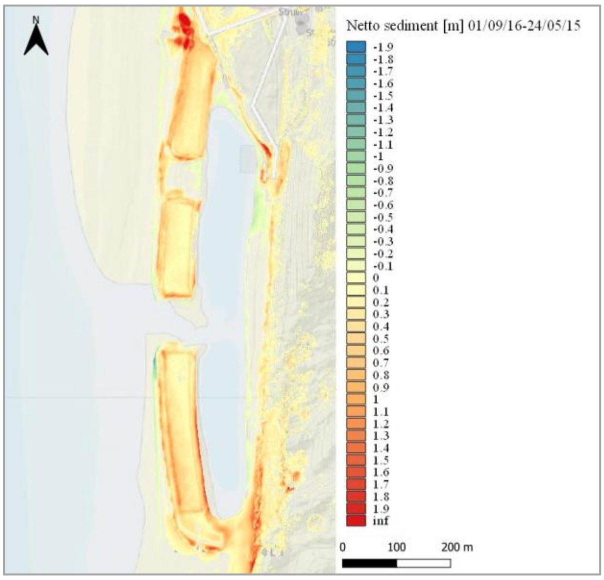


Figure 0-3: Sediment change lagoon area above 2 m NAP, between 01/09/16-24-05-15. Blue corresponds to erosion, red corresponds to accreting, yellow shows no changes.

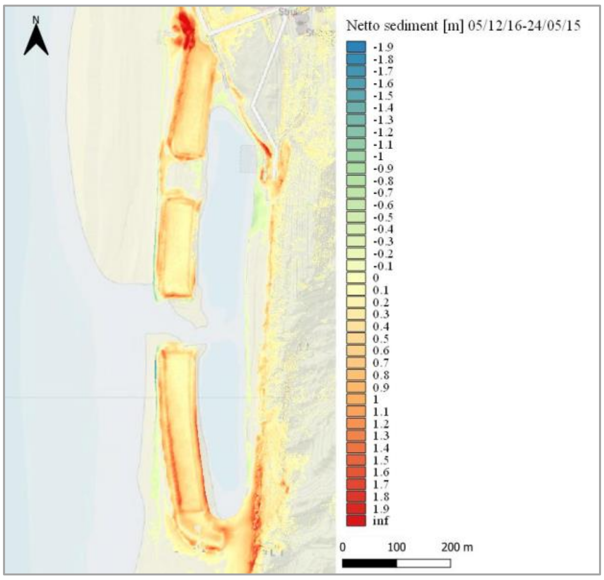


Figure 0-4: Sediment change lagoon area above 2 m NAP, between 05/12/16-24/05/15. Blue corresponds to erosion, red corresponds to accreting, yellow shows no changes.

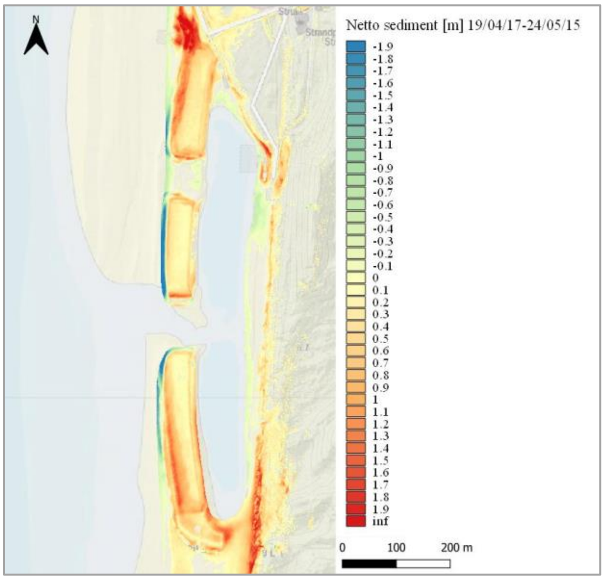


Figure 0-5: Sediment change lagoon area above 2 m NAP, between 19/04/17-24/05/15. Blue corresponds to erosion, red corresponds to accreting, yellow shows no changes.

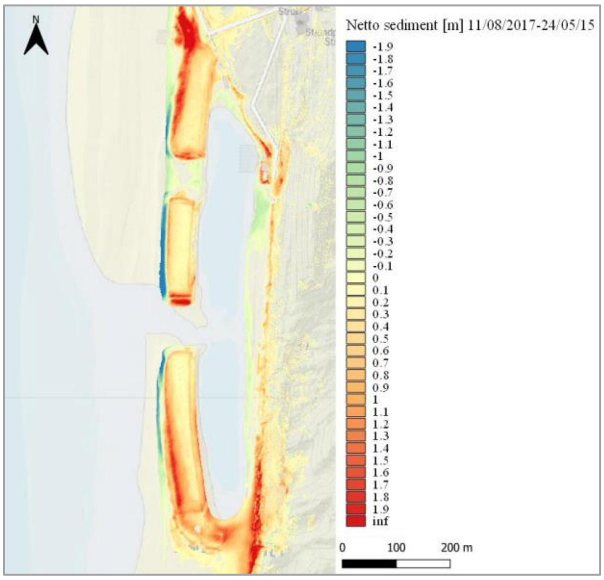


Figure 0-6: Sediment change lagoon area above 2 m NAP, between 11/08/17-24/05/15. Blue corresponds to erosion, red corresponds to accreting, yellow shows no changes.

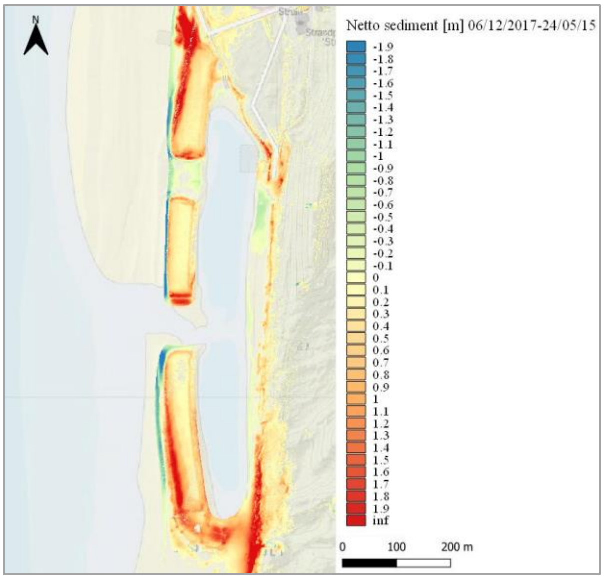


Figure 0-7: Sediment change lagoon area above 2 m NAP, between 06/12/17-24/05/15. Blue corresponds to erosion, red corresponds to accreting, yellow shows no changes.

C

Cross-sections lagoon

The cross-sections of the lagoon show the development of the lagoon in time, which is done by the use of gridlines in geographical measurements. The cross-sections have an underlining distance of 50 meter, starting in the north of the lagoon going to the south of the lagoon. The maximum water level for each time measurement is added to get an overview of the maximum water level in the lagoon that day, if the channel would have been open.

