Rijkswaterstaat WVL

The hydraulic load levels of the Scheldt Estuary

Version 2.0

Melanie Sinke
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Thesis

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Summary

In the following thesis, research is conducted on the effect of sea-level rise and expected hydraulic load levels for the Scheldt Estuary, currently and in the future. As climate changes advances and the sea-level rises, insight into the effects of the rise on our coastal area's is essential. Rijkswaterstaat wants an overview of the expected impacts for their involvement in the research program "*zeespiegelstijging"* using the new WBI2017 instruments. Now, this information is lacking and have asked several students to research it, with this thesis focusing on the Scheldt Estuary. The goal is to find and visualise the extent of the impact on dykes along the estuary using WBI2017 software, as well as providing insight into the impact that changing the wind statistics station from Vlissingen to Cadzand. The goal is divided into several sub-questions to answer its central question accurately. The first to aim to find out what the hydraulic load levels are being experiences in 2023, 2050 and 2100, relating the answer to the required crest heights for the w+ scenario. Third and fourth questions aim to determine which sections experience the most substantial loading and how significant the differences between sight years are for these locations. Lastly, a look was taken into the alternative wind data, and how significant the difference is between the two for the three years.

Answering these questions was done by a quantitative software analysis using Hydra-NL and statistical analyses on the calculation results. Each dyke segment was calculated on the water levels and hydraulic load levels for 2023, 2050 and 2100. These calculations resulted in a large quantity of information, which was then summarized using excels pivot tables. From the pivot table, several different graphs and tables were created all presented in chapter 5. Results and the data were also used as input for the GIS maps. The maps are situated at the end of results sub-section highlight the segments on the representing side and indicating the varying hydraulic loads and the explanation of it. The chapter sections summarise the results of the calculations, which are then related to each other in the representing maps per segment.

The results compared to the current dyke heights resulted in transgression percentages of at the lowest 3% in the south side of the Eastern Scheldt. At the highest 78% in the south of the Western Scheldt. With required dyke heights ranging from 4 meters to 14 at the most, depending on their location and orientation compared to the contributing wind direction. Then specific to the Western Scheldt, the different wind statistics show an average difference ranging from 4 cm to 70 cm, though the difference ranges further of -10 cm up to 1.2 meters. Even though a select few locations on the northern side show a decrease when using Cadzands data, the majority shows an increase in calculated hydraulic load levels.

The results presented show a global overview of the expected hydraulic load levels for a worst-case scenario in the W+ OI scenarios. However, there are a few discussion points mainly focussed on the Eastern Scheldt where several locations were missing in the calculations, and the results were therefore generalised per section. Also, the available profiles are somewhat out-dated as indicated by the waterboard the data lack the latest adjustments to the dykes as the last measurement was in 2010. Moreover, the results are challenging to validate as the used software is new, and these students performed assessments are the first indications. These points, the conclusions and recommendations formed from them are discussed at length in the final three chapters of the thesis.

Acknowledgements

Before I start the thesis report, I would like to thank a few people who have helped me during my internship. First, I would like to thank both my in-company supervisor Mr Slomp and the supervisor from school, Mr Nijssen. Both aided me greatly in giving feedback and answering questions as they arose, and for Mr Slomp also help to solve some software issues. Secondly, I would like to thank Mr Van De Rest of the waterboard who provided the data on dyke locations and profiles used in the thesis. As well as Mr Duits, who helped a lot with solving the software issues I had been having. He figured out what went wrong very quickly and giving tips to solve it. Last, I would like to thank Mr Bottema, who gave feedback on my results and gave some tips to for a bright and more detailed explanation.

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Glossary

The following Dutch terms are used within the report; here, they are linked to its translation and meaning. Most of these are used in English in the text though at the first introduction uses the Dutch term.

Term	***Meaning***
Belasting or Load	The outside influences on a water barrier, such a water level and waves. Too large loads lead to the failure of a dyke.
Dijknormaal	The orientation to the wind compared the north [0°]
Dijkring	A dyke ring; (levee system[1]) An area protected against the water by a continuous line of primary defences or high grounds. These dyke rings have been divided into stretches since the updated water act in 2014.
Dijkringgebied	Dyke ring area; An area which by a system of defences should be protected against flooding, primarily due to high storm surges, high water in lake IJssel or a combination of the two.
Dijkvak	Dyke section, a part of the defence with similar strengths, characteristics and loads.
Dijktraject	Dyke segment / Levee segment[2], a part of a primary barrier which has its norms
Faalkans	The probability of the failure of dyke tract by which the hydraulic load on the secondary dyke section significantly increases
Faalkansbegroting	The distribution of allowed ranges in the probability of failure for the failure mechanisms of a barrier so that the combination of probability ranges does not transgress the maximum allowed failure probability.
Faalkanseis	The norm for the probability of failure under particular stress.
Kader Richtlijn Water	The water framework directive is a European directive which set the water quality requirements of European water from 2015. (Rijksoverheid, 2000)
Norm	The allowed flood chance of a *Dijk traject* either by signalling value or bottom limit dependant on the managing body.
Ondergrens	Bottom limit of the failure probability
Overstromingskans	The probability of the failure of a dyke tract by which the dyke protected area floods to the point of mortality or substantial economic damage.
Signaleringswaarde	The signalling value for a dyke tract is together with the bottom limit, and the norm has taken up in the statutes. The value encompasses the flood probability chosen to the time limit for improvements; all primary flood barriers have a signalling value between 1/300 and 1/100.000
Waterwet	The Water Act, The law and regulations on water management for all water systems in the Netherlands

List 1 Sources (Duits, 2019) (Raad van State, 2020) (Rijkswaterstaat, 2020) (Bieman & Smale, 2015) (Kok, Jongejan, Nieuwjaar, & Tánczos, 2017)

[1] See pag 14/15 https://www.enwinfo.nl/images/pdf/Grondslagen/GrondslagenEN-lowresspread3-v.3.pdf
[2] See *grondslagen voor waterkeringen*, pag 48/49 https://www.enwinfo.nl/images/pdf/Grondslagen/GrondslagenEN-lowresspread3-v.3.pdf

Chapter 1. Introduction

''The storm Ciara, spring tide and large quantities of river water are causing a special situation. 3 of the 6 storm surge barriers have been closed to protect us from the high water levels. The closed barriers include the Hollandsche IJsselkering, Oosterscheldekering and the Haringvlietsluizen.'' (Rijkswaterstaat, 2020)

The quote above comes from a news report brought out by Rijkswaterstaat on the 10th of February 2020; storm Ciara caused three out of the six storm barriers to close. It was the most substantial storm of winter 2020, according to Weeronline, causing kilometres of dunes to be eroded to the point where the full slope at the bottom was washed out. A week later another storm hit the Dutch coast, though this time smaller the impact on the coastal defences was felt. Each winter period the Dutch coast experiences heavy storms, and historically several floods have been associated with the regular heavy storms. The effect of storms is expected to become more severe and frequent due to sea-level rise. The most well-known flood on the Dutch coast is the flood of 1953 which prompted the construction of the Delta works. Even before 1953, dykes have been built, polders created, and assessing their safety has become a staple since 1996. Regular policy studies have been carried out since 2001. The most recent policy study is the *''Kennisprogramma Zeespiegelstijging (KP ZSS)''* which aims to get a better insight in the expected sea-level rise and what this means for the coasts, rivers and hinterland and if the current strategy is still sufficient. This report belongs to the second part of the KP ZSS, aiming to find what the several sea-level rise scenarios mean for all of the coastal defences, the availability of freshwater and for the functional and space usage. (Waveren, Lodder, & Gool, 2020) In the report, two questions, from Rijkswaterstaat, related to the required crest height and longevity for the Scheldt Estuary for the expected sea-level rise are assed based on the hydraulic loads, see Figure 1 for an example illustration on the hydraulic load level and parameters.

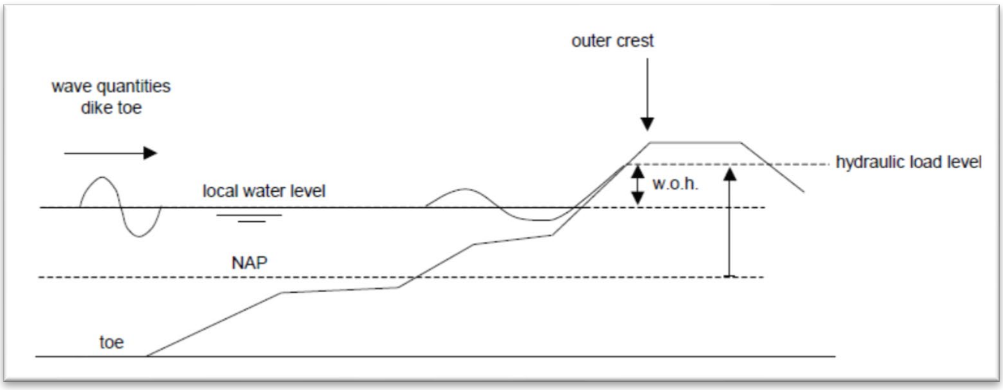


Figure 1 An overview of the concept for wave overtopping related to the hydraulic load levels (Geerse, 2011)

1.1. Problem analyses

Climate change is rising important for society, though more so for Rijkswaterstaat and the regional water authorities have to address the future challenges which climate change and especially sea-level rise present for the Netherlands. The Royal Dutch meteorological instate or KNMI creates their climate scenarios more suited to the Netherlands. The KNMI climate scenarios are being created and re-assessed following the IPCC, to adjust for new insights. The latest scenarios stem from 2014, with the formulation of new scenarios expected in 2020-2021. (Hurk, 2017)

In the Netherlands, we have long build defences to protect our low-lying areas, as the sea-level rises it will affect the longevity of the dykes and the safety of the hinterland. In addition to building the defences, there have been norms and requirements in place to ensure the safety level, with re-assessment periods laid out by the *''Water Act of 2014''* currently at least once every 12 years. There has not been a national publication with the new analysis of the safety level of the primary defences using the new WBI2017 instruments and regulations; this is expected in 2022.

The impact of the sea-level rise on primary defences is of importance to Rijkswaterstaat, for their involvement in the research program *''Zeespiegelstijging''*. (Waveren, Lodder, & Gool, 2020) At the moment, such an overview is lacking; therefore, several studies are being performed. The assignment comes from two questions posed by Rijkswaterstaat one regarding the sea-level rise and the required crest height to meet safety requirements and the other one regarding the wind statistics for the Western Scheldt. The first research questions look at the impact of sea-level rise on the dykes, to find if they will continue to meet the safety norms. The Scheldt estuary[3] has experienced several floods and other similar events, just like much of the Dutch coast, though none have occurred since 1953. The delta works and other barriers such as dykes, are periodically being re-assessed and strengthened when they do not meet the safety requirements. Because the WBI2017 has recently been published, there is no updated overview of the effects of sea-level rise for the current state of the primary defences for the entire Netherlands, 2050 and 2100. Besides, the lack of an overview, there is also no insight into changing the stations linked to the wind statistics. The current wind station is located in Vlissingen is quite sheltered, whereas the station in Cadzand is not sheltered whatsoever and is expected to generate higher load levels. Therefore, the question arose what a change of wind station will do for the hydraulic load levels in the Western Scheldt.

1.1.1. The problem statements

Rijkswaterstaat lacks a complete overview of the effects of sea-level rise on the primary flood defences of the Netherlands, for the climate scenarios and timeline of 2050, 2100, assessed with WBI2017 instruments. Rijkswaterstaat wants this information as input in the Research program *''Zee Spiegel Stijging''*. The lack of this information brings the risk of less adequate advice towards flood safety and the measures that the flood risk managers could be taking. Also, the Western Scheldt wind statistic is based on a sheltered measuring station, affecting the reliability and height of the resulting load levels for the assessment. Rijkswaterstaat expects that the current wind statistics are too low.

1.2. The goal

The goals of the research are to find and visualise the extent of the impact of sea-level rise on the dykes along the Scheldt Estuary, and by using the Hydra-NL software find the required crest height to withstand the changes. In addition to finding the required crest

[3] Other students are working on other areas; The Wadden Sea, the Rhine and Meuse Estuaries.

heights, an additional goal is to identify the dyke segments experiencing the highest hydraulic loads, and the conditions which lead to it. Also, in the Western Scheldt, two different wind statistics will be compared to provide insight into the impact of a change in the station (from Vlissingen/Flushing to Cadzand)

1.3. The research questions

The main question, *what is the impact of sea-level rise on dyke safety along the Scheldt Estuary for the years 2015-2050-2100, based on the required dyke height, and an alternative wind statistic for the Western Scheldt?*

The sub-questions;

1. What is the current situation (hydraulic loads for 2023), calculated in Hydra-NL using dyke data from 2010-2016? Related to the required crest height, ''benodigde kruin hoogte'', and the hydraulic load level
2. What is the needed crest height and hydraulic load level, as calculated in Hydra-NL, for the years 2050 and 2100 in the W^{+} scenario?
3. Compare the results and determine which dyke and dyke sections experience the most substantial hydraulic loads and under which conditions?
4. Moreover, how significant is the difference between the sight years 2023 (current), 2050 and 2100? For the dykes experiencing the most substantial hydraulic loads.
5. How significant is the difference in the calculated hydraulic loads in the Western Scheldt if using the alternative statistical wind data, from Cadzand instead of Vlissingen, for the current, 2050 and 2100 situations?

1.4. Project boundaries, pre-conditions and conceptual framework

Included	***Not included***
Dykes along Eastern and Western Scheldt	Dune stretches, and Scheldt river
OI2014 climate scenarios, based on KNMI'06 scenarios	Sandbanks are assumed to not grow with climate change. This project does not allow for new calculations. Physically this is a conservative approach.
Water level and Hydraulic load level calculations	Climate change scenario's: KNMI'14 as Hydra-NL is based on KNMI'6
Years 2050 and 2100, the base year 2023 for desired crest levels	other failure modes from the WBI2017
Two wind statistics for comparison, Vlissingen and Cadzand for the Western Scheldt	No additional wind statistic Eastern Scheldt, since this has already been corrected in the 2017 Hydra-NL database
Assessment based on crest height to meet the safety requirement	Return periods lower than the requirements for each dyke section
The height as the primary driver of failure by wave run-up and overtopping	Pipping, macro stability and other failure mechanisms were not included

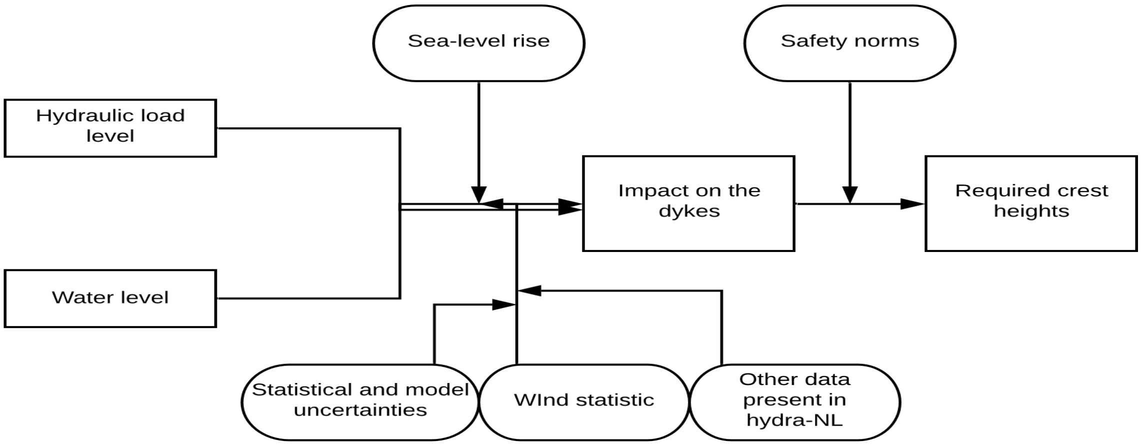


Figure 2 The conceptual framework, the square boxes are the variables and the round boxes moderating variables, with the arrows.

1.5. Reading guide

Chapter 1 introduced the topic from the origin of the topic to the problem statement and what will be included in the research and most importantly, the research questions. Following the assignment introduction is an overview of the water systems in chapter 2, giving some insight into the current state of the estuary. In chapter 3, the literature study is given form, going into the assessment and safety requirements as well as climate scenarios and lastly the hydraulic loads. Then in Chapter 4, the methodology used to answer the thesis questions is explained, and some information on the software is provided. The methodology is then applied to find and present the results in Chapter 5. After interpreting the results, they will be concluded in chapter 6, discussed in chapter 7. Lastly, a recommendation is given based on the previous chapters in the last chapter 8. Next to these chapters, a literature list and appendices have been added at the bottom.

Chapter 2. Area description

The Scheldt estuary lays in the South-West of the Netherlands as the southern part of the Rhine, Meuse and Scheldt delta. Rijkswaterstaat manages the water bodies and the primary defences, along with the Waterboard Scheldestromen, and the Western Scheldt has the department of ''*mobiliteit & openbare werken*'' from Belgium as an additional partner. Other managing bodies include ''*Staatsbosbeheer, Stichting* Het *Zeeuwse Landschap* and *Vereniging Natuurmonumenten*,'' who together with the waterboard manage the beaches, and nature areas. (Rijkswaterstaat, 2009). For the boundaries of the Eastern and Western Scheldt, showing its neighbouring water bodies see Figure 3; these boundaries are subsequently those of the research area.

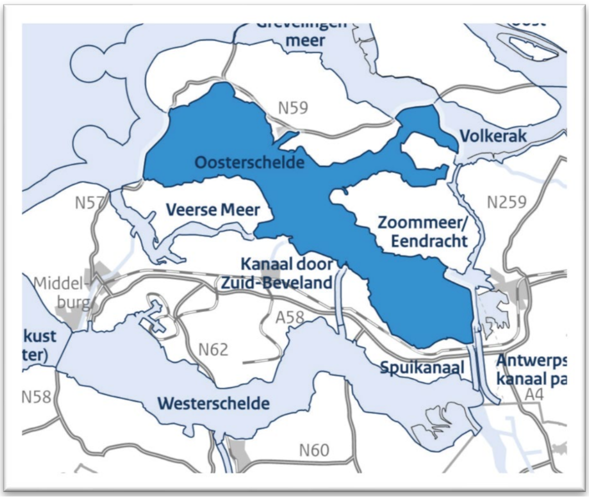


Figure 3 The waterbodies of the South-Western delta highlighting the Eastern Scheldt (Rijkswaterstaat, 2009)

2.1. The Eastern Scheldt

The Easter Scheldt is the eastern branch of the Scheldt Estuary in the south of the Netherlands. According to the Water framework directive or in Dutch *''Kader richtlijn water,''* it has the water type and status of K2 coastal water, sheltered and polyhaline and heavily modified water body covering about 351 km^2 (Rijkswaterstaat, 2009). The basis of the status is the modification by hydro morphological changes; just like the Wester Scheldt, all the shores have dykes which have built up into the 20th century. Furthermore, the sluice complexes, the closing of lake Grevelingen and the storm surge barrier of 1985 modify the hydro morphology of the Eastern Scheldt and affect the ecology (Rijkswaterstaat, 2009). Some characteristics include; that the average water depth is -9 m NAP, though the deepest point is -42m NAP, considered the shipping routes, recreational sailing and fishing. Its tidal range at Yerseke is about 3,25 meters (Rijkswaterstaat, 2009) The storm surge barrier does influence the safety of the flood defences by reducing the impact of storm surges. The barrier has an ecologic effect through the dampening of the tides (erosion of the tidal flats) and a more stable salinity gradient.