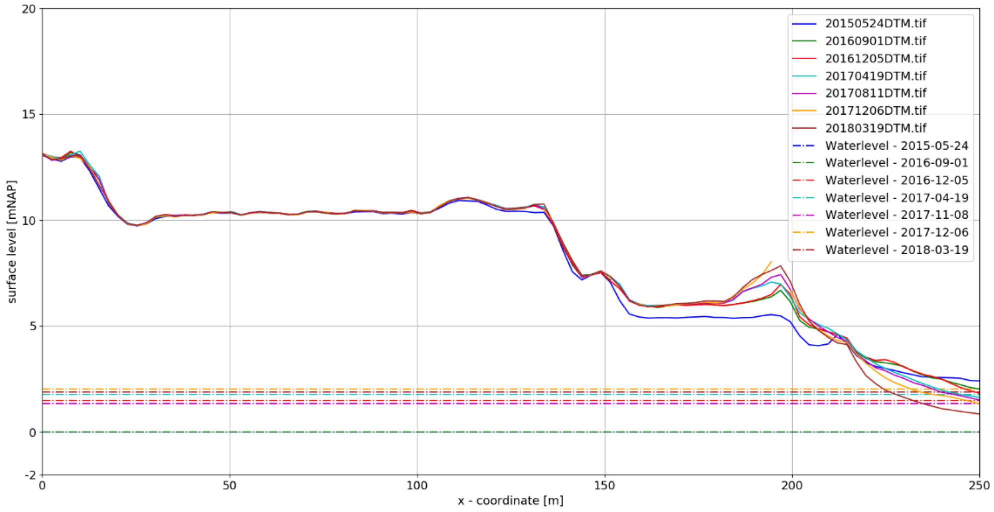


Figure 0-8: Gridline 0.00

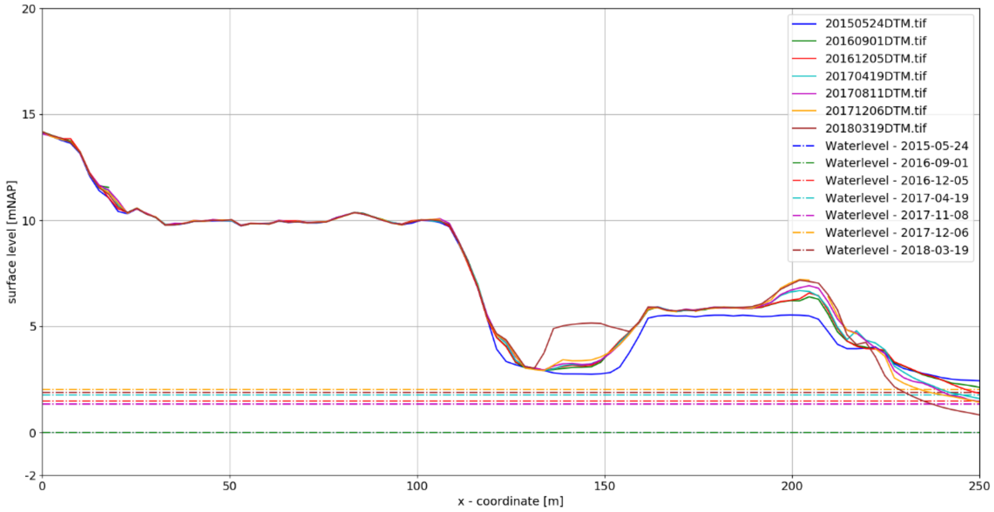


Figure 0-9: Gridline 50

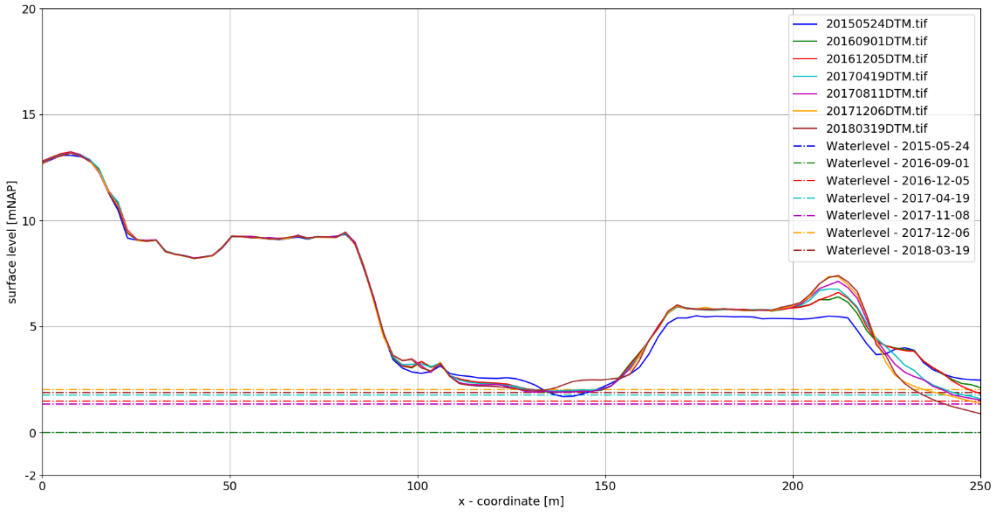


Figure 0-10: Gridline 100

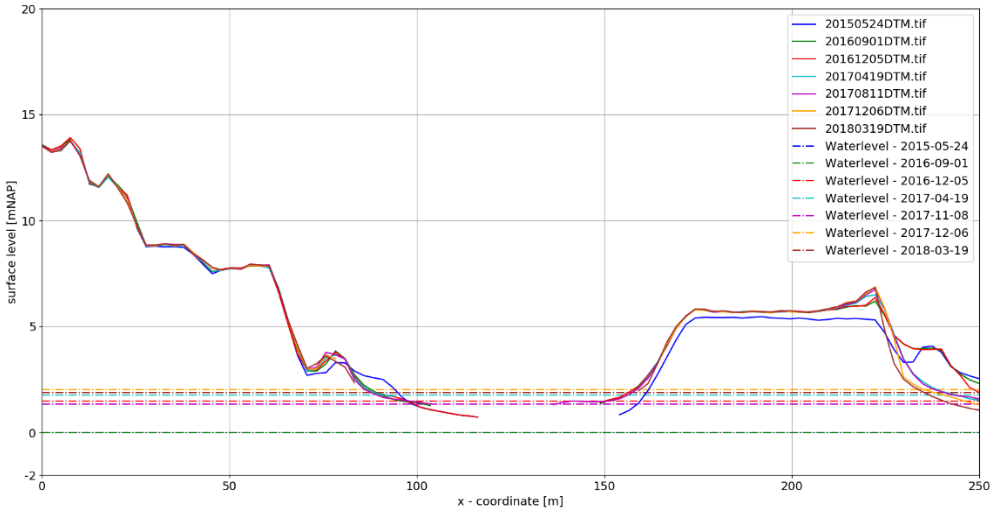


Figure 0-11: Gridline 150

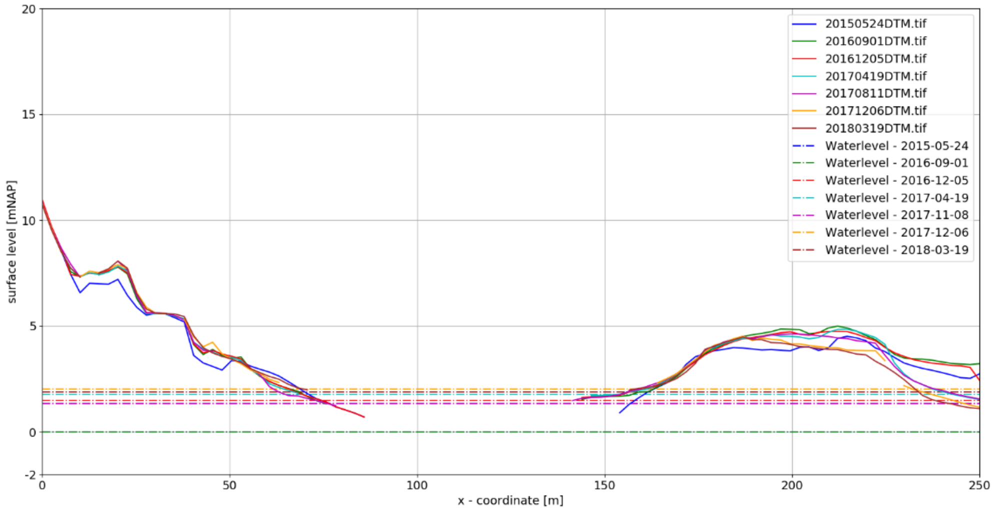


Figure 0-12: gridline 200

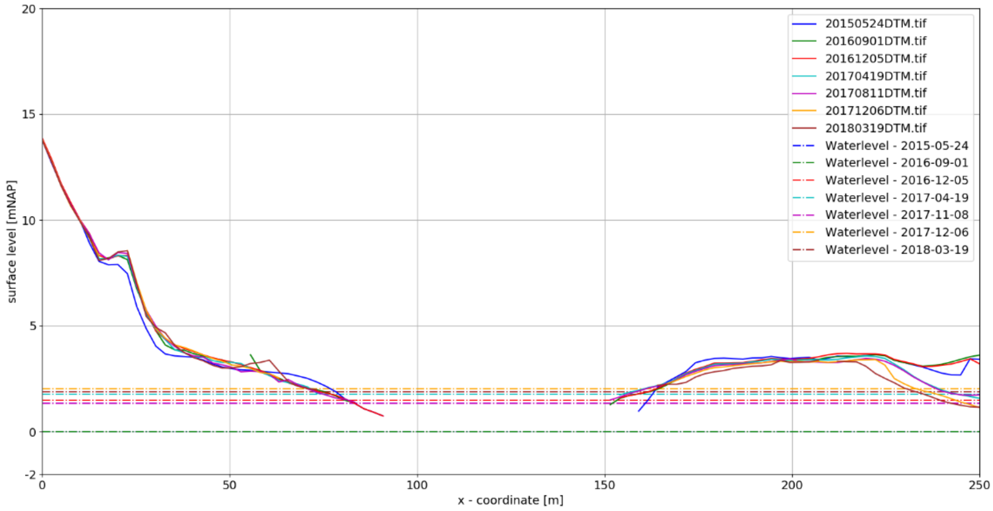


Figure 0-13: gridline 250

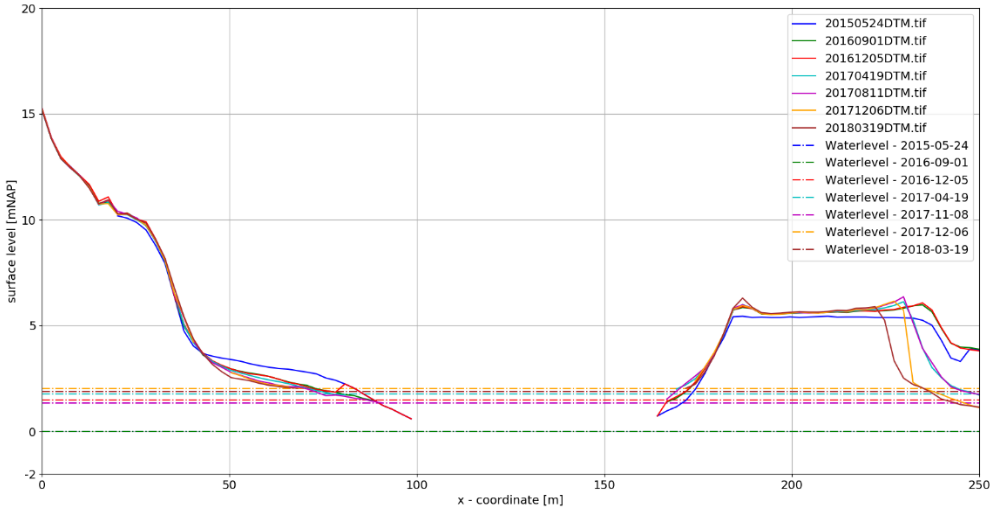


Figure 0-14: gridline 300

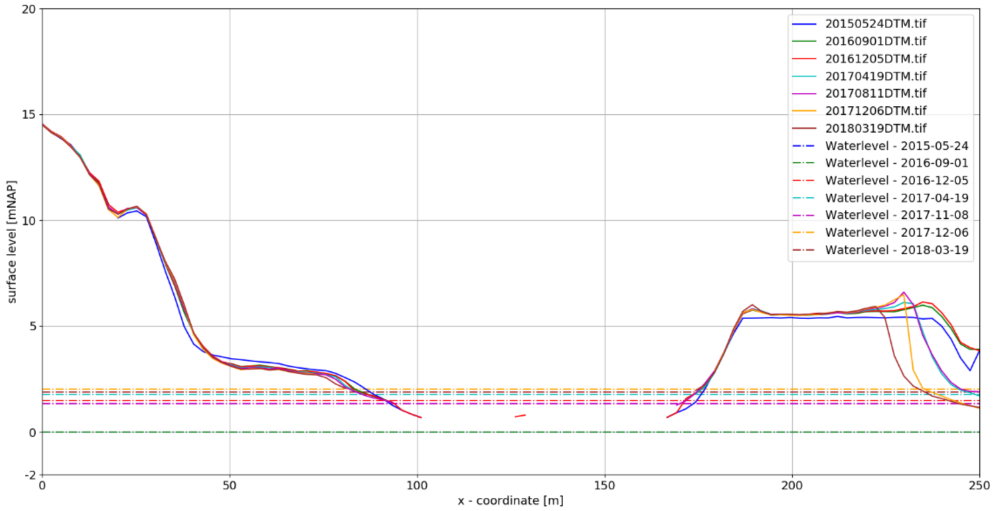


Figure 0-15: gridline 350

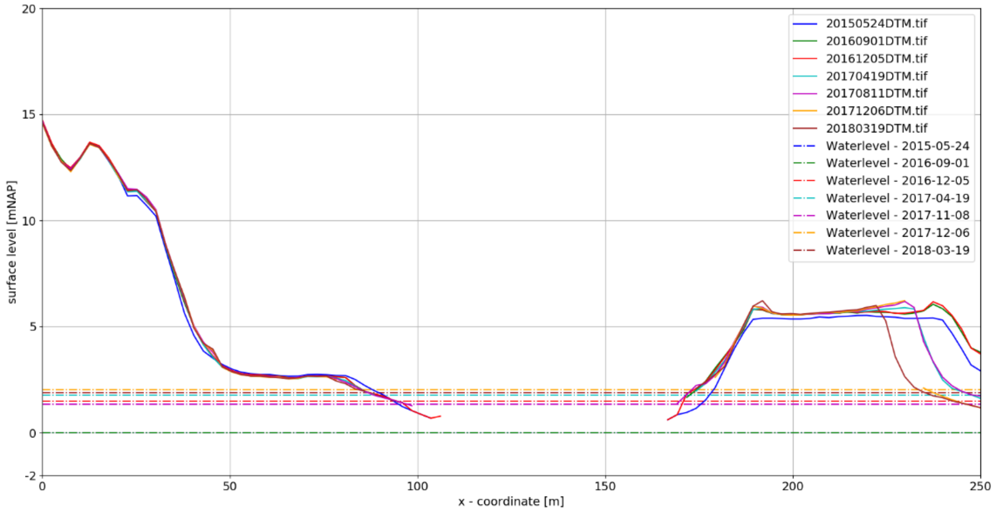


Figure 0-16: gridline 400

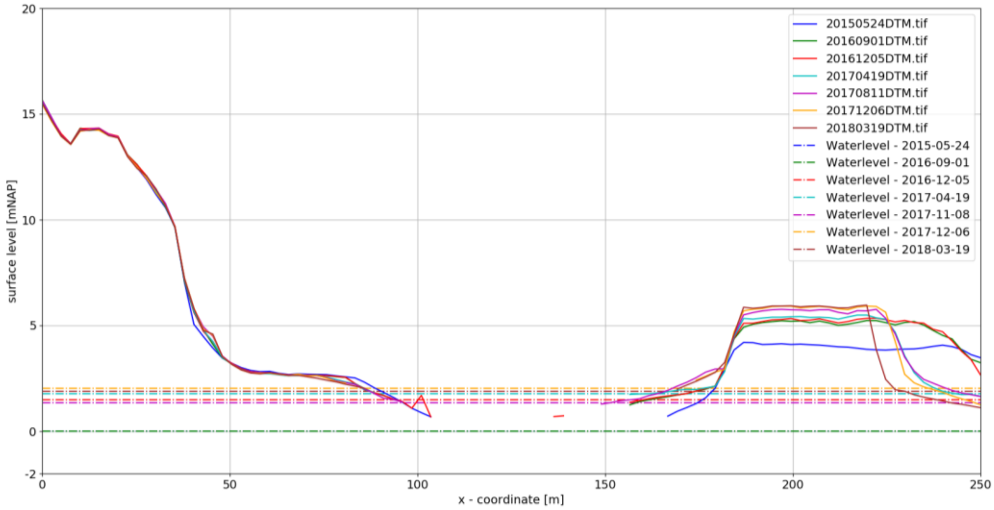