2.2. The Western Scheldt

The Western Scheldt lays in the south of the Netherlands ''west'' of the Eastern Scheldt. It covers an approximate area of 429,4 km^2, of which 196 km^2 of water (werkplaats Zuidwestelijke Delta, 2013). Compared to the Eastern Scheldt, the Wester Scheldt has no storm surge barrier and is, therefore, an open system, with tidal influence and a salinity gradient. (Rijkswaterstaat, 2009) The Western Scheldt's, characteristics include the high dykes and deep gullies, a tidal range of 3,80 m at Vlissingen and 5,50 m at Antwerpen; furthermore, the estuary has a funnel-shaped mouth and the sandbanks and saltmarshes grow with the gully system. (werkplaats Zuidwestelijke Delta, 2013) According to the Water Framework Directive, the type and status of the Western Scheldt is O2 Estuary with a moderate tidal difference and highly modified. The impact of the modifications is on the hydro-morphology; including deepening of gullies, sediment supplementations, along the entire shoreline dykes have been built and the rise in freshwater from the Scheldt river. (Rijkswaterstaat, 2009)

3.1. WBI2017 instruments

3.1.1. Background

''Wettelijk Beoordelingsinstrumentarium voor de beoordelings Periode 2017-2023'' or WBI2017, contains the prerequisites for the assessment of the hydraulic loads and the strength, and the procedural regulations for the safety assessments focussed explicitly on primary water defences. (Waal, 2016) The WBI 2017 gives the knowledge, insight and instruments for the first cycle (2017-2022) described by Waal, (2016) for ensuring the water safety; Ensure that the primary barriers meet the safety requirements by ongoing care from the governing bodies Rijkswaterstaat and the regional water authority Scheldestromen. Second re-assessing the defences when a change in norm, insight in the loads, or strength. The re-assessment is the legal assessment for water safety or ''*Wettelijke beoordeling waterveiligheid''*, periodically at least once every twelve years. The results will be the starting point for adaptation and improvement measures within the reconstruction programme ''*Hoogwaterbeschermingsprogramma*'' or HWBP. Lastly, a periodical re-assessment of the goal and norm on their implementation based on the current societal accepted flood risk. In the WBI 2017, there are a few prerequisites implemented, including systematically taking the uncertainties for assessing the hydraulic loads and the strength of the barrier into account during calculations of flood probability. (Waal, 2016) As well as taking mechanisms and water systems equally into account.

3.1.2. Probabilistic vs deterministic

Nederpel, Kolen, Hofman, & Fraikin (2009) mention two calculation methods for hydraulic loads deterministic and probabilistic. The deterministic approach uses a pre-determined combination of factors such as wind and precipitation, that are predominant on the barrier. Whereas, the probabilistic approach calculates a combination of representative combination, based on the probability of occurrence. The calculation gives a hydraulic load and the probability, which in turn determines the absolute load and its probability. The WBI instruments use the probabilistic approach for the calculations, as it is the current standard for safety calculations. Performing the probability calculation within a WBI2017 assessment instrument is either probabilistic or a semi-probabilistic. (Waal, 2016) The *probabilistic* calculations result in the form of probability. Whereas, *semi-probabilistic* calculations lead to a test score by pre-calibrated values of the strength and loads. However, in hydra-NL, the output will be the probabilistically calculating the expected hydraulic load level in m+NAP for the return periods instead of the failure probability.

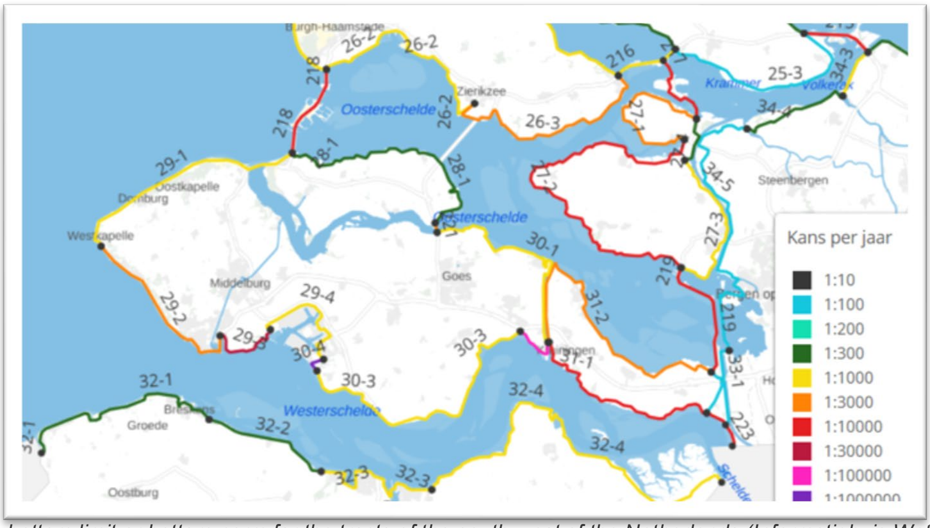
3.1.3. Statistics and uncertainties

Uncertainties, Waal (2016) states that to take all uncertainties into account on an equal basis requires a systematic use of probabilistic calculations methods, specification of the conditions for each test section and explicate specification of the uncertainties or stochastics. The uncertainties are divided between Inherent uncertainty, in time or space, and knowledge uncertainty, statistical or from the model. The calculations within the WBI2017 are based on several *''kansvariabelen''* or stochasts, divided into discrete and continuous stochasts. (Waal, 2016). *Discrete stochasts*, the discrete stochastic, such as wind direction, are those that have a finite number of possible realisations or calculations. (Waal, 2016) The calculation generates several probabilistic values. *Continuous stochasts,* the majority of stochasts are described as continuous stochasts, including the wind speed and water level; these do not

have a finite number of options. The calculation for the continuous stochastic variables generates a probability density.
The calculation method, as described by Waal (2016), has for each discrete stochastic a probabilistic calculation based on the addition of continuous stochasts together to find the failure probability taking the realisation of the discrete stochasts into account. For most calculations within the dyke sections or ''dijkvakken,'' a detailed test is used. It will often lead to a semi-probabilistic calculation for a combination of continuous and discrete stochastics.

3.2. Safety requirements or *''Faalkanseisen.''*

The *Waterwet* (2014) gives the safety requirement for all primary defences' safety, at a period of twelve years, then reported to the minister of Infrastructure and Water Management and parliament (Chbab, 2015). The basis of the assessment is the probability of failure under hydraulic loads; each barrier needs to withstand a specific norm to pass the tests. Waal (2016) states that such assessments of flood probability define failure as the transgression of the boundary state, caused by a failure mechanism or a combination of multiple. See Appendix 1. ''Faalkanseisen'' and Map 1 for the current norms, focussing on the signalling value and bottom limit.



Map 1 The bottom limit or bottom norm for the tracts of the south-west of the Netherlands (Informatiehuis Water, 2020)

3.2.1. Laws and regulations

The safety norms of a dyke segment are laid out in the Water Act update from 2014 ''Waterwet'', forming the basis of the National Water Plan 2016-2021 and the yearly Delta Program. The signalling value and bottom limit, as seen in appendix, Appendix 1. ''Faalkanseisen'' are of importance to the research. Transgression of the signalling value is often an early sign towards reinforcing a flood defence. (Ministerie van Infrastructuur en Milieu , 2016) Transgression of the bottom limit is the point where the dyke segment does not meet the maximum allowable flood risk or failure probability (Ministerie van Infrastructuur en Milieu , 2016). The 2014 norms/safety levels with the current system of dykes and flood defences systems will remain the basis for any future flood risk management, as stated in the National Water Plan, 2016-2021. Optimising the estuary with the current using flexible solutions whenever possible. (Ministry's of Infrastructure and the Environment, and Economic affairs, 2014)

3.2.2. The background of the norms

The base safety norm is derived from three factors, the Local Individual Risk (LIR), the social cost-benefit analysis (MKBA), and the group risk. (Vrijling, Schweckendiek, & Kanning, 2011) The government's goals are for all inhabitant behind the dykes to have a protection level of 10^{-5} per year through the LIR. The LIR is defined as the chance each year of mortality at a specific location caused by flooding, taking possible evacuation and flood scenarios into account. (Ministerie van Infrastructuur en Milieu, 2016) The LIR is harmonised with the MKBA to find the maximum allowable flood probability. The economic optimal protection level is dependent on de economic damage due to a flood and the costs made to decrease the probability, based on an MKBA. (Vrijling, Schweckendiek, & Kanning, 2011) Lastly, the group risk is a dependent probability of flooding of segments, the number of casualties and the dependability of the segments to each other. (Vrijling, Schweckendiek, & Kanning, 2011)

3.3.3. The safety requirements.

Taking the allowable flood risk of a dyke segment or the norm from the method, dividing the test segments ''*Faalkansbegroting''* so that per segment, it takes the length effect into account, giving a norm for each segment. The dyke segments 26-32, 216, 217, 219, 222 and 223 encompass both the Eastern and Western Scheldt, thus the geographical focus area of the thesis research. In the project ''*Veiligheid Nederland in Kaart vnk,*'' the risk for each of the dyke ring was calculated using a research model (with other model uncertainties and failure mode descriptions). The WV21 and VNK provided the information which was needed to determine the new safety levels for the Netherlands, in the current *''Waterwet''.* The VNK mapped the signalling norms and the bottom limits of all primary dyke rings, whereas in the current law uses dyke segments. The difference between segments is due to the distribution of the acceptable failure probability of dyke ring structure, which is established. (Vrijling, Schweckendiek, & Kanning, 2011) These are then further divided by establishing an acceptable probability of failure per mechanism for that segment, then adding in the length effect to come to the dyke segment requirement. (Vrijling, Schweckendiek, & Kanning, 2011)

3.3. The climate scenarios

Climate scenarios are at the basis of calculations, and the main question, the Netherlands currently use the KNMI'14 scenarios (for most policy analysis) though a re-assessed version is expected in 2021. (Hurk, et al., 2014). The scenarios take a set of several consistent variables into account for a time-horizon, also referred to as sight years, assessed by both linear and non-linear models. (Hurk, et al., 2014) Sea-level rise data comes from the so-called PSMSL data or Permanents Service for Mean Sea Level. (Hurk, et al. 2014) The data comprises of measurements from 6 stations along the coast, including Vlissingen, for the period 1901-2012, corrected for tidal effects. Hurk, et al., (2014) state that the sea-level scenarios are a derivative of two analyses, one of the CMIP5 model archive and then a detailed analysis of the various processes with their uncertainty and relative contribution. The scenarios take several processes into account, though disregard the change in surface elevation, thus resulting in absolute sea-level changes. The processes show a slow varying trend, and faster-fluctuating components both of these undergo considerable uncertainty, Hurk et al., (2014) explains the three main reasons for uncertainties. The reasons are as follows; natural variability, ensemble spread, and model uncertainties. Though with the uncertainties in mind; an approximation of the sea-level rise was made for complete and separate processes, see Appendix. 2. The climate scenarios.

3.3.1. KNMI'06 scenario's

KNMI (2006), gives an estimate of absolute sea-level rise by 2050 to be 15 to 35 cm, and by 2100 35-85 cm, see appendix 2.1. KNMI'06. In figure 4, an overview of the expected changes to the climate that form the basis of the climate scenarios used here in the Netherlands—expecting that in the most significant sea-level rise occurs in W⁺.

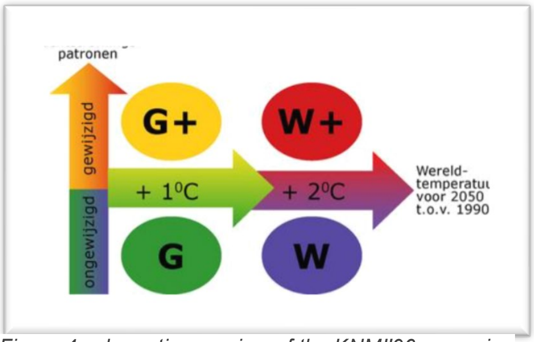


Figure 4 schematic overview of the KNMI'06 scenarios (KNMI, 2006)

3.3.2. KNMI'14 scenario's

The analysis for the 2014 scenarios results in a global average and one for the North sea, separated in Low and High scenarios referring to the difference in sea-level rise between the G-scenarios ''L'' and W-scenarios ''H'', see Table 1.

Table 1 KNMI'14 Sea-level scenarios range Global and North Sea (concerning 1995, for the reference period 1985-2005), The values are from a 5-95% uncertainty range, rounding to 5 cm precision (Hurk, et al., 2014)

KNMI'14 scenario	Low (2050)	Low (2085)	High (2050)	High (2085)
dT_{glob}	+1.0°C	+1.5°C	+2.0°C	+3.5°C
Global mean	15 to 30 cm	30 to 60 cm	20 to 35 cm	45 to 75 cm
North Sea	15 to 30 cm	25 to 60 cm	20 to 40 cm	45 to 80 cm

3.3.3. OI2014 scenario's

The *''Ontwerp instrumentarium 2014''* or OI2014 takes climate change into account in determining the design load during the planned longevity of a dyke. (Rijkswaterstaat, 2015) (Rijkswaterstaat, 2015) (Rijkswaterstaat, 2015) Each designed longevity takes the scenario W⁺ into account, though its effects are smaller in shorter longevity periods. Rijkswaterstaat states that a dyke design has to meet the requirements related to the W⁺ at the end of the design period though basing it on milder scenarios is allowed if the dyke can be adapted. (Rijkswaterstaat, 2015) The KNMI scenarios which are included in Hydra-NL are those of 2006, as they do not vary significantly for sea-level rise in coastal systems, and therefore, were not updated. Smale (2019), states that there are no new formal Eastern Scheldt databases as it was not available at the time of publication. The Western Scheldt uses the Hydra-NL 2.4.1 and the WBI2017 databases.

Table 2, shows the applied sea-level rise quantities of Hydra-NL, which compared to the end

Scenario	Zeespiegelstijging t.o.v. 2017 (m)
2023 – KNMI2006 G	0.00
2023 – KNMI2006 W+	0.00
2050 – KNMI2006 G	0.05
2050 – KNMI2006 W+	0.25
2100 – KNMI2006 G	0.25
2100 – KNMI2006 W+	0.75

of the range in Table 1 are more conservative though fall within the uncertainty presented.

Table 2 The expected sea-level rise in the OI2014 scenarios in meters compared to the sea-level of 2017 (Duits, 2019)

3.4. Hydraulic loads and failure mechanisms

The hydraulic load level[4], the minimal required crest height and the critical overtopping Overtop discharge are essential for assessing the safety of a dyke. (Rijkswaterstaat, 2015) The minimal required crest height is used to assess the meeting of safety standards. Which is Assessed based on the hydraulic loads Rijkswaterstaat states that the resulting crest height requires the transgression probability of the critical over top speed to be lower than the failure norm on the cross-segmental level. (Rijkswaterstaat, 2015) In Figure 5, the minimal required crest height and the variables for an example test are shown; it is the point where the wave height reaches. However, the figure is outdated and somewhat simplified, at the moment the *''toetspeil''* is not used anymore for the hydraulic load level calculation. Also, though Riskeer the WBI and OI include grass erosion of the crest and inside slope next to the hydraulic load level. Added on to the minimal required design crest height is a margin for subsidence and settlement, though this does not happen during the assessments.

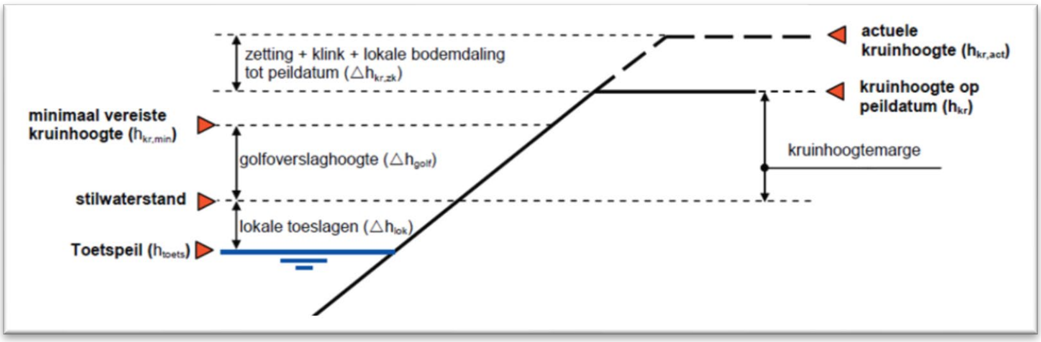


Figure 5 The actual crest height and Dutch names of several example variables for the calculation of the height. **(STOWA, 2007)**

3.4.1. Hydraulic loads and basis stochasts

The hydraulic loads are mainly composed of, the physical relationship between the water level and the wave for a significant number of a location near primary defences. The driving forces, including wind, the statistics behind the mechanisms, and of the knowledge uncertainties around the hydraulic load. (Waal, 2016) A hydraulic load of water levels, and wave conditions, have an inherent uncertainty due to the natural variability, included in the calculation methods of WBI2016 instruments. (Chbab & Waal, 2017) Parameters concerning them include (Chbab & Waal, 2017) & (Waal, 2016); the water level [m+NAP], significant wave height H_s [m], the peak period T_p [s] and the average wave direction.

In the case that there is no (measured) information available such as local water-level, then information is taking from statistics related to physical relations between local hydraulic loads, a random probabilistic stochastic or the source of local hydraulic loads. (Waal, 2016) The Western Scheldt has the following relevant basis stochasts, wind (direction and speed) and water level, for the Eastern Scheldt, wind (direction and speed), water level and the condition of the storm surge barrier, according to Waal (2016). These parameters are used by hydra-NL to calculate the hydraulic load level, presented in chapter 5.