Figure 0-17: gridline 450

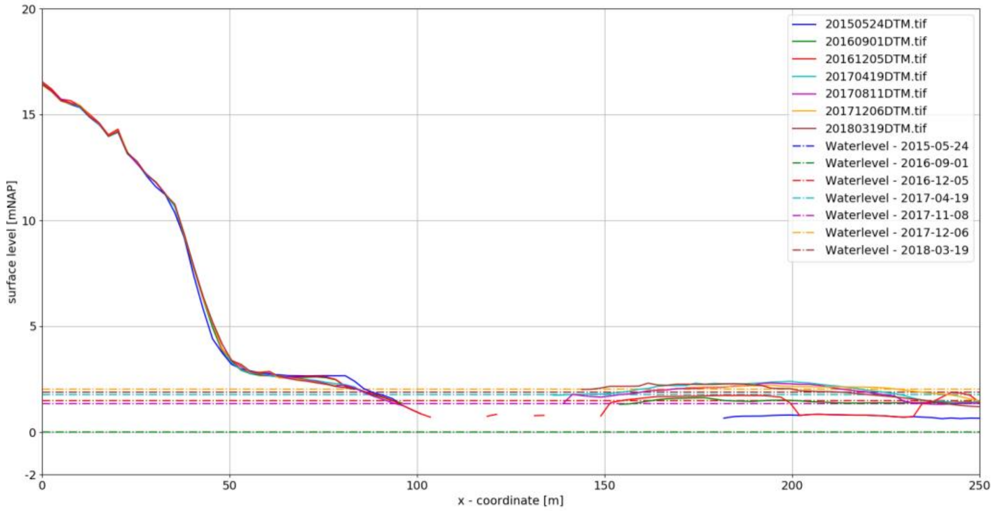


Figure 0-18: gridline 500

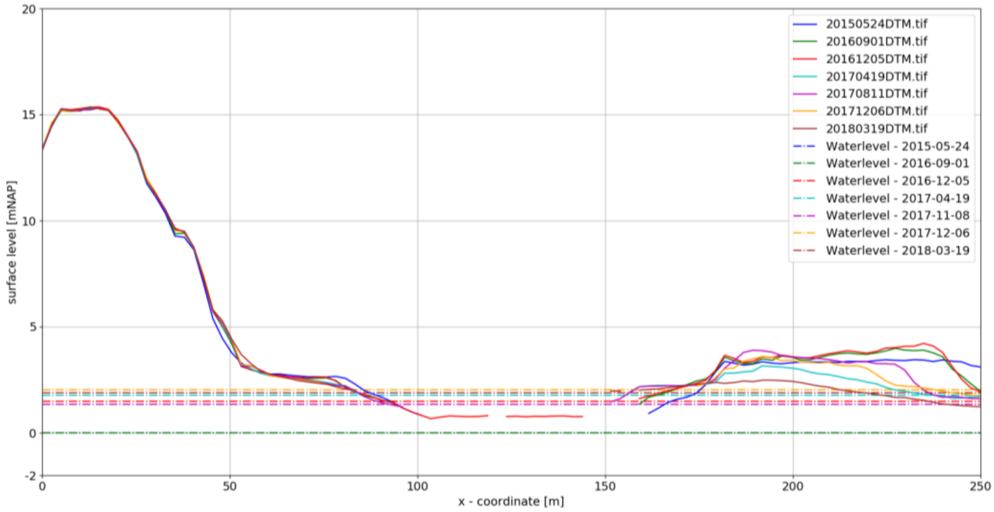


Figure 0-19: gridline 550

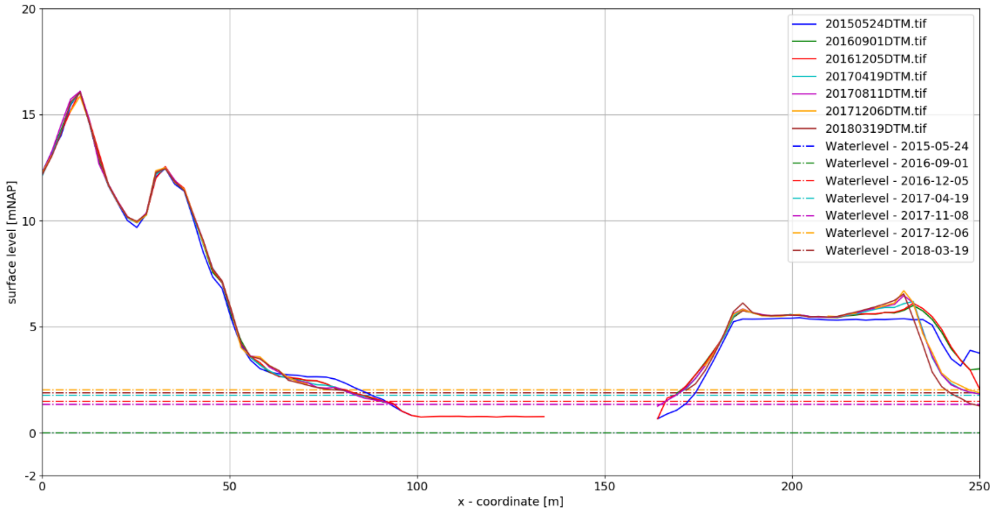


Figure 0-20: gridline 600

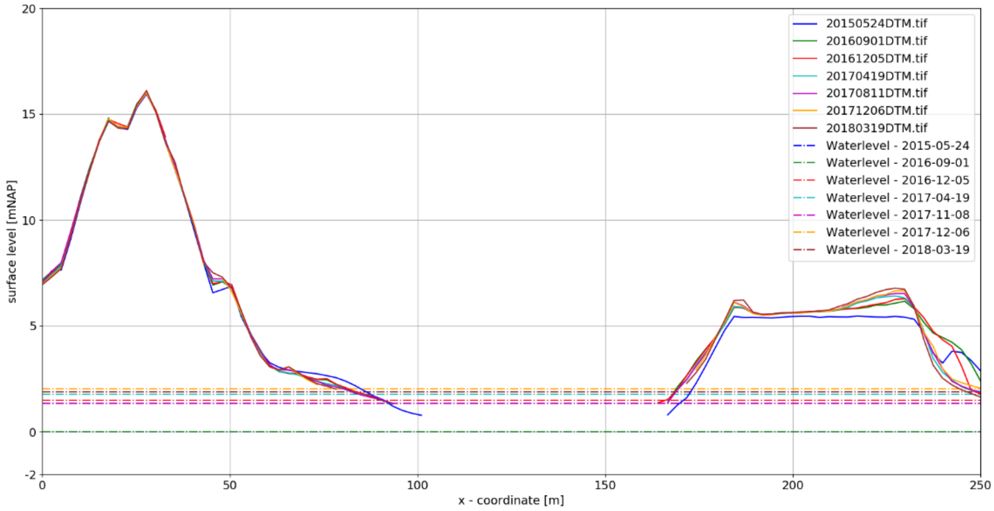


Figure 0-21: gridline 650

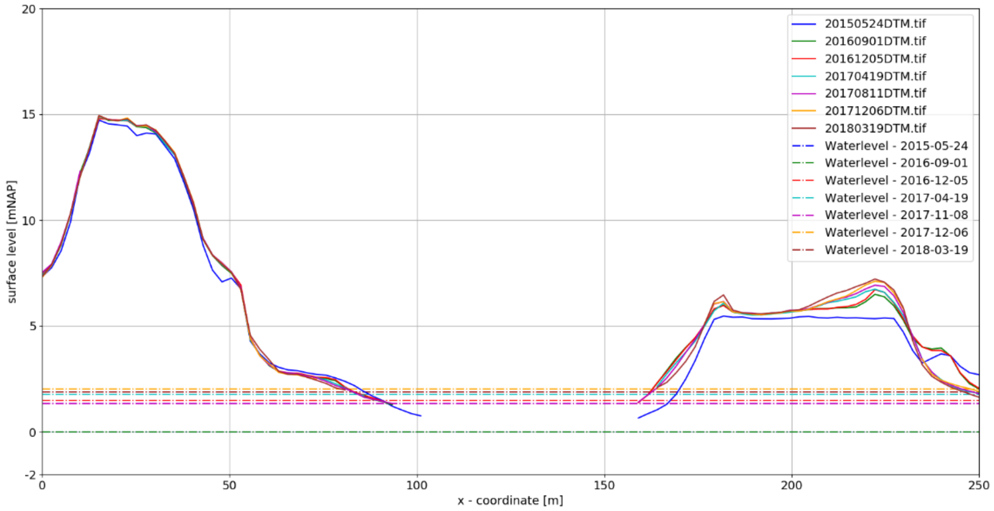