Wind; The wind is one of the primary forces creating waves and therefore a vital part of water systems, especially influencing the high water levels. The quick stochastic composes of two components the wind direction and speed, fluctuating in a relatively short

[4] The hydraulic load level in m+NAP is the sum of the local water level and the wave overtopping height

period. The wind direction is a discrete stochastic, calculating for 16 known number of possible realisations based on the north as 0°. (Waal, 2016) Each realisation represented the sector around it and generated in a table. However, wind speed is a continuous stochastic; a KNMI measuring station facilitates the statistics. The measuring stations of the wind statistics used in the thesis are at Cadzand 51°23’00.0’’N 3°23’00.0’’E and Vlissingen 51°27’00.0’’N 3°36’00.0’’E. (KNMI, 2016) Cadzand is an alternative for Vlissingen, as it is less sheltered the thesis will take a look at the difference in results for the two.

Water level (sea), the water level is another quick stochastic, diurnal variations due to the tides, with spring and neap tides. In the water system type ‘’Zee’’, includes the Western Scheldt, the statistic for water level is not determined the same way as wind and other stochastics; instead, it is using a triangular interpolation[5] of the statistic of three reference locations. (Waal, 2016). Whereas for the Eastern Scheldt uses the model WAQUA. (Ministerie van Infrastructuur en Milieu , 2016) SWAN[6] models are used in both the Eastern and Western Scheldt. (Ministerie van Infrastructuur en Milieu, 2016)

3.4.2. Failure mechanisms

There are several failure mechanisms associated with the failure of a dyke, see Figure 6, with the most important to the thesis being overflow and overtopping[7]. During the calculations, an overflow debit of 5-10 l/s is assumed, for the wave run-up and overtopping discharge. During an overtopping event, the crest height is lower than the level of the highest waves, cause water to flow over the dyke. (Meer, 2002) Other combinations of factors can cause an overtopping event such as the water level, in combination with the wave height, or combined with the wave-runup height, could cause overtopping as well. A high water level often causes the overtopping when combined a high wave height; as sea-level rises, the overflow can occur more frequently even at the same wind speeds. The wave run-up height is measured compared to the calm waterline, where the number of waves that transgresses the level 2% all incoming waves. (Meer, 2002) When the waves overflow, they can infiltrate and erode the inner-dyke and cause it to fail. Relating these to the water level and the impact of the dyke coverage will result in a required crest height for each dyke section.

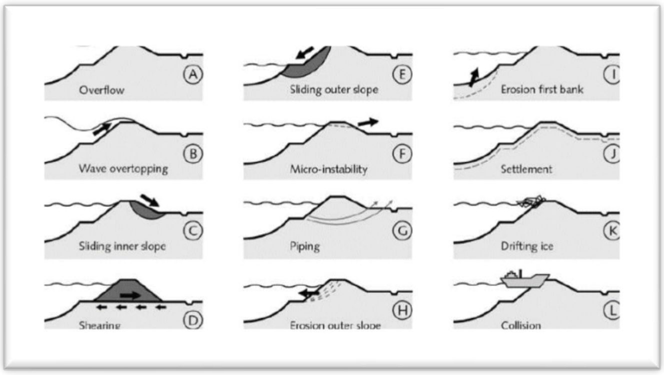


Figure 6 The most critical failure mechanisms of a dyke (Vrijling, Schweckendiek, & Kanning, 2011) & (TAW,1998)

[5] Triangular interpolation uses three points to derive the statistical information on local bias within the range of the data points with the assumption of relationship between the data, to get a local gradient on for example windspeed. (Watson & Philip, 1984) & (TU Delft, 2019)
[6] SWAN is a wave model, developed at Delft University of Technology, that computes random, short-crested wind-generated waves in coastal regions and inland waters (SWAN, 2020)
[7] The overtopping discharge is measured as average discharge per metre along the dike.

3.5. The cross-sectional specific failure norm

Assessing the dyke segments on the required safety norm is a somewhat simplified version, during a detailed test on the hydraulic load level, a cross-sectional failure norm is used, which is often several times stricter than the required safety norm in appendix 1. Two components of such a cross-sectional norm are mentioned by Kok, Jongejan, Nieuwjaar, & Tánczos, (2017) the failure probability of a segment is affected by the Length effect and the interdependencies of the failure mechanisms.

The failure mechanisms relate to the failure probability budget mentioned in figure 7. The required failure probability at the cross-sectional level can be calculated in two steps as described by Kok, Jongejan, Nieuwjaar, & Tánczos, (2017). First, the required failure probability per mechanism at the segment level is determined, which is subsequently translated to the required failure probability for a representative cross-section. The standard flood probability is divided between different mechanisms, 10 per cent piping, 24 per cent on the height, adding all of them up to 100 per cent. (Knoeff & Bree, 2016) The division is made based on the importance of a mechanism; for example, piping and macro stability are assumed to be of substantial importance in the estuary; therefore, they have higher percentages. The division in figure 7, has the standard norm 1 in 1000 is divided, a mechanism with 10% gets a norm of 1 in 10.000. The remaining 90% is divided between another mechanism which creates their mechanism-specific norm. The division of failure mechanisms is of importance to the testing as there is no complete software to perform an in-depth analysis of all mechanisms at the same time. Therefore, a stepwise method in the calculation is used when calculating the required failure probability at the cross-sectional level.

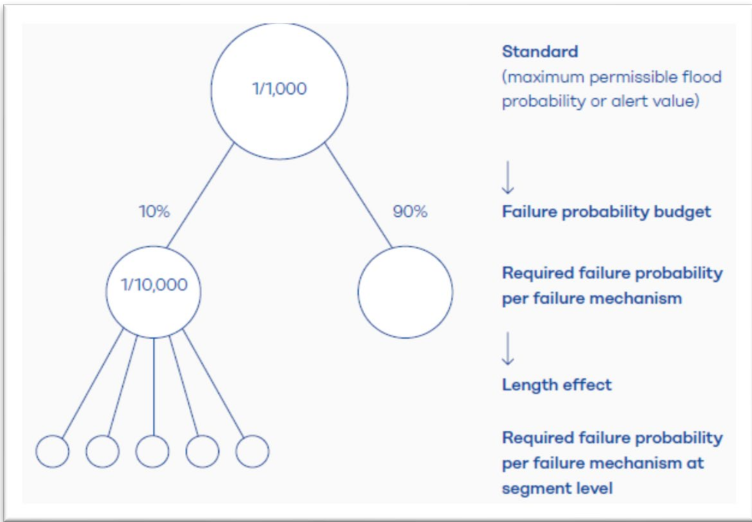


Figure 7 An example of going from the standard to the required failure probability per failure mechanism for a representative cross-section (Kok, Jongejan, Nieuwjaar, & Tánczos, 2017)

Then the length effect; A levee system is comprised of several defence structures which resemble the links in a chain, and the chain is only as strong as its weakest links. Kok, Jongejan, Nieuwjaar & Táncos (2017) further explain that if one of the links fails, the entire system fails. Therefore, the length effect is defined as *''The probability that a long stretch of the levee will fail at some point is higher than the probability that a segment will fail at one specific point.''* The length effect for a specific failure mechanism is converted to a probability by dividing the segment into a section with the same properties. From this, the failure probability per section based on representative cross-sections is calculated, which is then put as the probability for the entire section. The probabilities for all sections are then combined, producing a failure probability for the entire segment.

Chapter 4. The method

The method of research is a combination of literature-based desk research to understand the background and improve interpretations and data-analysis. In addition to the literature, a software analysis took place; which is mainly quantitative. After a round of calculations, analysis of the results took place, evaluating the outcomes to find which sections to highlight. A relevant dyke segment is when it experiences high hydraulic load levels, or a dyke segment does not show the expected levels—therefore reasoning the causes behind the results. In addition to the hydraulic load level per calculation, a comparison between the two wind statistics was made using the standard deviation function in excel for the selected location. In the end, it serves to answer what is the impact of sea-level rise on dyke safety along the Scheldt estuary for the sigh years 2015-2050-2100, and what does a different wind statistic mean for the Western Scheldt's required dyke heights.

4.1. Hydra-NL

4.1.1. Background

Hydra-NL is a model creates as an assignment from Rijkswaterstaat. It is one of the WBI 2017/ OI instruments for assessing and designing the safety of our primary water defences. In chapter 6. Discussion, the choice of software, is explained further. The research uses the WBI2017/ OI to give an overview of the effects of sea-level rise and the associated wave action on the safety of the dykes. By using the design mode or ''*ontwerp modus,*'' several variables can be calculated, under which the water-level, hydraulic load level and wave action on the dyke geometry and roughness, for different climate change scenario's see Appendix 3. Workflow diagram, for an overview of the steps.

4.1.2.The Data input

The data encompasses dyke profiles, and shapefiles, made available by the Waterboard Scheldestromen, see figure 8. The wave run-up shapefiles consist of the X and Y coordinates, location names, dyke ring numbers, ID and the profile files' name, related to each location. Lastly, a more comprehensive database per dyke segment is requested and downloaded from the Helpdesk water.

```
VERSIE   4.0
ID  P000155
RICHTING  80.00
DAM   0
DAMHOOGTE  0.0
VOORLAND  0
DAMWAND   0
KRUINHOOGTE  12.22
DIJK  4
-37.47  -0.42  1.000
94.58  7.13  1.000
100.12  7.45  1.000
148.97  12.22  1.000
MEMO
invoergenerator waterschap Scheldestromen met profielen uit
Toetsing2010
```

Figure 8 *Example of profile supplied by the water board*

4.1.3 Dyke profile

Using the software *Profielgenerator* or profile generator, a new shore location file is created by filing in the X- and Y-coordinates, location name, dyke height and orientation. Arcadis created the software at the request of Rijkswaterstaat. It generates the work folder with the same set-up as those generated by hydra-NL, thus making it easier to combine the two. Next, the coordinates from the waterboard data and the corresponding hydra-NL database are compared in Riskeer, to find the profile which corresponds to the location in de database. The coordinates and names are taken directly from the database, whereas the height and orientation are from the corresponding profiles. To open the sub-folders within hydra-NL's a water level calculation is performed for each track which opens up a folder for each location within the full work folder. Combining the created hydra-NL folder and the one from the profile generator, allows for the importing of Hydra-NL profiles and shapefiles, to generate a work folder combining it with the work folder from Hydra-NL.

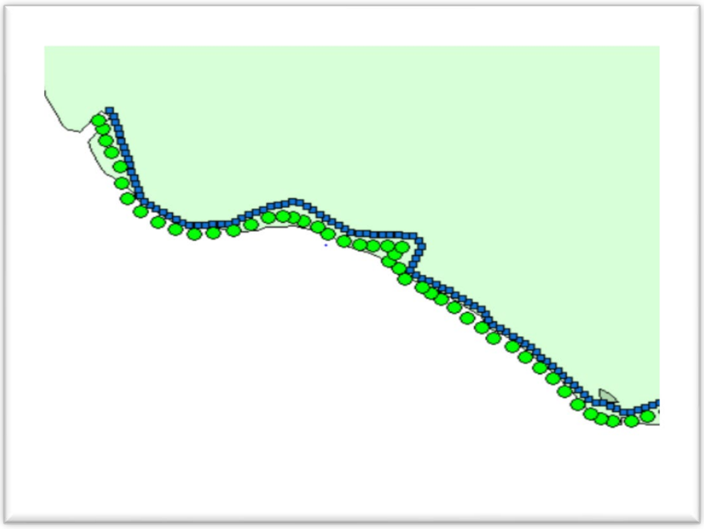


Figure 9 A section of dyke segment 30_3 in the Western Scheldt showing the difference between the database locations (green dots) and the locations from the Waterboards shapefile (smaller blue rectangles) presented in hydra-NL

The combined folders create the ''*Verkenner''* or file manager within Hydra-NL. Each location is now visible with a corresponding profile. These profiles need to match the requirements of Hydra-N: checking them and if needed editing to match the requirements with the profile editor tab. Missing profile data is supplemented by comparing the coordinates of each location to the *''Actueel Hoogtebestand Nederland''* or AHN to find the closest height of the dykes. The orientation is then based on a protractor with the north at 0°. This method was used on the south side of the Western Scheldt; the dyke height will show slight changes to that of the actual situation. The most significant difference is that of the orientation as this is based on maps and not a measured orientation. The supplementation of data though less exact does serve towards the purpose of the thesis. The remaining dyke profiles are often outdated, as indicated by the waterboard the last measurements took place in 2010, thus lacking the most recent reinforcements or adjustments to the profiles—the segments comprising of primary defences in the form of dunes. The most substantial limitation of this method is that hydra-NL has a limited number of locations within the database, as the waterboard supplied more data points. However, the database encompasses enough data points for the thesis, but the limitation is kept in mind for the analysis.

4.1.4 The calculation steps

The calculations were started using tab ''Dijkvakberekeningen'' in which the tab parameters allows for selecting the sight year the three parameters. In the tab the calculation is given a name, ''WS 2023 W+'', showing the parameter, sight year and climate scenarios. The output consists of an excel file, and a comprehensive HTML file provides more context to the results in the excel file. This file included the contribution of wind directions, wind speed, and water level, to name a few, the file is specific to the location. In contrast, the excel file summarises all locations for all calculations.

Water level.

The Water level calculation is relatively simple compared to the others; in this calculation, the hydraulic load level in m+NAP is calculated for the change in water level alone. This calculation is limited, but it serves to better understand the hydraulic load level calculation as the change in sea-level influences it. Originally the wave action on dyke geometry and the cover was also calculated; however, this calculation was excluded as they did not add any additional value.

Hydraulic load level.

The Hydraulic load level or ''Hydraulisch belastingniveau'' has two failure mechanisms associated with it the 2%-wave run-up ''2%-Golfoploop'' and the water overtopping and overflow ''golfoverslag en overloop''. (Duits, 2019) The former is not used as much; therefore, the latter was chosen for the calculations. Using the second failure mechanism, golfoverslag and overloop for the assessments, and the overtopping discharge was assumed to be critical at either 5 or 10 l/s/m for the calculations. Even though the critical overtop discharges are often calculated at 0.1; 1 and 10 l/s/m, a flow rate of 5 l/s/m was favoured to decrease the increment between the two discharges. This difference does not affect de validity of the results, as the purpose is to give a more general insight rather than an in-depth test/assessment which would require multiple discharges and calculations.

4.1.5. Data analysis

The data analysis was performed within excel, using both a quantitative statistical test and qualitative tests in a data comparison format. Each dyke segment has a complete file, of the results for the two tests for the years 2023, 2050 and 2100. The full pivot tables per dyke segment are shown in Appendix 8. The pivot tables of raw hydra-NL data In the case of the Western Scheldt, there are two files per segment, one for each of the wind statistics used, though they were combined for the analysis and the appendix 5. Using a pivot table the return periods were represented in the rows, with the locations as the columns. Within the table, the results were summarised per calculation in two ways; first, the averages and maximums for the entire segment, and secondly by the bias between the two wind statistics for each segment and the three years. The difference is calculated per segment in excel, deducting the reference or Vlissingen from the new results or Cadzands indicating the results in meters difference.

Average Hydraulic load level [m+NAP]/ Wave parameter [m]/[s]/ Strength dyke cover [-]	Location				
	WS_1_29-3_dk_00002				
	OI2014_2023_W+				
	Cadzand				Vlissingen
	Wave conditions	Flow rate [l/s/m]		Water level [m]	Wave conditions
Return period [year]	[-]	5	10	-	[-]
30	0.29	4.952	4.775	4.173	
100	**0.85**	**5.261**	**5.076**	**4.476**	**0.83**
300	1.07	5.537	5.338	4.756	1.06
1000	**1.23**	**5.832**	**5.628**	**5.065**	**1.24**
3000	1.37	6.082	5.873	5.352	1.37
10000	**1.5**	**6.327**	**6.121**	**5.674**	**1.5**
30000	1.59	6.527	6.331	5.977	1.6
100000	**1.69**	**6.738**	**6.553**	**6.321**	**1.71**
300000	1.79	6.941	6.775	6.642	1.79

Figure 10 Pivot table dyke segment 29 comparing both wind statistics.

A graph was made per calculation, comparing current dyke height in metres to the hydraulic load level results. The data was analysed by filtering on the results for the corresponding safety norm as taken from the *water wet* to compare them against the dyke heights, see Chapter 5. Results. The choice on the required safety norm per segment instead of the same one for all segments was made so that each segment presented results are specific to it. Instead of having all segments corresponding to each other by the same return period, which would make comparisons easier though the results would not correspond to the actual norms. However, in the tables on water level and hydraulic load level, all return periods are presented, whereas in the other tables, graphs and visualisations the safety norm was used. These graphs will show which locations will experience transgression of the dyke height by the hydraulic load level for its norm.

4.2.Visualisation

Next to the tables and graphs created using excel, creating maps to show the hydraulic load levels for each dyke segment using GIS.

4.2.1. GIS

GIS software allows the user to make coherent maps showcasing a lot of data types; in this case, hydraulic load level results at specific locations. The version of GIS used for the maps was the ArcGIS pro 2.5.0 for desktop use. Both the Western and Eastern Scheldt got their project within the folder, in which the edits were made. First of the base map was changed from the world map to the ''*Dijkenkaart van Nederland''* which shows all the dykes and a Dutch topography map as the bottom layer. Adding the shapefiles from Hydra-NL as layers on top of the base map that way, the calculation results and location will correspond. By opening the attribute tables, four rows were added, the current crest heights and the results of 5 l/s/m for 2023, 2050 and 2100. For points in the Eastern Scheldt data was generalised for some dyke sections, for example, the western side of dyke segment 26_2 calculated two to three points per dyke section representing all orientations.

After the data is inserted in the attribute tables, the symbology of the layers was edited to use graduated colours for the classes and label the classes with one decimal number. The same symbology was then used for all layers to get a somewhat consisted overview, by importing the symbology and updating the ranges into each layer. After this is done, the layout is created for each dyke segment, adding in each year separately locking the maps and legend not to change them on accident. Each layout is completed by adding in the previously made graphs, a north arrow and ruler for the distance. As well as, an explanation so that each dyke segments maps page is readable on its own.

Each map is then subsequently used to determine an approximate required crest height per dyke section, by comparing the results to the locations of dyke sections to the index of Delta Expertise, (n.d). The index was mainly used for getting the correct names of dyke sections and the locations corresponding to them. The hydraulic load levels within a dyke section are then compared, and roughly the highest load is chosen and added to the table, see chapter 5. The comparisons are repeated for every section in all significant dyke segments until there is a relative overview of required crest heights of each segment of the estuary.