Figure 0-22: gridline 700

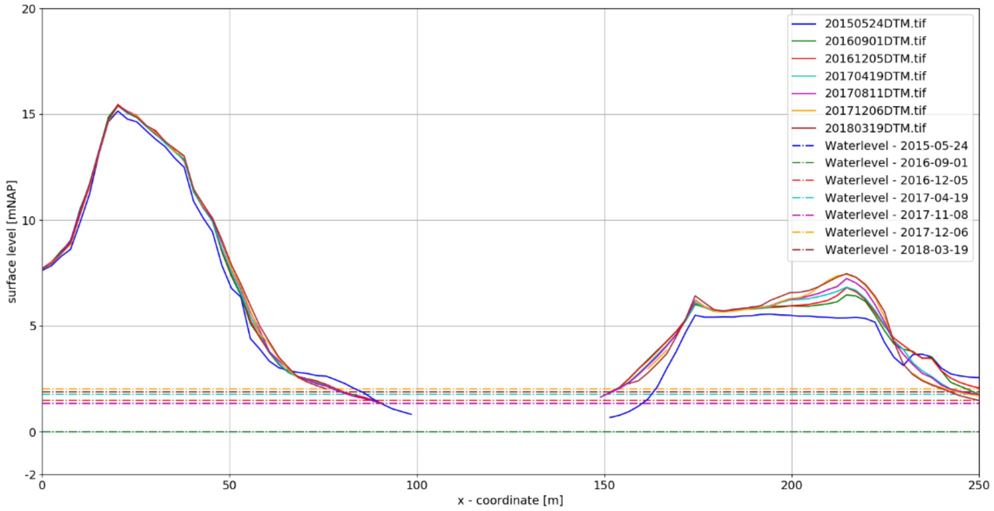


Figure 0-23: gridline 750

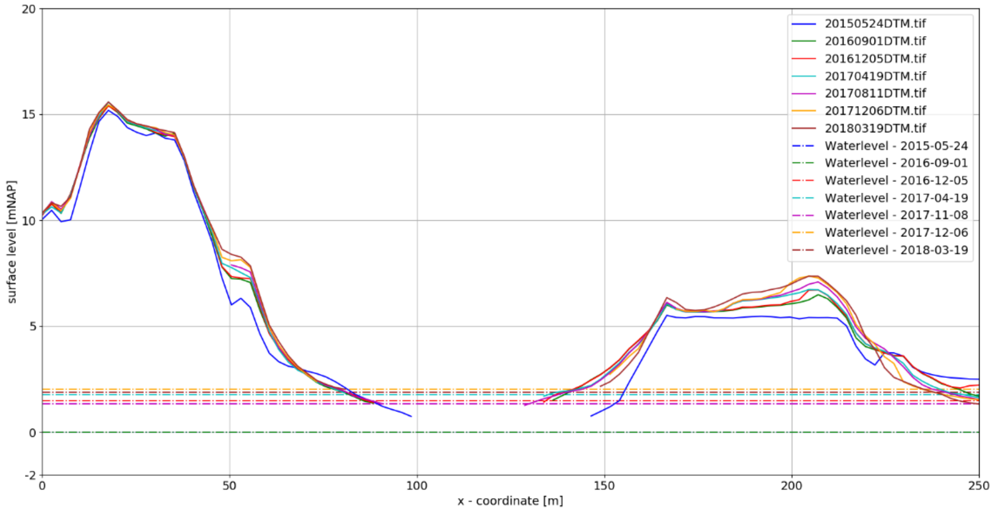


Figure 0-24: gridline 800

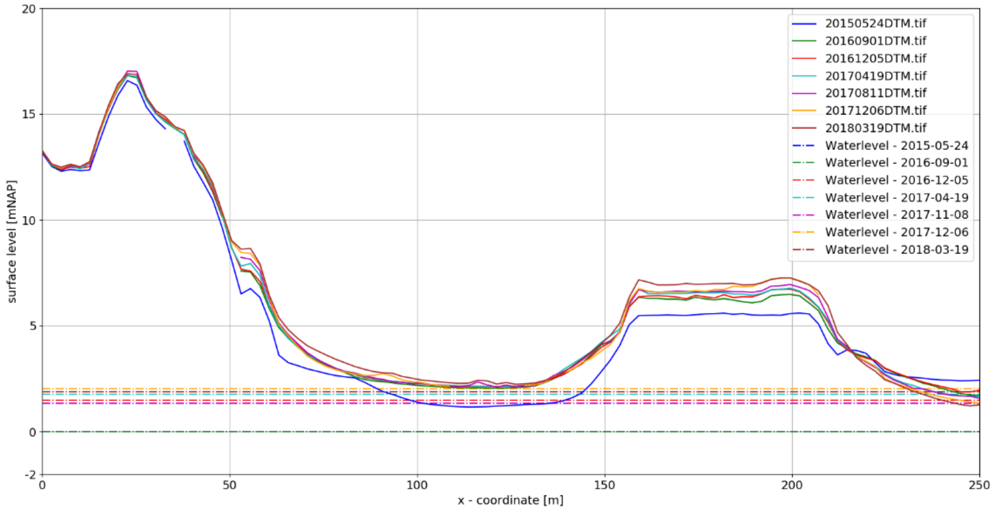


Figure 0-25: gridline 850

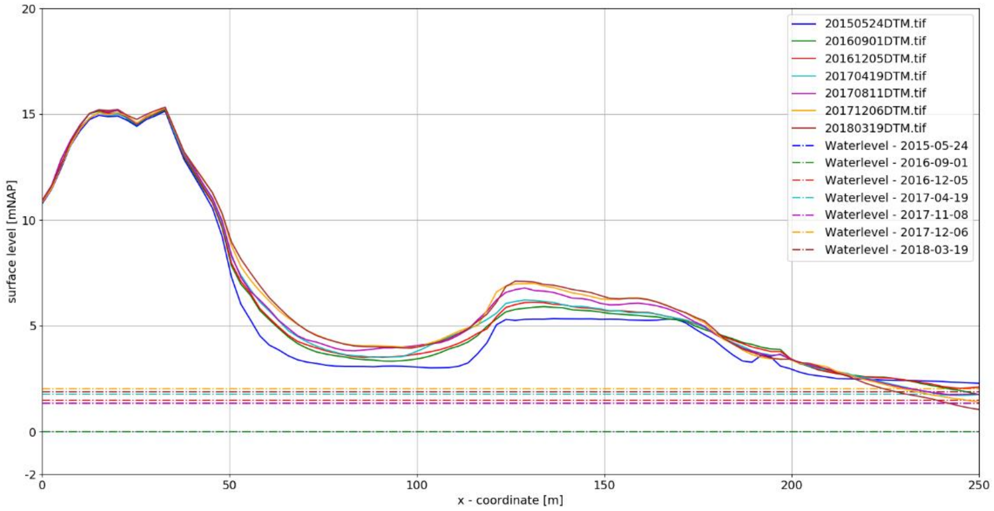


Figure 0-26: gridline 900

D
Cross-section channel area

The figures show the location of the channel cross-section and the channel cross-sections for all geographical measurements.

Figure 0-27:Gridline channel cross-section at the southern opening of the lagoon.

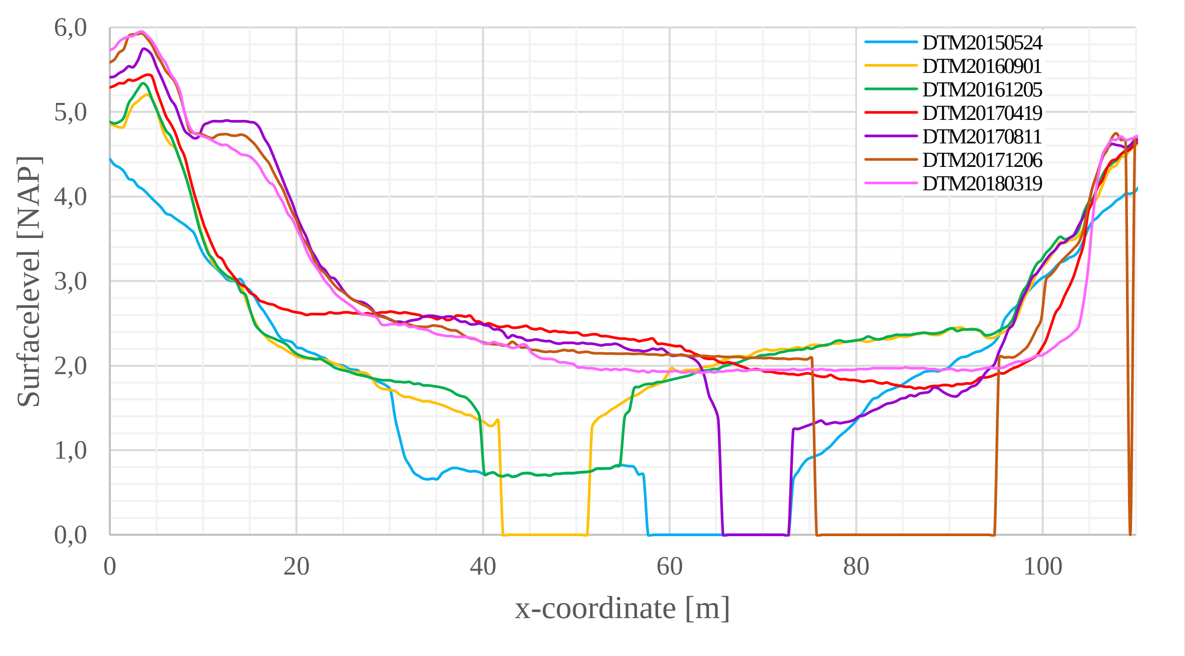


Figure 0-28:Cross-section of the channel for all geographical measurements.