5.1. Western Scheldt

5.1.1. The north side of the Western Scheldt

Water level calculations

The northern part of the Western Scheldt runs from dyke segment 29_2 to 223, with safety norms ranging from 1 in 1000 to 1 in 1.000.000 years. It encompasses sheltered and non-sheltered dykes, with varying degrees of hydraulic load levels— Appendix 4. Table 1 presents the water level height resulted from the water level calculation for the four major dyke segments. A similar pattern occurs in all segments; there is a slight increase for the sight years though little to no variation between points, see the appendix for the average results. In the graphs for representing the water level calculation, the uniformity over all locations is apparent, as well as the limited increase through time. Results between dyke segments show more deviations from each other; however, this can be explained to the orientation of the dyke sections and their location within the estuary, see the maps for details on their orientation, five are in Appendix 7. The remaining maps and one is below this section.

Hydraulic load level calculations

Where the water level calculations show little variation between locations, nor differences between the wind statistics, the hydraulic load level does result in significant differences between them. Between the two calculated discharges, a minimal difference is observed, with the overtopping discharge of 5 l/s/m resulting in the highest load levels. The results of the 5 l/s/m calculation form the basis of each map. Using the wind statistic from Vlissingen often resulted in lower results which are fairly significant when comparing the averages. Within all dyke segments except 223, there is substantial variation in hydraulic load levels of the locations, is seen in the graphs and maps of each dyke segment. Dyke segment 223 is the shortest presented in table 3; it has the highest load levels of this side of the Western Scheldt, which are relatively uniform throughout the segment though the averages increase as the dyke segments move east. As table 3 shows the averages for the entire segment, Appendix 5. Table 1 gives a general required crest height based on the hydraulic load level per dyke section. Each section of the northern part of the Western Scheldt is shown with varying required dyke heights from 5.5 to 11.5 m+NAP. Comparing the table to the maps below indicate the same locations, for example, the *''Van Citterspolder'',* experience the most substantial hydraulic load levels. Whereas the sheltered *''Buitenhaven Vlissingen''* experiences the lowest level, see Appendix 5. Table 1 for a complete overview of the required crest heights per segment per year.

	Cadzand						Vlissingen					
Discharge	5			10			5			10		
29												
Return period	**2023**	**2050**	**2100**	**2023**	**2050**	**2100**	**2023**	**2050**	**2100**	**2023**	**2050**	**2100**
10	5.088	5.351	5.838	4.933	5.191	5.669	4.73	5.011	5.508	4.579	4.8	5.3
100	5.413	5.670	6.153	5.254	5.501	5.973	5.366	5.637	6.108	5.214	5.414	5.922
300	5.705	5.959	6.444	5.538	5.781	6.252	5.658	5.927	6.395	5.498	5.688	6.197
1000	6.026	6.277	6.772	5.850	6.091	6.572	5.978	6.245	6.718	5.809	5.990	6.511
3000	6.321	6.572	7.091	6.136	6.380	6.886	6.271	6.540	7.032	6.092	6.268	6.821
10000	6.654	6.913	7.473	6.462	6.715	7.264	6.601	6.877	7.410	6.413	6.591	7.196
30000	6.974	7.251	7.847	6.777	7.050	7.636	6.916	7.212	7.780	6.724	6.915	7.562
100000	7.358	7.658	8.281	7.158	7.452	8.068	7.295	7.614	8.209	7.100	7.306	7.989
300000	7.738	8.051	8.694	7.539	7.847	8.479	7.671	8.006	8.620	7.477	7.691	8.398
30_3												
10	4.940	5.511	6.003	4.801	5.343	5.826	5.188	5.435	5.964	5.026	5.277	5.798
100	5.664	6.261	6.760	5.513	6.063	6.554	5.936	6.169	6.706	5.746	5.983	6.507
300	5.982	6.633	7.159	5.832	6.422	6.933	6.290	6.523	7.091	6.086	6.325	6.873
1000	6.301	7.068	7.638	6.154	6.839	7.390	6.688	6.932	7.553	6.470	6.717	7.314
3000	6.590	7.500	8.117	6.436	7.252	7.849	7.077	7.338	8.013	6.842	7.106	7.756
10000	6.928	8.020	8.682	6.761	7.752	8.391	7.544	7.829	8.554	7.289	7.578	8.277
30000	7.268	8.534	9.234	7.093	8.249	8.923	8.013	8.317	9.080	7.742	8.051	8.787
100000	7.680	9.137	9.876	7.503	8.835	9.539	8.569	8.893	9.694	8.283	8.612	9.379
300000	8.084	9.713	10.48	7.909	9.394	10.12	9.115	9.453	10.28	8.815	9.156	9.946
31_1												
10	5.48	5.70	6.23	5.328	5.559	6.084	5.339	5.622	6.154	5.202	5.483	6.015
100	6.376	6.553	7.029	6.207	6.394	6.855	6.213	6.461	6.934	6.058	6.305	6.773
300	6.768	6.943	7.452	6.589	6.769	7.253	6.598	6.837	7.331	6.434	6.669	7.151
1000	7.206	7.403	7.977	7.005	7.204	7.752	7.017	7.270	7.821	6.838	7.082	7.618
3000	7.644	7.884	8.512	7.421	7.659	8.265	7.437	7.717	8.325	7.237	7.508	8.100
10000	8.194	8.474	9.169	7.947	8.221	8.896	7.958	8.269	8.945	7.735	8.038	8.699
30000	8.758	9.078	9.813	8.491	8.797	9.514	8.497	8.841	9.558	8.255	8.591	9.289
100000	9.436	9.786	10.546	9.146	9.474	10.217	9.156	9.520	10.264	8.894	9.248	9.967
300000	10.069	10.440	11.215	9.757	10.095	10.857	9.784	10.159	10.921	9.501	9.863	10.60
223												
10	6.136	6.386	6.885	5.938	6.185	6.694	5.970	6.263	6.774	5.778	6.070	6.590
100	7.141	7.313	7.713	6.935	7.103	7.491	6.967	7.186	7.581	6.763	6.985	7.373
300	7.538	7.704	8.126	7.319	7.472	7.876	7.362	7.560	7.962	7.151	7.344	7.729
1000	7.959	8.167	8.646	7.712	7.901	8.370	7.778	7.987	8.440	7.541	7.740	8.179
3000	8.379	8.644	9.213	8.106	8.355	8.916	8.187	8.422	8.961	7.921	8.148	8.680
10000	8.904	9.262	9.918	8.614	8.948	9.597	8.704	8.989	9.610	8.413	8.694	9.312
30000	9.459	9.904	10.604	9.161	9.573	10.260	9.267	9.585	10.253	8.960	9.276	9.934
100000	10.122	10.645	11.371	9.815	10.29	11.000	9.944	10.284	10.984	9.621	9.956	10.64
300000	10.756	11.300	12.041	10.40	10.93	11.649	10.567	10.921	11.639	10.23	10.58	11.27

Table 3 The calculated average hydraulic load level [m+NAP] for the critical overtopping discharges 5 and 10 l/s/m as calculated for dyke segments in the north of the Western Scheldt, comparing both wind statistics

The occurrence of transgression

Within the northern part of the Western Scheldt the percentage of locations which experience transgression based on discharge 5 l/s/m; increases to 53% by 2100 from 24% in 2023, see Appendix 5. Figure 2. In table 4, the percentages are put in quantified numbers and compared to the wind statistics from Vlissingen. In the case of the northern part of the Western Scheldt, in the current situation, there is little difference between the two. For the dyke segment, 29 one more location would not experience transgression, whereas 30_4 experiences more transgression. It is becoming apparent that the wind statistics influence the segments differently, 30_3 shows fewer locations experiencing transgression, whereas 233 shows no difference in 2100 but more transgression in 2023.

		Cadzand		***Vlissingen***	
		Pass	Fail	Pass	Fail
29	2023	20	2	21	1
	2050	20	2	18	4
	2100	19	3	18	4
30_4	2023	6	0	2	4
	2050	3	3	2	4
	2100	1	5	2	4
30_3	2023	100	0	100	0
	2050	97	3	97	3
	2100	74	26	83	17
30_2	2023	0	13	1	12
	2050	0	13	0	13
	2100	0	13	0	13
31_1	2023	44	34	45	33
	2050	16	62	21	57
	2100	4	74	3	75
233	2023	10	7	8	9
	2050	1	16	3	14
	2100	0	17	0	17

Table 4 The comparison between the number of locations that experience transgression (fail) and which ones do not (pass) for both wind statistics.

The difference between wind statistics

The deviation between the wind statistics based on the water level calculations showed a difference of zero and was therefore excluded from the table. The hydraulic load level calculation does show significant differences between the two wind statistics. The differences shown in table 4 are those between the averages, which would indicate significantly higher differences of 20 to 60 cm. Whereas table 6 shows the average relative difference between the results of both wind statistics. This table indicates that the average differences lay between 0.044 and 0.384 meters or 4 cm to 38.4 cm on average. The majority of locations on the northern side experience differences of 10 to 30 cm, with a smaller difference in the current situation and more extensive by 2100, see figure 11 and 12. On the northern side, some locations results show that Cadzand is slightly lower. The decrease happens specifically in segment 29 and a few isolated locations, though that difference is below 5 cm.

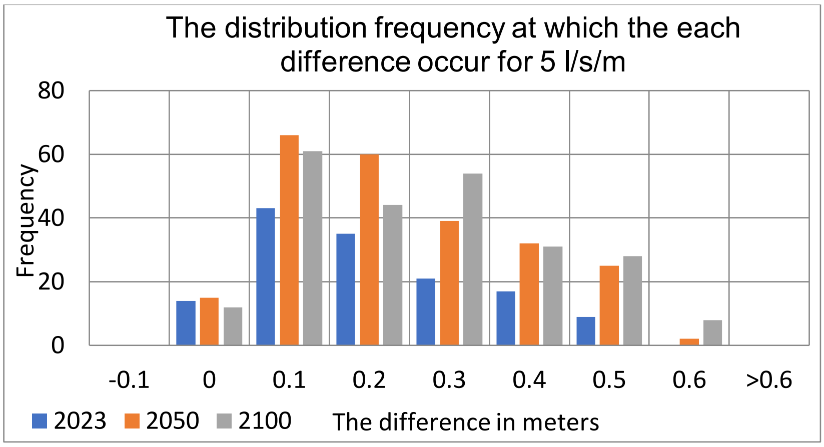


Figure 11 The frequency at which the difference between the two wind statistics in meters occurs for 5 l/s/m

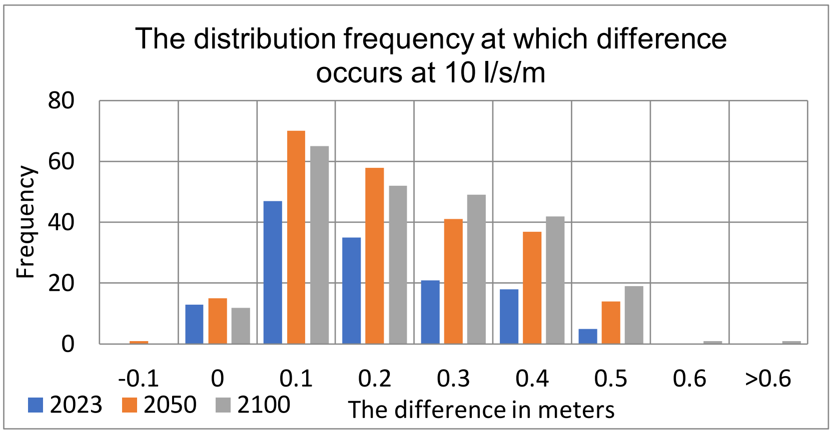
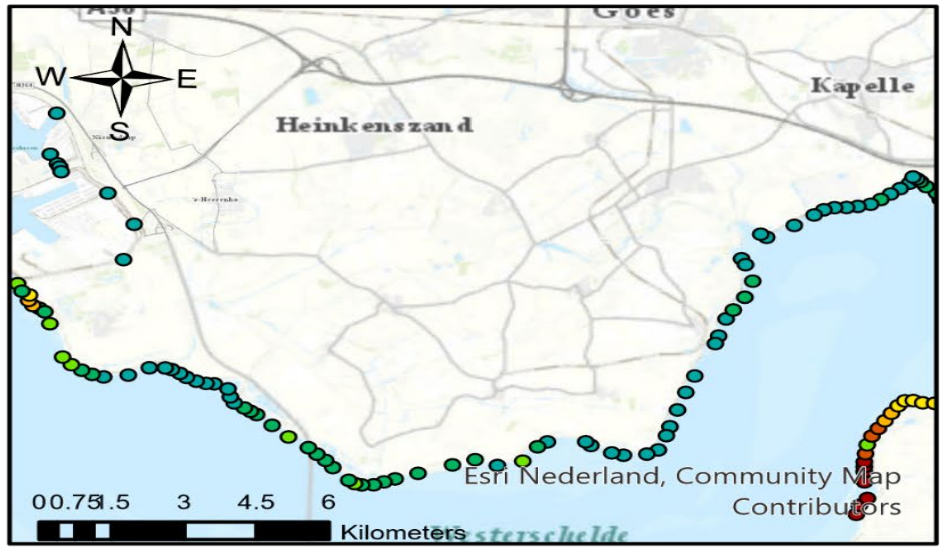
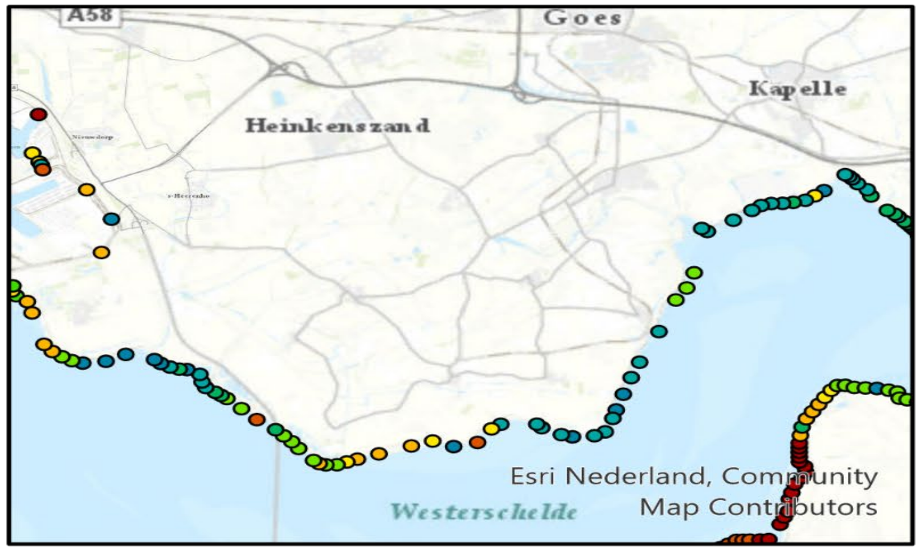


Figure 12 The frequency at which the difference between the two wind statistics in meters occurs for 10 l/s/m

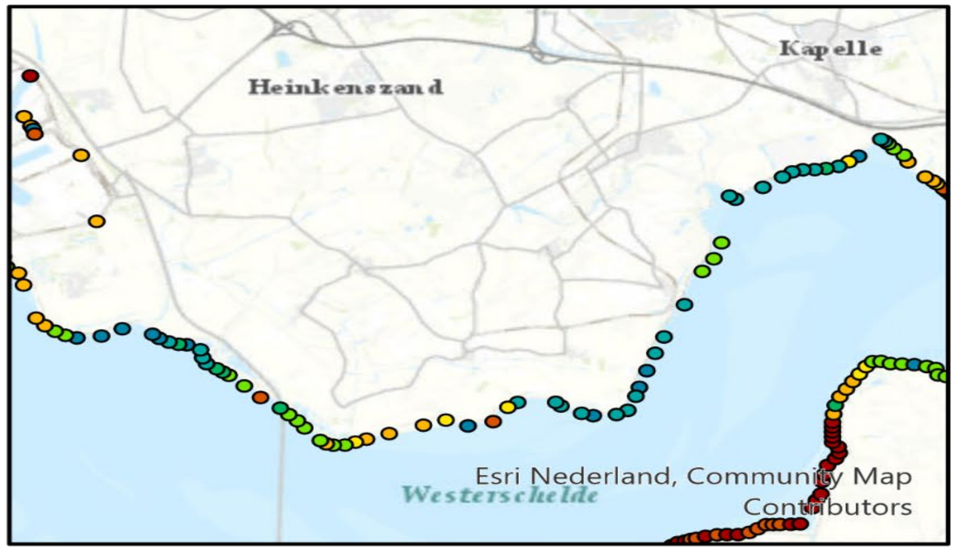
The hydraulic load level results of dyke 30_3 for the years 2023, 2050 and 2100



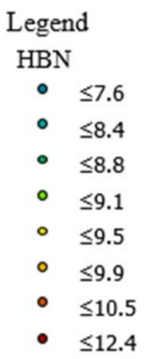
2023

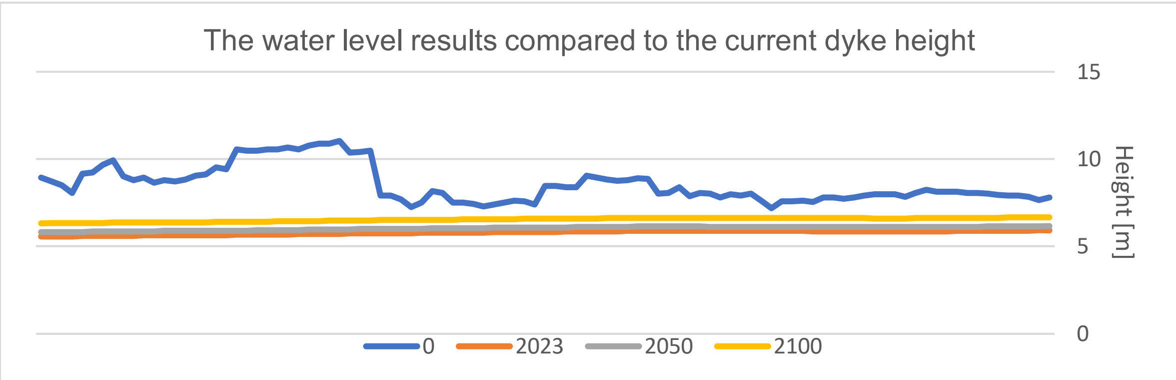


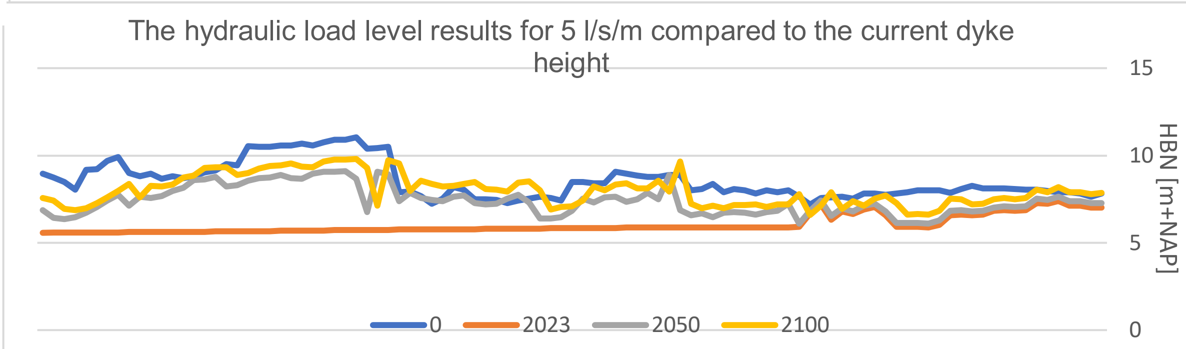
2050

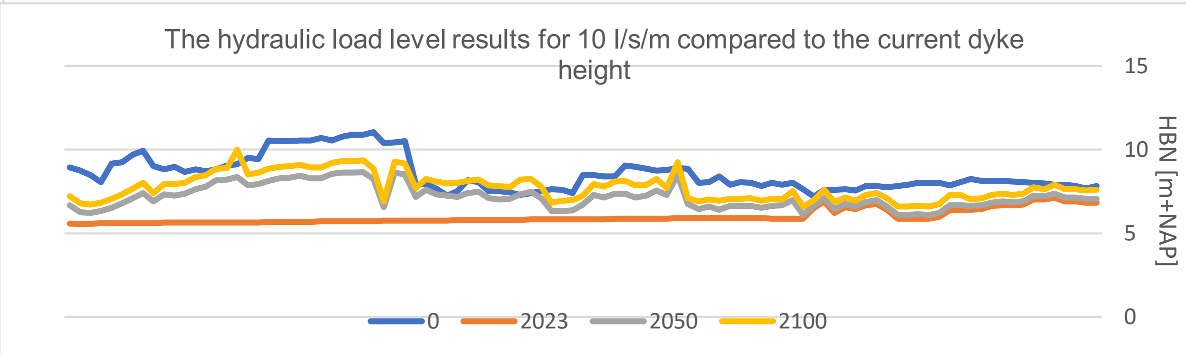


2100



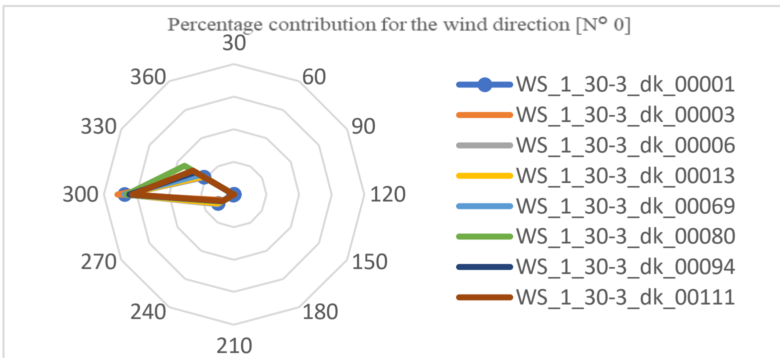






Each of the maps represents one of the calculated years, showing the hydraulic load level in m+NAP based on the critical overflow rate of 5 l/s/m. Dyke section 30_3 is a significantly larger segment compared to the previous two; however, non-uniform distance applies. The distance is not uniform but is presented as such by the x-axis in the graphs. Though as shown in all maps the distances do vary quite a bit between locations. The cause of variations is partly the database used in hydra-NL and subsequently as the layer within GIS. The maps represent all calculated locations, but these do not encompass all of the locations provided by the waterboard. Therefore, the results show a global point of view on the transgression locations. As previously said, the water level calculations have uniform results of all locations, compared to the highly varying results of the critical overtopping discharges.
In the current situation (2023), there no locations that experience transgression of the crest, however, the majority of points in 2023 result in the same hydraulic load level for the water level calculation as the overtopping discharge calculations. The highest experience load level is 7.394 m+NAP; with an average level of 6.590 m+NAP. By 2050 the maximum load level increases to 9.809 m+NAP, and the average increases by 0.910 m to 7.50 m+NAP. However, by 2100 the maximum experiences load level increases to 10.486 m+NAP, and on average to 8.117 m+NAP. The majority of the locations of dyke section 30_3 pass their safety norms now and in the future, with only a few locations showing transgression of the current heights, by 2100 26 of the 100 locations experience transgression. When comparing the differences between the time frames, the most substantial change is between 2023 and 2050 at 0.91 meters. The average relative difference ranges between 0 and 50 cm.

Comparing the wind direction contributions to the dyke orientations does support the higher hydraulic load levels at the locations facing the west and the lower levels of those facing east. The dykes angled towards the west are less sheltered from the wave actions, which is apparent from the maps as well. The highest load levels are seen in sections *Borsselepolder west; Everingepolder van Hattumpolder,* and *Zuidpolder.*



Graphs 1, 2, 3 and 4 The hydraulic load level results of several calculations in m+NAP compared to the current dyke heights, graph four represents the contribution of each wind direction [%].

Maps 2, 3 and, 4 The hydraulic load level results per location on dyke track 30_3, showing the results m+NAP

5.1.2. The south side of the Western Scheldt

Water level calculations

The southern part of the Western Scheldt runs from dyke segment 32_1 to 32_4, with safety norms ranging from 1 in 1000 to 1 in 3000 years. Segment 32_1 is excluded from these results as the segment is composed of dunes rather than dykes. The three segments encompass sheltered and non-sheltered dykes, with varying degrees of hydraulic load levels—appendix 4. Table 2 presents the average water level height resulted from the water level calculation at nine different return periods. They indicate minimal increase for the sight years; they are increasing with 0.5 meters at the most. However, the minimal observed variation is a gradual increase in the water levels as the locations move east. In the graphs for representing the water level calculation, the uniformity over all locations is apparent, as well as the gradual increases. Comparing the three dyke segments show that the hydraulic load levels are the highest in 32_4, which is explained by the orientation as the first half is perpendicular to the mouth of the Western Scheldt. Whereas the second half is sheltered, 32_2 and 32_3 are also sheltered to some degree as perpendicular run-up cannot occur; instead, the water comes in at an angle, see the maps for more details, the map for 32_2 is presented in appendix 4.

Hydraulic load level calculations

Where the water level calculations result in little to no variation between locations, the hydraulic load level does result in significant differences between them. The two calculated discharges result in a minimal observed difference, with the overtopping discharge of 5 l/s/m resulting in the highest load levels. Using the wind statistic from Vlissingen often resulted in lower results which are fairly significant when comparing the averages. Within all dyke segments, there is substantial variation in hydraulic load levels of the locations, as is seen in the graphs and maps of each dyke segment. Dyke segment 32_2 shows the smallest amount of deviations between locations, as the dyke orientation changes only minimally. Whereas 32_3 and 32_4 experience more considerable variations as the dyke orientations change more often. Dyke sections in the southern segments of the western Scheldt experience higher load level compared to the northern side; therefore, the required crest heights also increase. Each section in the table below has a crest height ranging between 7.7 to 14.0 meters. Looking specifically at Terneuzen, in segment 32_2 indicated quite high required crest heights of 9.6 to 13.3 meters. These locations are at the outer part of the harbour; through their orientation, they experience higher levels. Segment 32_4 is an example of sections facing towards the mouth of the estuary in the beginning and therefore resulting in significantly higher load levels. While the second half of the segment faces away and therefore results in smaller required crest heights after the *Kop van Ossenisse, s*ee Appendix 5. Table 2.

	Cadzand						Vlissingen					
	5			10			5			10		
	32_2											
Return period	**2023**	**2050**	**2100**	**2023**	**2050**	**2100**	**2023**	**2050**	**2100**	**2023**	**2050**	**2100**
10	5.848	6.215	6.943	5.645	5.996	6.710	5.543	5.888	6.587	5.369	5.705	6.384
100	7.067	7.455	8.219	6.822	7.193	7.939	6.728	7.094	7.833	6.500	6.855	7.564
300	7.662	8.059	8.839	7.404	7.783	8.543	7.303	7.677	8.435	7.054	7.415	8.143
1000	8.326	8.735	9.533	8.056	8.444	9.228	7.939	8.324	9.099	7.669	8.041	8.788
3000	8.949	9.368	10.18	8.670	9.067	9.866	8.535	8.928	9.720	8.249	8.628	9.391
10000	9.651	10.08	10.91	9.361	9.768	10.59	9.208	9.609	10.42	8.906	9.292	10.075
30000	10.31	10.75	11.60	10.01	10.43	11.27	9.843	10.25	11.08	9.527	9.923	10.723
100000	11.05	11.50	12.37	10.75	11.18	12.04	10.57	10.99	11.83	10.24	10.64	11.456
300000	11.75	12.20	13.09	11.44	11.87	12.75	11.25	11.68	12.54	10.91	11.33	12.150
	32_3											
10	6.655	6.973	7.654	6.312	6.624	7.286	6.220	6.542	7.183	5.933	6.247	6.873
100	8.097	8.430	9.152	7.669	7.993	8.694	7.543	7.879	8.549	7.177	7.505	8.157
300	8.804	9.143	9.884	8.335	8.664	9.381	8.196	8.539	9.223	7.795	8.129	8.793
1000	9.587	9.931	10.69	9.073	9.408	10.15	8.931	9.281	9.979	8.488	8.829	9.507
3000	10.31	10.66	11.44	9.755	10.1	10.85	9.616	9.974	10.68	9.136	9.483	10.17
10000	11.11	11.47	12.28	10.52	10.86	11.64	10.39	10.75	11.48	9.865	10.23	10.92
30000	11.86	12.22	13.05	11.22	11.57	12.37	11.11	11.48	12.22	10.55	10.91	11.63
100000	12.69	13.06	13.91	12.01	12.36	13.18	11.92	12.30	13.06	11.32	11.68	12.42
300000	13.45	13.83	14.70	12.73	13.09	13.94	12.68	13.06	13.85	12.04	12.41	13.17
	32_4											
10	6.330	6.692	7.289	6.021	6.379	6.995	6.038	6.351	6.972	5.807	6.112	6.718
100	7.686	8.081	8.691	7.290	7.678	8.320	7.280	7.605	8.248	6.982	7.298	7.924
300	8.370	8.784	9.398	7.933	8.335	8.988	7.906	8.237	8.890	7.576	7.897	8.533
1000	9.147	9.580	10.20	8.662	9.080	9.747	8.618	8.954	9.620	8.250	8.578	9.225
3000	9.883	10.33	10.96	9.350	9.785	10.47	9.291	9.632	10.31	8.889	9.221	9.882
10000	10.72	11.19	11.83	10.14	10.59	11.29	10.06	10.41	11.11	9.616	9.955	10.63
30000	11.51	12.01	12.67	10.88	11.35	12.08	10.79	11.14	11.87	10.31	10.66	11.36
100000	12.41	12.94	13.62	11.73	12.23	12.98	11.62	11.98	12.74	11.10	11.46	12.18
300000	13.24	13.80	14.49	12.51	13.03	13.81	12.40	12.79	13.56	11.85	12.22	12.96

Table 5 The calculated average hydraulic load level [m+NAP] for the critical overtopping discharges 5 and 10 l/s/m as calculated for dyke segments in the south of the Western Scheldt, comparing both wind statistics

The occurrence of transgression

Relating the required crest heights presented to the locations which experience transgression of their crests by 2100 would reach 78%. Putting a number to the number of locations experiencing transgression is done in table 6. By 2100 a total of 219 locations divided among the three-section experience transgression of their crest height. However, using Vlissingens wind data results in 188 locations experiencing transgression. Where 32_3 indicates minimal differences in the number of locations with transgression, 32_4 and 2 show a more considerable amount of locations that will pass in using Vlissingens data. The data based on whether the load level transgresses the crest height, the difference at the locations between the two datasets see Appendix 6. Table 1, figures 13 and 14.

		Cadzand		Vlissingen	
		Pass	Fail	Pass	Fail
32_2	2023	41	6	46	1
	2050	37	10	51	6
	2100	21	26	35	12
32_3	2023	3	61	14	50
	2050	2	62	6	58
	2100	1	63	2	62
32_4	2023	81	89	104	66
	2050	62	108	91	79
	2100	40	130	56	114

Table 6 The comparison between the number of locations that experience transgression (fail) and which ones do not (pass) for both wind statistics.

The difference between wind statistics

The calculated average representing the differences between the two wind statistics on averages ranges between 0.39 and 0.76 meters or 39 cm to 76 cm. Compared to the results of the average hydraulic load levels of table 5, these do differ slightly as the differences range between 30 to 80 cm. The distribution of the frequency at which the differences occur can be seen in figures 14 and 15; they indicate a relatively uniform distribution of relative differences. 2023 had somewhat lower differences compared to 2050 and 2100, as indicated in the table and figure; this also occurred on the northern side. Though on the south side the differences are quite a bit larger, where the north did not experience differences above 0.6 m and the majority lay between 0.1 and 0.3 meters. The south experiences difference of above 1 meter for a selected location in all three segments, as well as a substantial amount of locations experiencing differences of over 0.5 meters

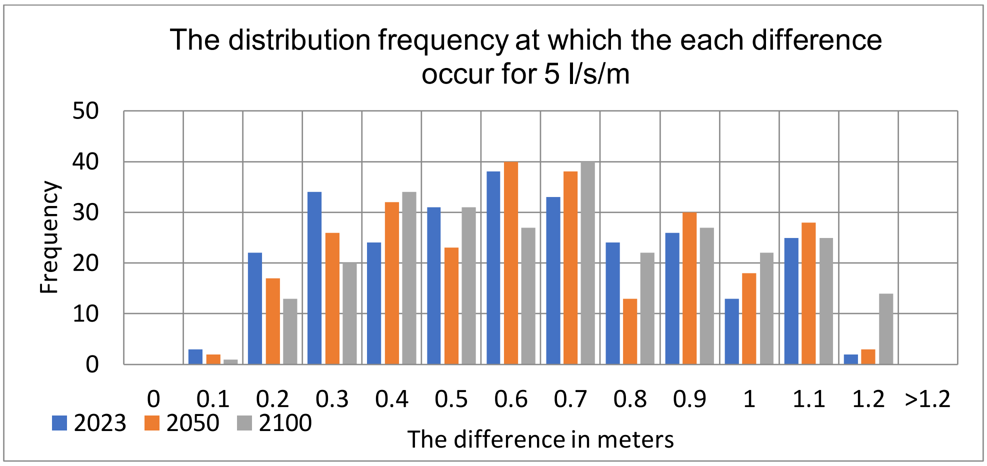


Figure 13 The frequency at which the difference between the two wind statistics in meters occurs for 5 l/s/m

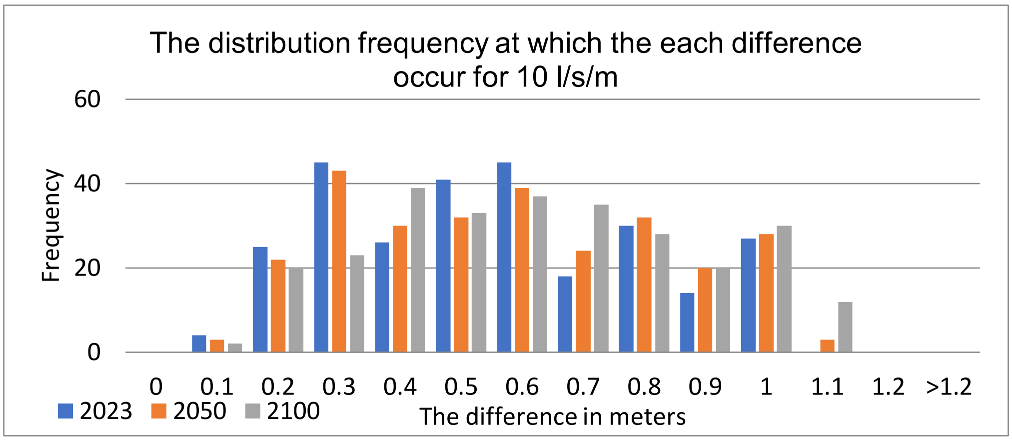
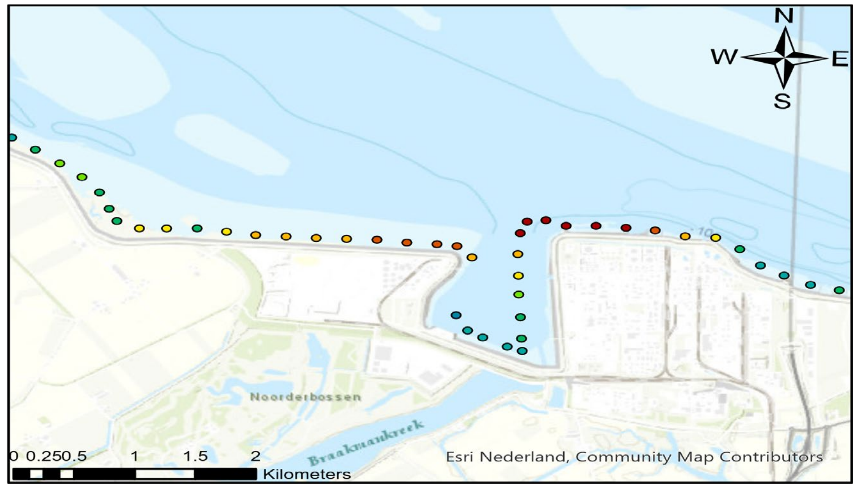