E

Overview water level lagoon for different significant wave height

The figures give an overview of the water level inside the lagoon for a Hs of respectively 240, 350 and 400 cm.

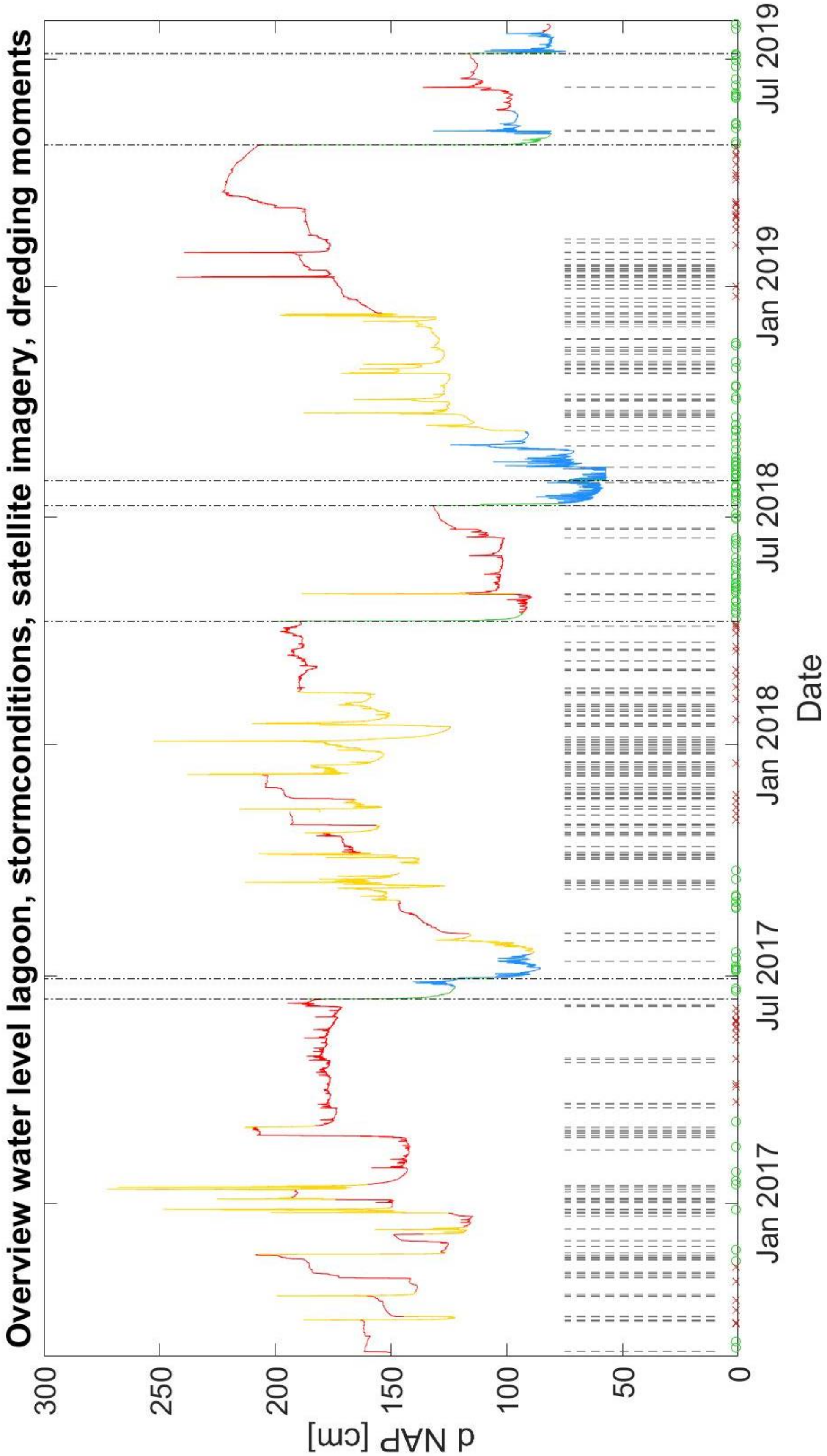


Figure 0-29: Overview of the water level in the lagoon including storm events, satellite imagery and dredging moments. Satellite images are indicated at the x-axis, with green circles for an open channel and red crosses for a closed channel. The grey dashed lines in the bottom of the figure indicates storm events with a Hs>240 cm. The black vertical dashed-dotted lines are dredging events. A dredged moment in the water level is indicated with green. Blue lines show an open channel where water exchange is possible. Episodic events are marked as yellow and a closed channel is indicated with red.