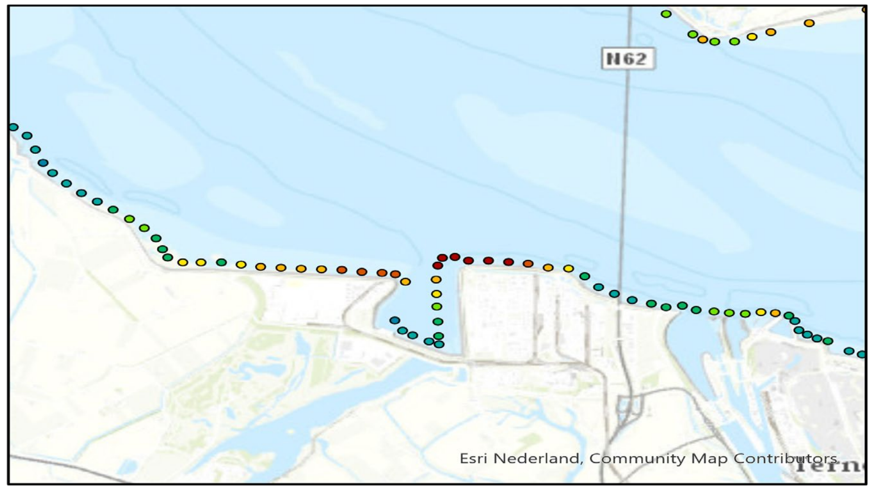
Figure 14 The frequency at which the difference between the two wind statistics in meters occurs for 10 l/s/m

THE HYDRAULIC LOAD LEVEL RESULTS OF DYKE 32_3 FOR THE YEARS 2023, 2050 AND 2100

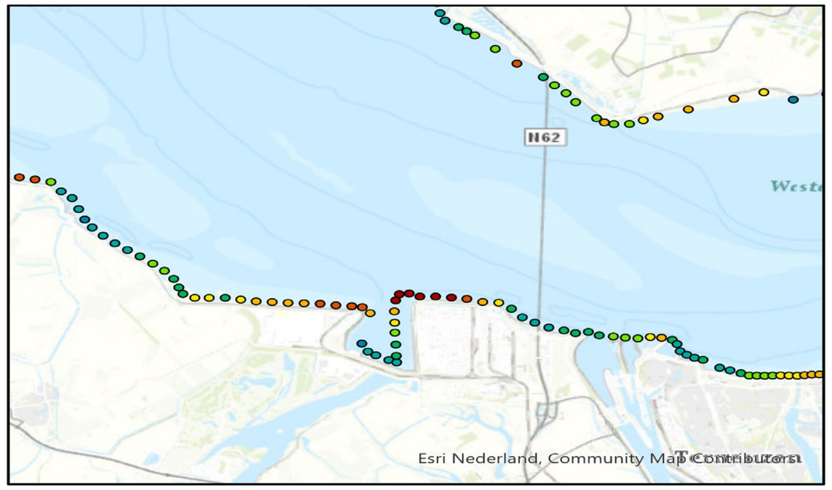
Map 5, 6, and 7 The hydraulic load level results per location on dyke track 32_3, showing the results m+NAP



2023

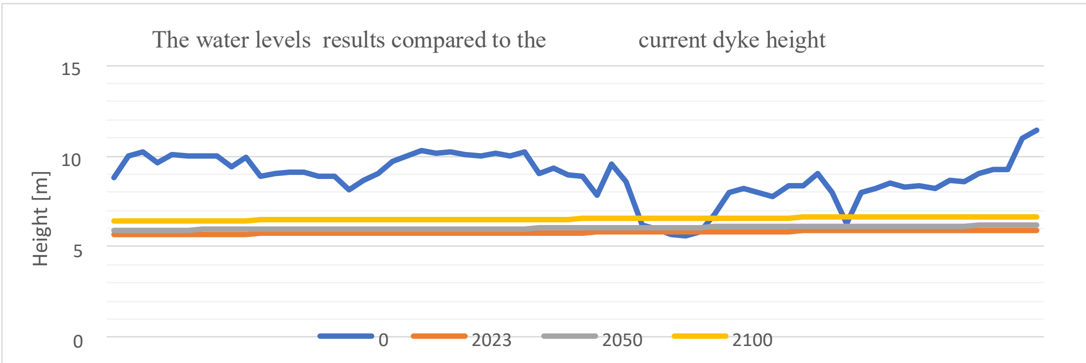


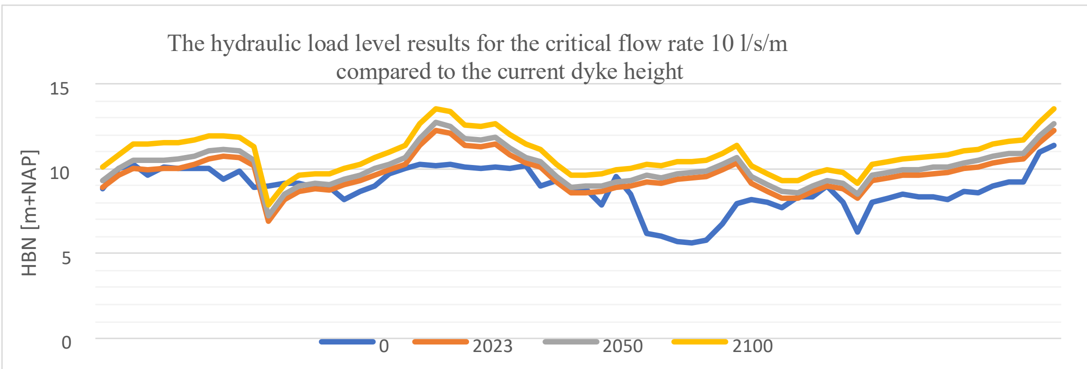
2050

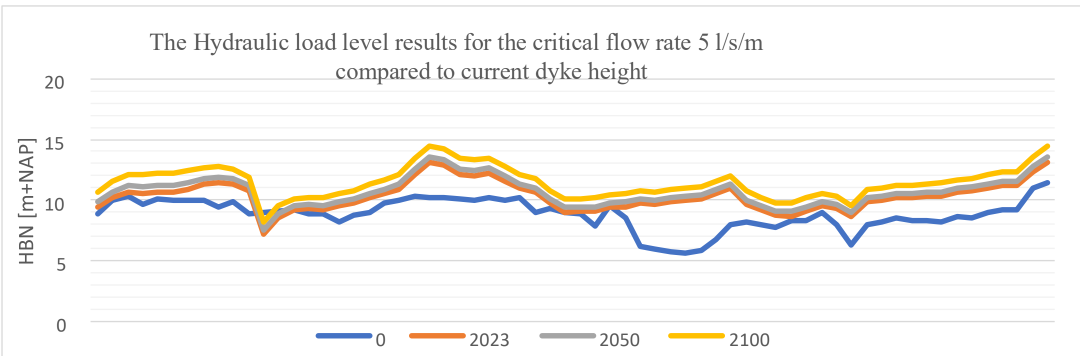


2100

Legend
- ≤8.1
- ≤10.3
- ≤10.8
- ≤11.3
- ≤11.8
- ≤12.3
- ≤12.7
- ≤14.5

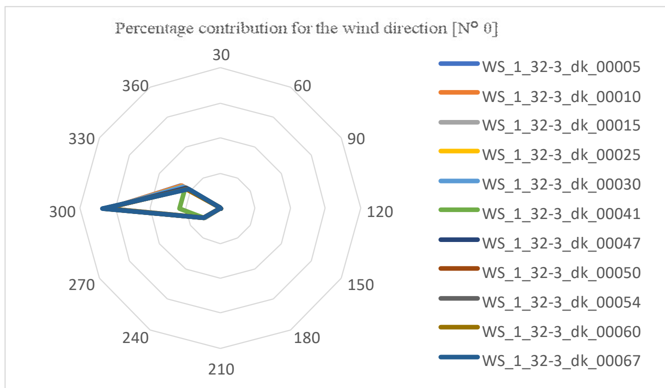






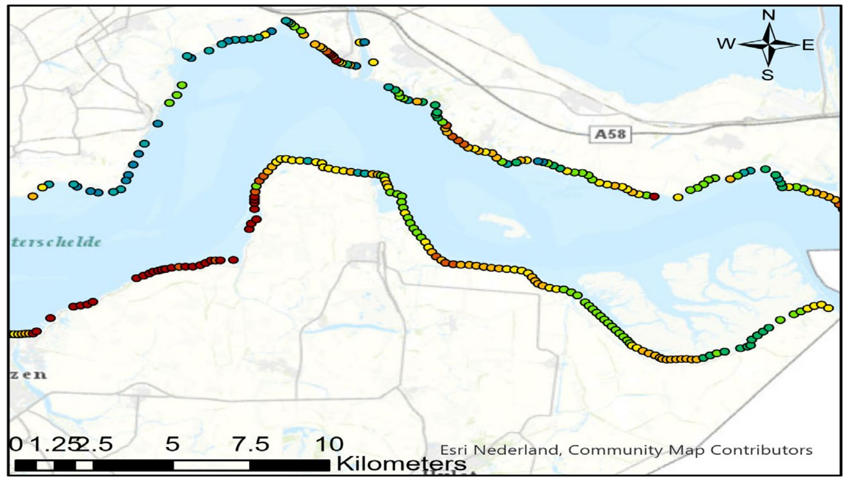
The maps represent a calculated sight year, basing the shown hydraulic load level on the critical flow rate of 5 l/s/m. The locations are relatively uniform in the maps as well as on the x-axis of the graphs. These locations were calculated using the AHN for the crest heights instead of the waterboards profiles, though the waterboard did provide more locations than the hydra-NL database encompasses. Therefore, the results give a global overview of the hydraulic load levels of the locations. The water level calculations have uniform results of all locations, with no decrease or increase. At the moment (2023), the highest experience load level is 13.143 m+NAP; with an average level of 10.31 m+NAP. Whereas by 2050, the maximum load level increases to 13.586 m+NAP, and the average increases to 10.66 m+NAP. However, by 2100 the maximum experiences load level increases to 14.484 m+NAP, and on average to 11.44 m+NAP. 61 out of 64 locations experience transgression at the moment which rises to 63 out of 64 by 2100. When comparing the differences between the time frames, then the highest increase in overtime is 0.78 meters, between 2050 and 2100. The relative difference of wind statistics ranges between 10 and 120 cm.

In the maps, the highest hydraulic load level is calculated for the bay where the Dow is situated. Comparing the orientations to the wind direction contributions shows that their orientation faces the highest contributing direction. Whereas more protected areas, facing slightly away from the mouth of the Western Scheldt, show lower hydraulic load levels.

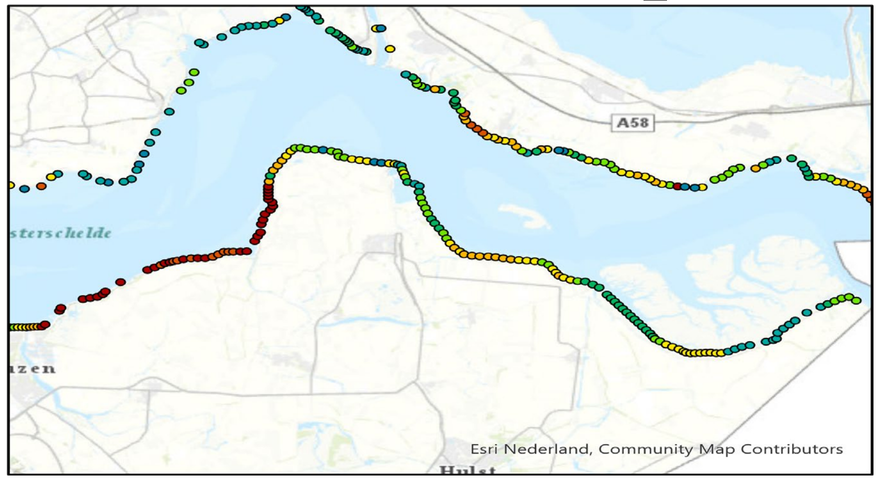


Graph 5, 6, 7, 8 The hydraulic load level results of several calculations in m+NAP compared to the current dyke heights with graph twelve represents the contribution of each wind direction [%]

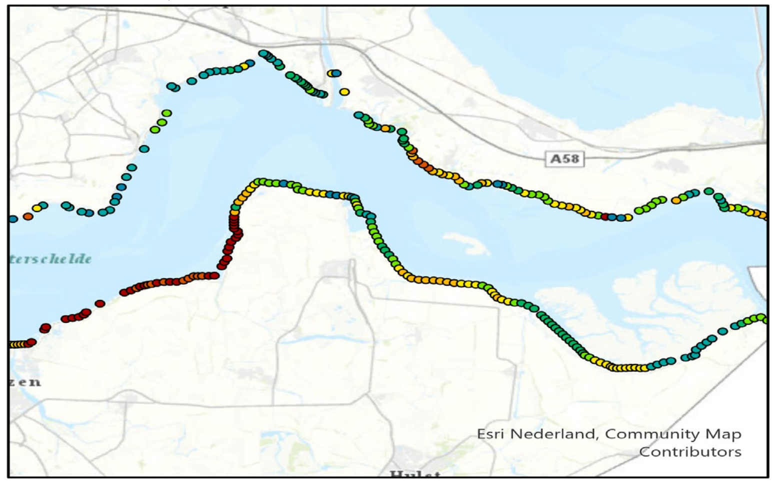
THE HYDRAULIC LOAD LEVEL RESULTS OF DYKE 32_4 FOR THE YEARS 2023, 2050 AND 2100



2023



2050

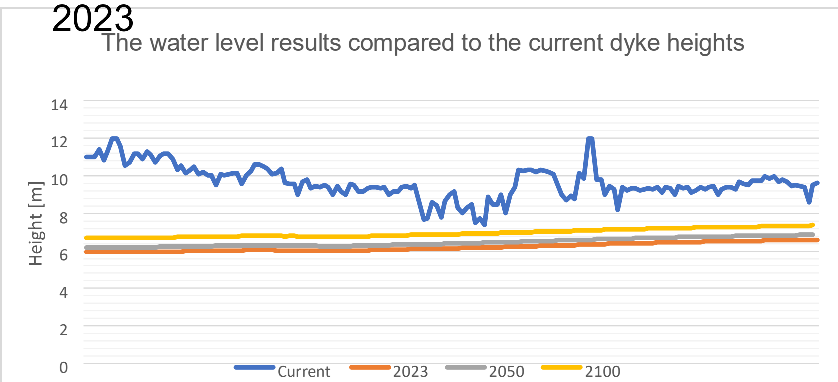


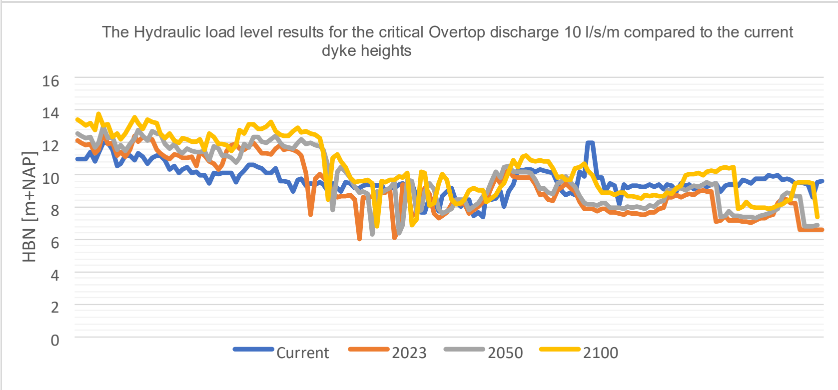
2100

Map 8, 9, 10 The hydraulic load level results per location on dyke track 32_4, showing the results m+NAP

Legend 2023
- ≤0.0
- ≤7.5
- ≤8.4
- ≤9.4
- ≤10.4
- ≤11.5
- ≤12.4
- ≤13.4

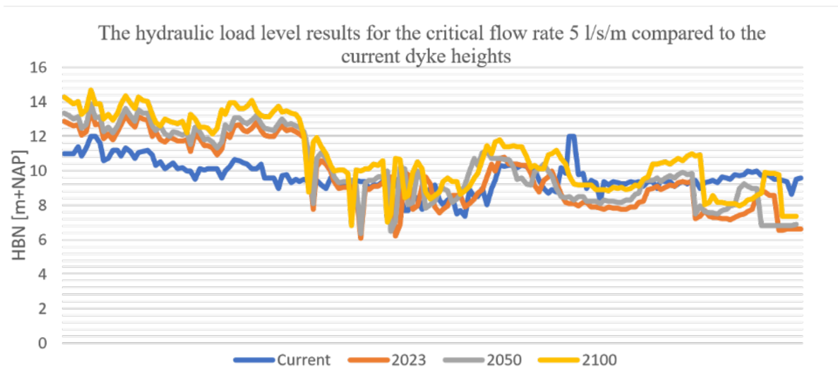
Legend 2050, 2100
- ≤7.7
- ≤8.6
- ≤9.3
- ≤10.2
- ≤11.1
- ≤12.1
- ≤12.8
- ≤13.8

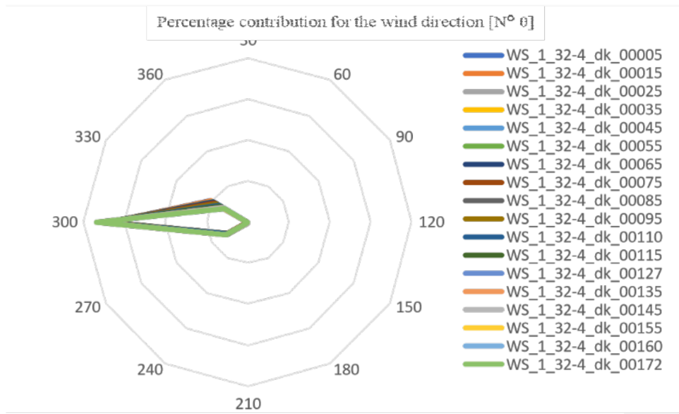




The maps represent a calculated sight year, basing the shown hydraulic load level on the critical flow rate of 5 l/s/m. The locations are relatively uniform in the maps, missing only a few locations. The x-axis of the graphs sets out all data as uniform distance. The represented locations were calculated using the AHN for the crest heights instead of the waterboards profiles. The waterboard did provide more locations points than the hydra-NL database encompasses, though most are represented. The results are, therefore giving a global view on the hydraulic load levels of the locations. The water level calculations have consistent results of all locations, increasing as the locations move east, and with time. The hydraulic load level calculations, on the other hand, indicate high variability between the locations. At the moment (2023), the highest experience load level is 13.442 m+NAP; with an average level of 9.883 m+NAP. Whereas by 2050, the maximum load level increases to 13.845 m+NAP, and the average increases to 10.33 m+NAP. However, by 2100 the maximum experiences load level increases to 14.67 m+NAP, and on average to 10.96 m+NAP. About 89 out of 170 location experience transgression of the crest in 2023 which increases to 130 out of 170. When comparing the differences between the time frames, then the highest increase in overtime is 0.63 meters, between 2050 and 2100. The majority of locations do not pass their safety standards, even for the current situation. With the relative difference between wind statistics ranging between 10 and 120 cm.

In the maps, the right side facing Terneuzen experiences the highest hydraulic load levels indicated by the red colour of the dots. The area in front of the stretch is quite open, causing the accumulation of wave actions, as well as the funnel shape concentrating loads. Comparing these results to the dyke orientations and the contribution of wind directions shows that they are perpendicular to the highest contributing wind direction. In and after the bend is where the load levels are decreasing. The stretches which experience higher loads are oriented almost perpendicular to the bend creating a semi-open area in which the same accumulation of water levels and wave heights can occur.





Graph 9, 10, 11, and 12 The hydraulic load level results of several calculations in m+NAP compared to the current dyke heights with graph sixteen represents the contribution of each wind direction [%].

5.1. Eastern Scheldt

5.2.1. The north side of the Eastern Scheldt

Water level calculation

The northern part of the Eastern Scheldt runs from dyke segment 26_2 to 27_2, with safety norms between 1 in 3000 and 1 in 10.000 years. Most dykes' sections are sheltered though there are some non-sheltered dykes, with varying degrees of hydraulic load levels. Appendix 4. Table 3 presents the average water level height resulted from the water level calculation for all segments showing a similar pattern of minimal variation between locations. However, the final sections show slightly more variation, though very minimally at below 0.25 m. In the representing graphs, the uniformity is seen for each segment; the sight years often overlap showing only the line of 2100 indicating the minimal change between the years. Each of these segments is sheltered from north to north-western wind due to their southern orientations. See maps, 27_1 and 26_3 are in Appendix 4, whereas 26_2 and 27_2 are shown at the end of the section.

The hydraulic load level calculation

The hydraulic load level does result in significant differences between locations compared to the water level calculation. There a minimal observed difference between the two discharges results in 5 l/s/m having the highest load levels. However, just like the water level calculation, there is little to no difference between the sight years, see Table 7. Segment 26_2 and 26_3 experience substantial variation in hydraulic load levels per location, shown in the representing graphs and maps. These two segments on Schouwen-Duivenland are somewhat sheltered though the orientation between sections changes more, causing the more substantial variations between locations. Segments 27_1 and 27_2 encompass Sint-Phillipsland and Tholen, have more uniform hydraulic load levels. There are still observed differences between locations. However, these are not significant; instead, they stay within a range of about 2.5 meters. 27_2 on average has the highest load levels on this side of the Eastern Scheldt. As indicated by the averages in Table 7, there is only a minimal increase over time, which is shown by the overlapping of the other sight years. Comparing Appendix 5. Table 3 to the results in the maps indicate the same sections with high hydraulic load levels. The Eastern Scheldt's dykes require lower crest heights at their safety requirements compared to the Western Scheldt. In the represented northern side of the Eastern Scheldt, the crest heights range between 4 and 9.2 meters. Though the differences are relatively minimal segments *kisters of Suzannas inlaag* and *Zierikzee* jump out, these have a somewhat higher required crest heights, then for example section *Anna Jacobapolder.*

	5			10		
			26_2			
Return period	**2023**	**2050**	**2100**	**2023**	**2050**	**2100**
10	3.734	4.037	4.141	3.580	3.851	4.001
100	4.181	4.472	4.450	4.010	4.256	4.295
300	4.359	4.650	4.589	4.180	4.419	4.424
1000	4.539	4.835	4.743	4.342	4.583	4.567
3000	4.696	4.998	4.886	4.478	4.726	4.702
10000	4.866	5.174	5.051	4.626	4.882	4.861
30000	5.018	5.331	5.225	4.760	5.024	5.039
100000	5.183	5.504	5.461	4.910	5.185	5.291
300000	5.342	5.676	5.716	5.059	5.358	5.571
			26_3			
10	4.185	4.329	4.529	4.091	4.184	4.363
100	4.712	4.810	4.942	4.589	4.635	4.745
300	4.942	5.022	5.133	4.803	4.834	4.920
1000	5.181	5.246	5.340	5.024	5.043	5.110
3000	5.390	5.443	5.530	5.216	5.226	5.284
10000	5.608	5.654	5.743	5.419	5.422	5.482
30000	5.801	5.843	5.960	5.598	5.598	5.688
100000	6.008	6.056	6.256	5.791	5.798	5.980
300000	6.200	6.278	6.568	5.973	6.013	6.295
			27_1			
10	4.131	4.215	4.243	4.003	4.038	4.166
100	4.520	4.567	4.535	4.360	4.348	4.423
300	4.685	4.727	4.680	4.511	4.489	4.554
1000	4.860	4.901	4.844	4.670	4.642	4.705
3000	5.016	5.059	4.998	4.811	4.780	4.850
10000	5.185	5.232	5.177	4.965	4.933	5.022
30000	5.341	5.393	5.366	5.106	5.077	5.211
100000	5.513	5.579	5.656	5.265	5.249	5.530
300000	5.678	5.780	6.029	5.423	5.450	5.931
			27_2			
10	4.349	4.445	4.569	4.202	4.294	4.409
100	4.823	4.874	4.939	4.640	4.686	4.743
300	5.027	5.066	5.113	4.824	4.858	4.899
1000	5.245	5.274	5.309	5.019	5.044	5.074
3000	5.441	5.463	5.493	5.195	5.214	5.240
10000	5.652	5.669	5.703	5.385	5.400	5.433
30000	5.841	5.858	5.918	5.558	5.573	5.635
100000	6.049	6.073	6.227	5.748	5.772	5.942
300000	6.245	6.297	6.625	5.930	5.987	6.342

Table 7 The calculated average hydraulic load level [m+NAP] for the critical overtopping discharges 5 and 10 l/s/m as calculated for dyke segments in the north of the Eastern Scheldt.

The occurrence of transgression

Another indication of the lower load level is the percentage of calculated dykes which experience transgression, which is substantially lower than those of the Western Scheldt—rising from 16% by 2023 to 20% in 2100.

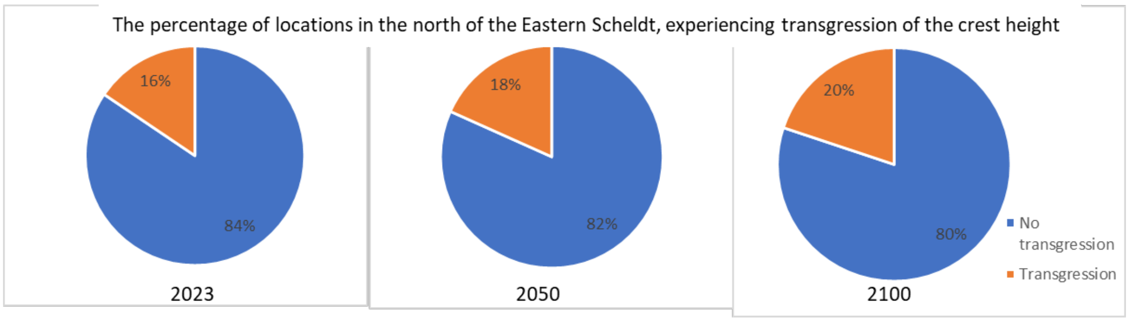
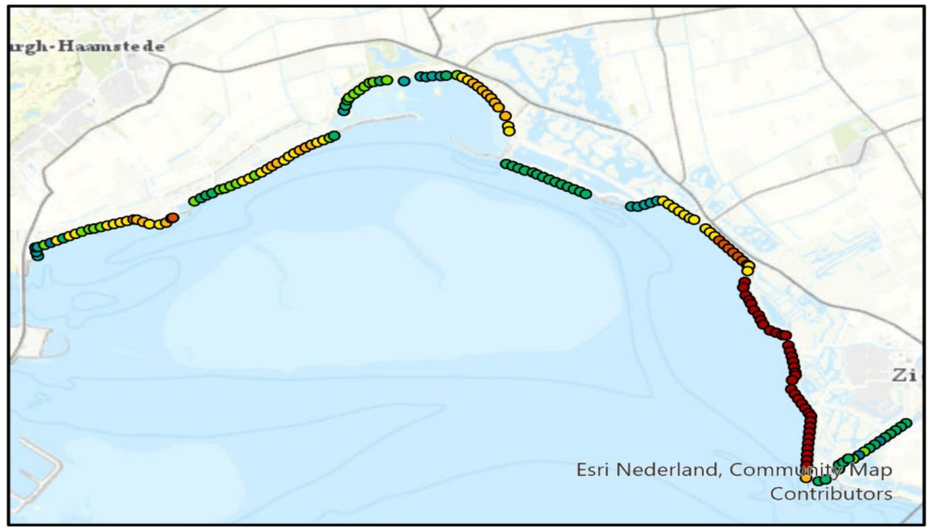
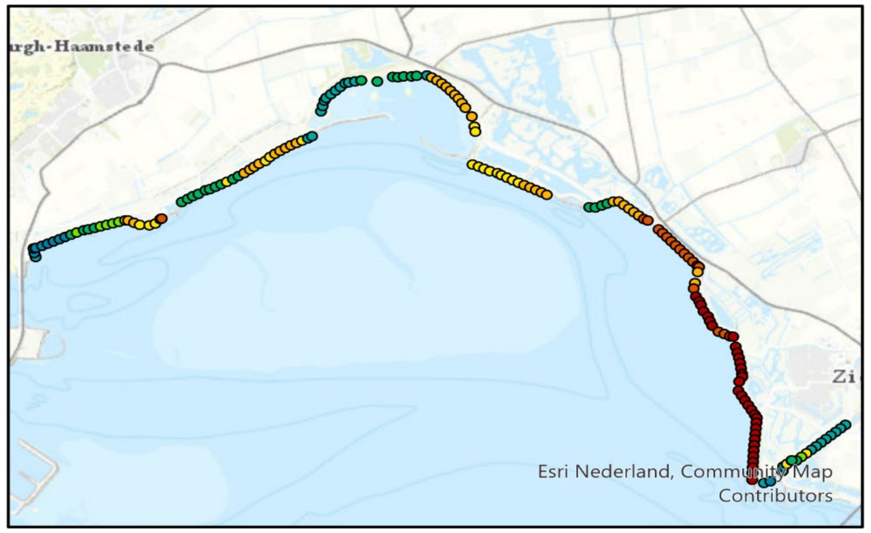
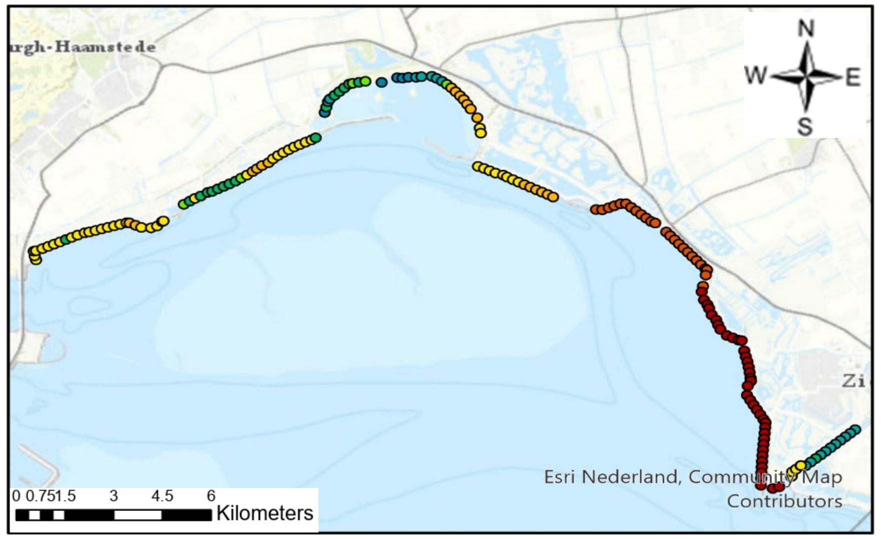


Figure 15 The fail and pass percentages of all locations on the north side of the Eastern Scheldt combined, for each of the calculated years

THE HYDRAULIC LOAD LEVEL RESULTS OF DYKE 26_2 FOR THE YEARS 2023, 2050 AND 2100





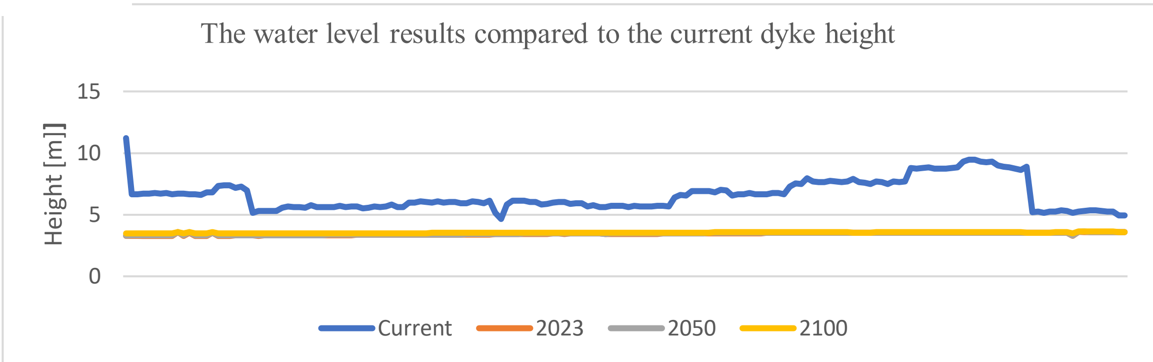


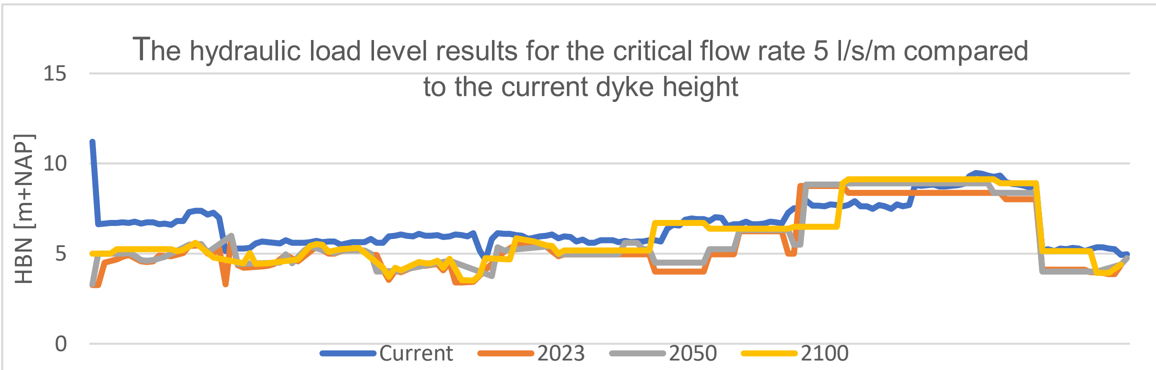
Map 11, 12, 13 The hydraulic load level results per location on dyke track 26_2, showing the results m+NAP

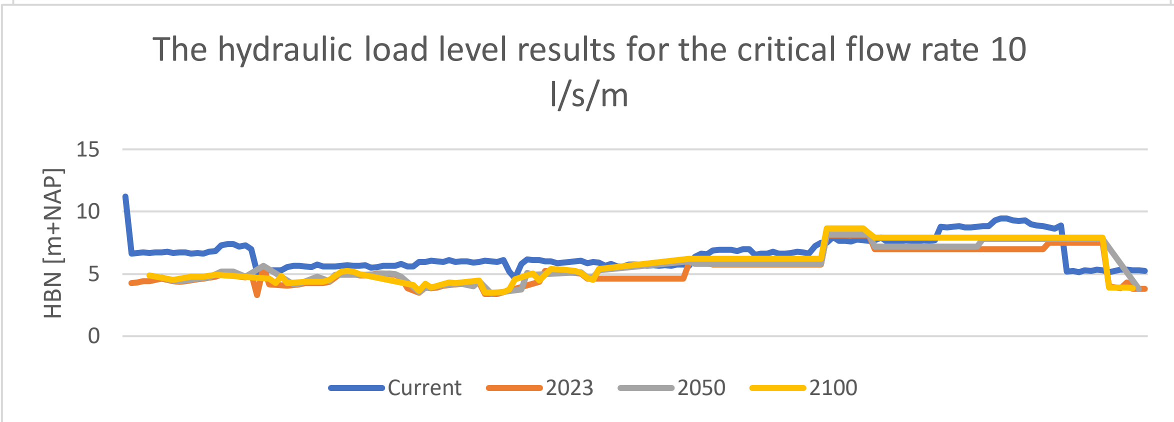
2023 2050 2100

HBN
- ≤3.72
- ≤4.08
- ≤4.53
- ≤4.79
- ≤5.32
- ≤5.87
- ≤6.69
- ≤8.90

HBN 2023
- ≤0.00
- ≤3.60
- ≤4.20
- ≤4.60
- ≤5.13
- ≤5.58
- ≤6.24
- ≤9.20





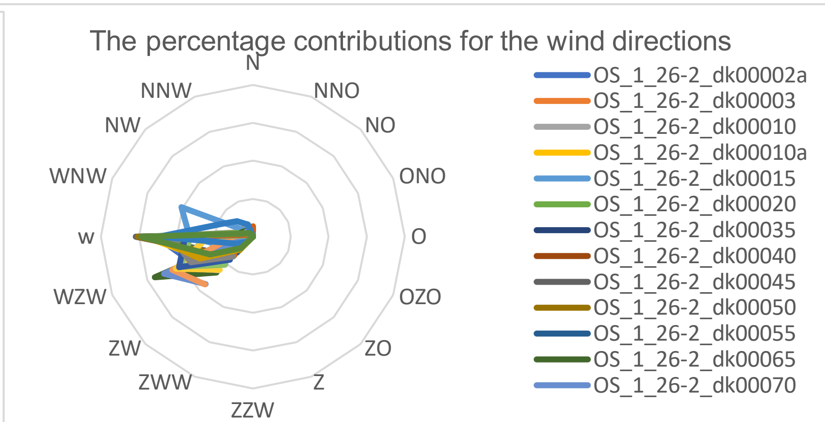


Graph 13, 14, 15, 16 The hydraulic load level results of several calculations in m+NAP compared to the current dyke heights with graph twenty represents the contribution of each wind direction [%].