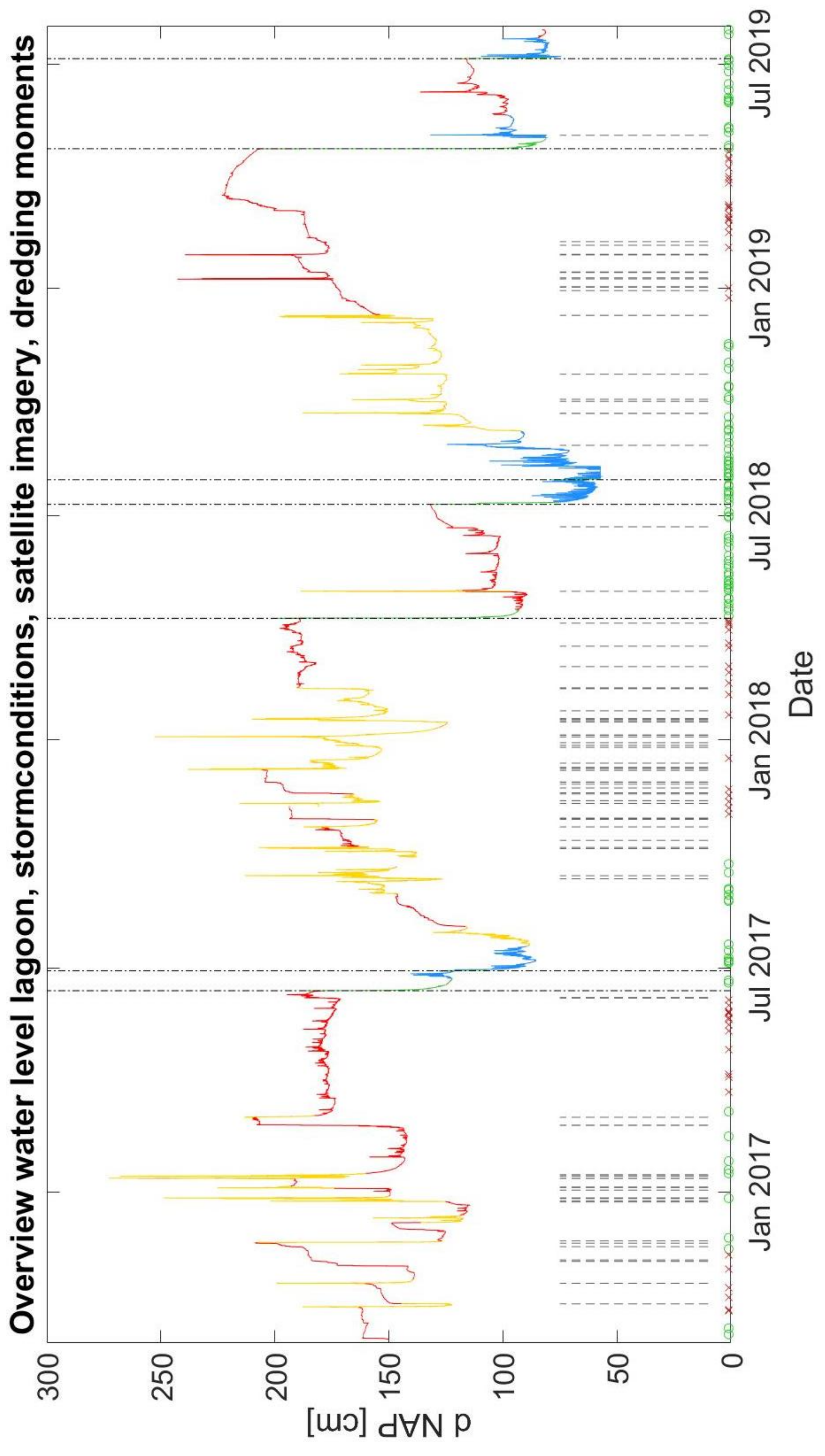


Figure 0-30: Overview of the water level in the lagoon including storm events, satellite imagery and dredging moments. Satellite images are indicated at the x-axis, with green circles for an open channel and red crosses for a closed channel. The grey dashed lines in the bottom of the figure indicates storm events with a Hs>350 cm. The black vertical dashed-dotted lines are dredging events. A dredged moment in the water level is indicated with green. Blue lines show an open channel where water exchange is possible. Episodic events are marked as yellow and a closed channel is indicated with red

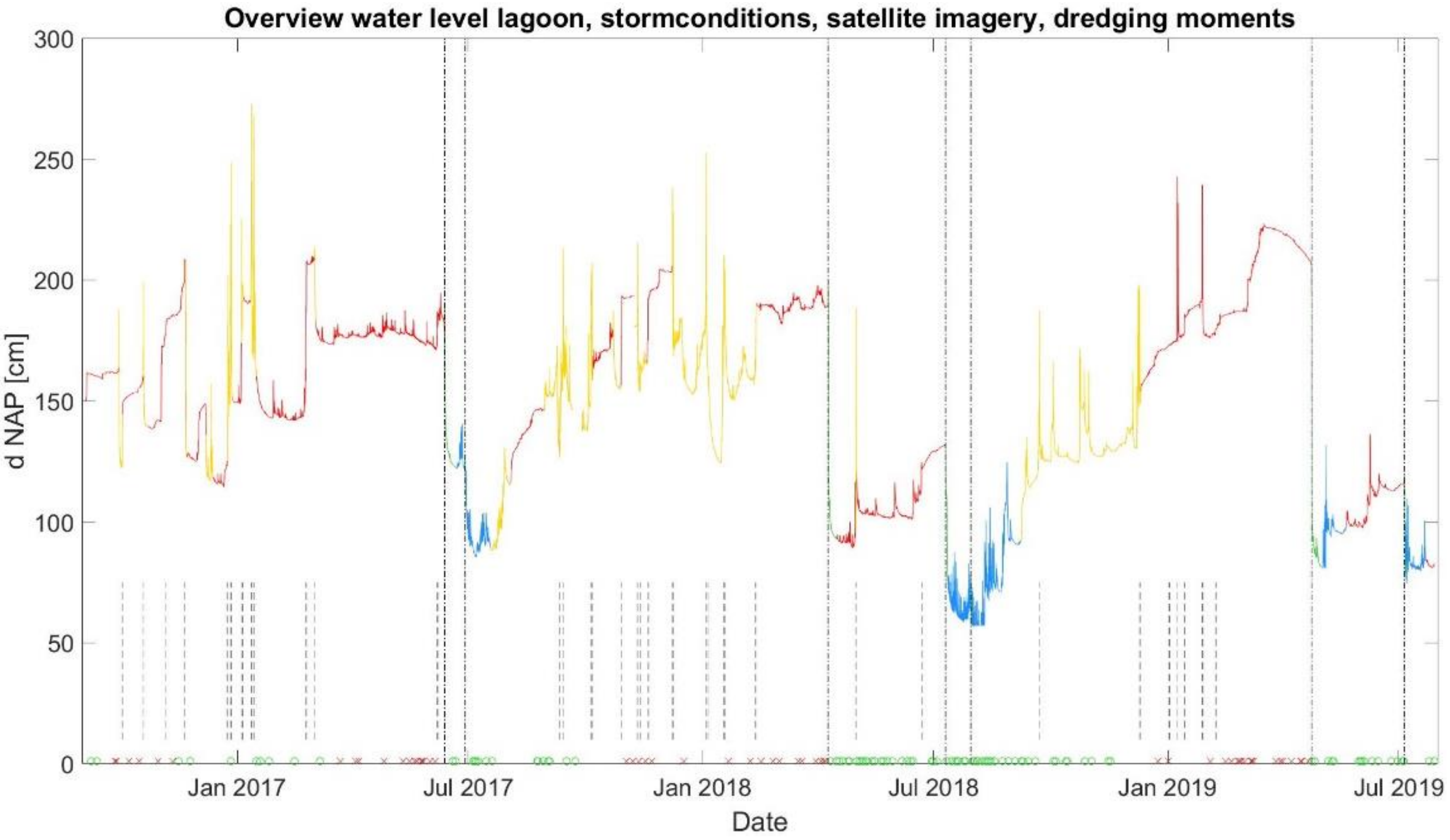


Figure 0-31: Overview of the water level in the lagoon including storm events, satellite imagery and dredging moments. Satellite images are indicated at the x-axis, with green circles for an open channel and red crosses for a closed channel. The grey dashed lines in the bottom of the figure indicates storm events with a Hs>400 cm. The black vertical dashed-dotted lines are dredging events. A dredged moment in the water level is indicated with green. Blue lines show an open channel where water exchange is possible. Episodic events are marked as yellow and a closed channel is indicated with red.