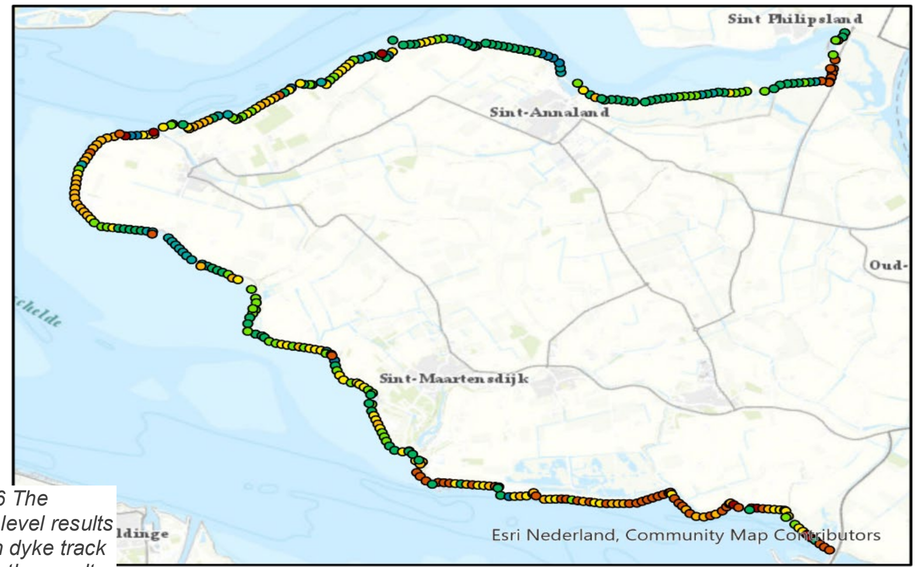
Each map represents one of the calculated years, showing the hydraulic load level in m+NAP based on the critical overflow rate of 5 l/s/m. Dyke section 26_2 is the first section in the north of the Eastern Scheldt, representing both sheltered and non-sheltered dyke sections. The distance between locations is not entirely uniform as between some of the dyke sections; there are more significant gaps. The x-axis does show the range as uniform, also indicates that not all locations were calculated towards the end. The database of hydra-NL has a limited amount of points, using the shapefile of them as the maps layer, thus representing the estimated locations of the database. However, these locations do not encompass all of the locations provided by the waterboard. Even though the majority of locations were calculated, some of them were still missing, though every dyke section and orientation had at least 1 point calculated. Therefore, the results show a global point of view on the transgression locations.

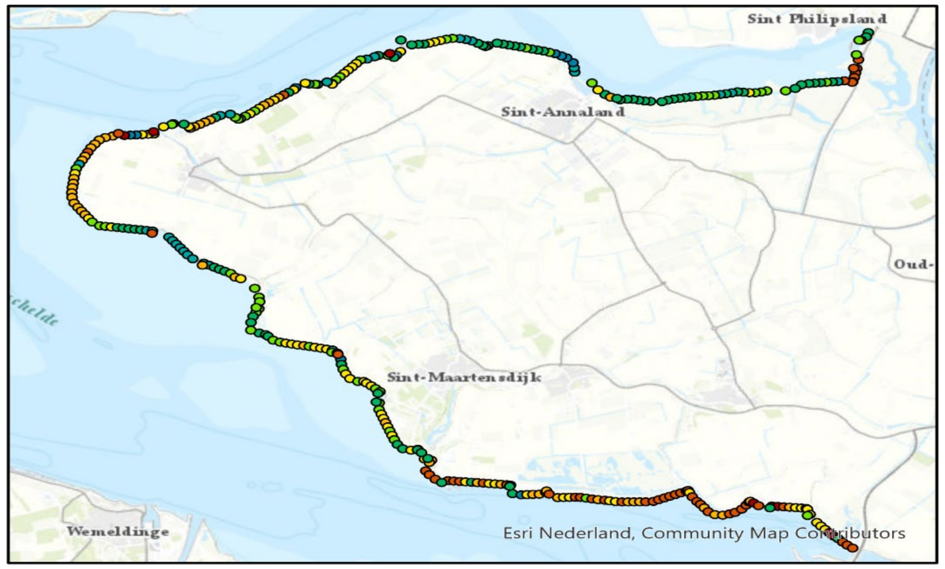
As previously said, the water level calculations have little differences in results of all locations, compared to the varying results of the critical overtopping discharges. In the current situation (2023), there some locations that experience transgression of the crest, though the majority does not. The highest experience load level is 3.605 m+NAP; with an average level of 3.406m+NAP. By 2050 the maximum load level increases to 3.615 m+NAP, and the average increasing to 3.426 m+NAP. However, by 2100 the maximum experiences load level increases to 3.641 m+NAP, and the average to 3.465 m+NAP. The majority of the locations do pass their safety norms in the future. In the current situation, there are locations which do experience transgression, by 2050 and 2100, more locations start failing the norm.

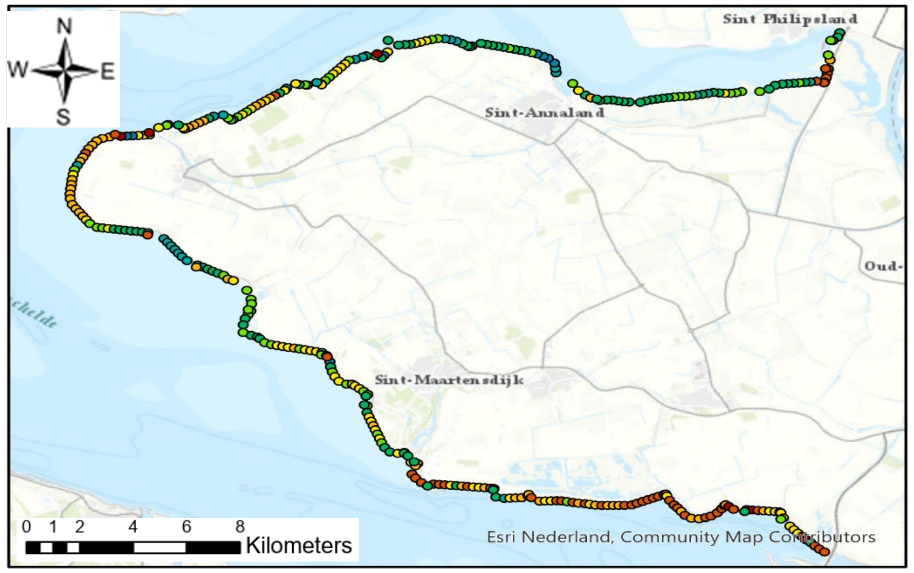
The most substantial wind directions contribution varies between locations, though mostly from western wind directions. Looking at the orientation and how it changes between points, shows that locations on the eastern side experience the highest load levels and are not sheltered. In contrast, the western side is highly sheltered and experience the highest loads at a more southwestern direction.



THE HYDRAULIC LOAD LEVEL RESULTS OF DYKE 27_2 FOR THE YEARS 2023, 2050 AND 2100





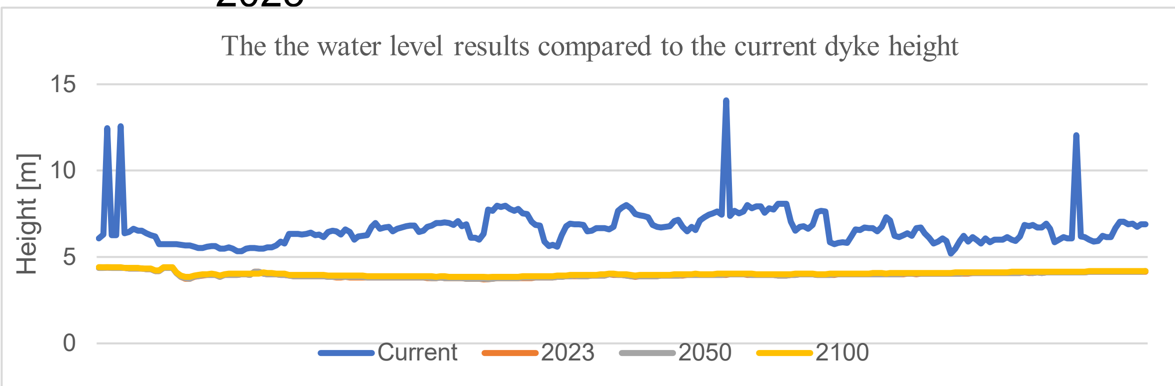


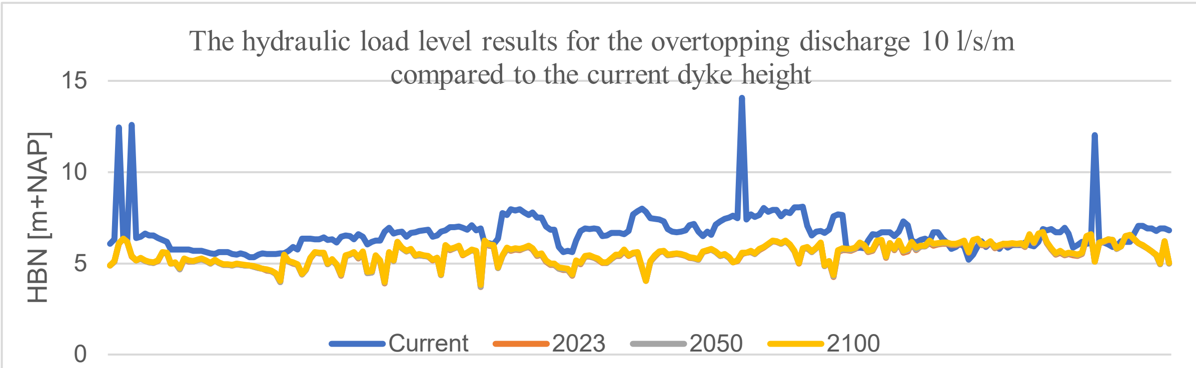
Map 14, 15, 16 The hydraulic load level results per location on dyke track 27_2, showing the results m+NAP

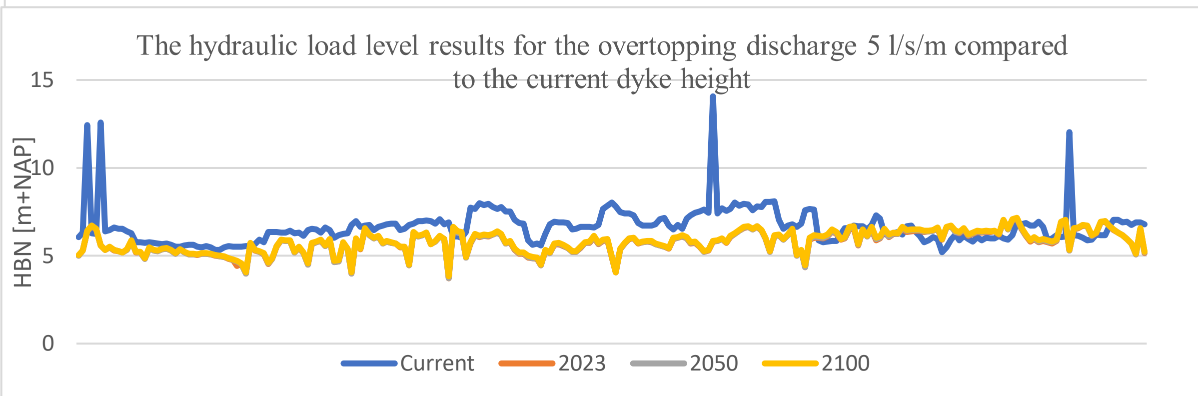
2023 | 2050 | 2100

Legend

- ≤4.17
- ≤4.96
- ≤5.45
- ≤5.77
- ≤6.06
- ≤6.38
- ≤6.76
- ≤7.98



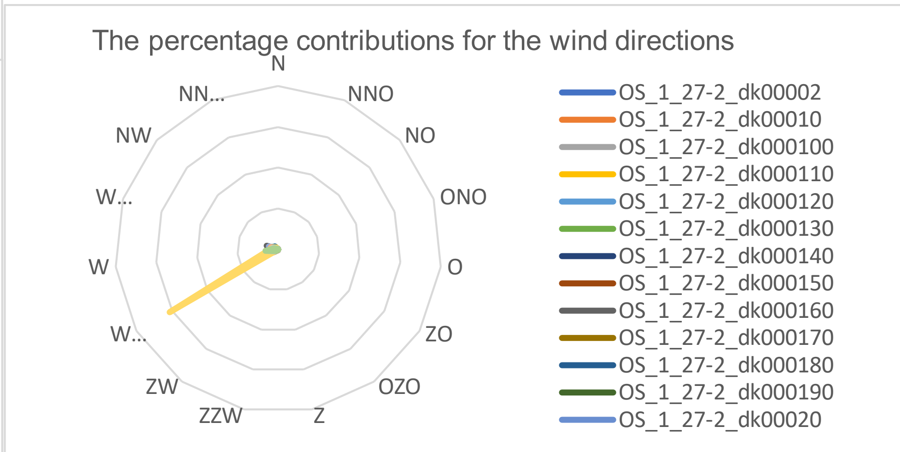




Each map represents one of the calculated years, showing the hydraulic load level in m+NAP based on the critical overflow rate of 5 l/s/m. The distance between locations is not entirely uniform as between some of the dyke sections; there are more significant gaps. The x-axis does show the range as uniform. The database of hydra-NL has a limited amount of points, using the shapefile of them as the maps layer, representing the estimated locations of the database. However, these locations do not encompass all of the locations provided by the waterboard. Thus, the result is a global overview of the hydraulic load levels.

As previously said, the water level calculations have little differences in results of all locations, compared to the varying results of the critical overtopping discharges. In the current situation (2023), 2050 and 2100, there are no locations which experience transgression of their crests. At the moment, the highest experience load level is 7.894 m+NAP; with an average level of 5.652 m+NAP. By 2050 the maximum load level increases to 7.927 m+NAP, and the average increasing to 5.669 m+NAP. However, by 2100 the maximum experiences load level increases to 7.981 m+NAP, and the average to 5.703m+NAP. The differences between the sight years are minimally throughout all locations; this is indicated within the graphs. The majority of locations do pass their norms, though the northern side of Tholen does not pass it, indicated by the red dots Sint Phillipsland.

These results compared to the orientation of the dykes and the locations of the dyke section show that most locations in the north are more sheltered compared to the south.



Graph 17, 18, 19, and 20 hydraulic load level results of several calculations in m+NAP compared to the current dyke heights with graph twenty-four represents the contribution of each wind direction [%].

5.2.2. The south side of the Eastern Scheldt.

Water level calculations

The southern part of the Eastern Scheldt runs from dyke segment 28_1 to 31_2, with safety norms ranging from 1 in 1000 to 1 in 10.000 years. It encompasses sheltered and non-sheltered dykes, with varying degrees of hydraulic load levels. Appendix 4. Table 4 presents the average water level height resulted from the water level calculation for the three dyke segments. Each segment's results throughout their locations show the same pattern of little to no variation between locations, nor do they show any gradual increase or decrease. In the graphs for representing the water level calculation shows the uniformity throughout locations and time frames. Comparing the three calculated timeframes shows minimal increases, though, in the graphs, the lines overlap. Even comparing the three dyke segments to one another indicate a minimal increase towards the east. However, the averages of 30_1 and 31_2 are higher when separating the channel's results. In the maps, it is more clearly indicated how these differences are caused, though they follow the same pattern as previous segments. As they included sheltered sections turned away from the mouth, or in the channel, and also sections which face the most contributing wind directions or at acute angles of the mouth. See two maps below the section and one in Appendix 7.

Hydraulic load level calculations

In contrast to the water level calculations, the hydraulic load level calculations do result in significant differences between the locations. The two calculated discharges show a minimal difference, with the overtopping discharge of 5 l/s/m resulting in the highest load levels. Comparing the result between sections of the dyke segments show higher variability caused by the orientation and location of each point. Each representing graph shows the variability between locations, though also the similarity between the sight years. The return periods show only a minimal average increase with time in the three segments, except for a few points. The differences between locations can again be explained based on their orientations, compared to the hinterland and contributing wind directions. Some of which are facing away from the mouth, whereas the remaining are often at an acute angle. In Appendix 5. Table 4, the generalised crest heights for the sections along the southern part of the Eastern Scheldt, which range between 4.5 to 7.5 meters in height. These show even lower required crest heights than the northern side, which is also indicated in the percentage of locations experiencing transgression. Only *Stormesandepolder* and the *Tweede Bathpolder* result in a required crest height of above 7 meters, whereas the majority range between 6 and 6.6 meters.

	5			*10*		
			28_1			
Return period	**2023**	**2050**	**2100**	**2023**	**2050**	**2100**
10	4.031	4.267	4.399	3.915	4.022	4.123
100	4.568	4.766	4.815	4.405	4.454	4.484
300	4.782	4.978	5.009	4.588	4.627	4.641
1000	5.009	5.211	5.222	4.783	4.817	4.818
3000	5.212	5.421	5.420	4.962	4.992	4.987
10000	5.429	5.646	5.649	5.158	5.187	5.188
30000	5.624	5.853	5.885	5.336	5.369	5.404
100000	5.840	6.092	6.222	5.532	5.589	5.717

300000	6.056	6.339	6.645	5.729	5.840	6.107
		5			***10***	
			30_1			
Return period	**2023**	**2050**	**2100**	**2023**	**2050**	**2100**
10	4.096	4.088	4.270	3.990	4.021	4.130
100	4.329	4.283	4.446	4.208	4.207	4.287
300	4.558	4.481	4.632	4.421	4.396	4.452
1000	4.751	4.651	4.799	4.598	4.561	4.599
3000	4.949	4.831	4.979	4.781	4.735	4.761
10000	5.119	4.990	5.146	4.939	4.890	4.912
30000	5.295	5.159	5.338	5.103	5.055	5.087
100000	5.449	5.313	5.552	5.246	5.204	5.291
300000	5.619	5.497	5.921	5.402	5.382	5.669
			31_2			
10	4.458	4.535	4.626	4.019	4.093	4.232
100	4.906	4.946	4.990	4.373	4.406	4.506
300	5.108	5.139	5.170	4.508	4.533	4.627
1000	5.327	5.352	5.375	4.651	4.671	4.766
3000	5.525	5.546	5.568	4.785	4.804	4.905
10000	5.738	5.758	5.790	4.937	4.957	5.079
30000	5.930	5.952	6.018	5.082	5.108	5.288
100000	6.141	6.174	6.365	5.249	5.292	5.629
300000	6.344	6.426	6.715	5.418	5.534	5.983

Table 8 The calculated average hydraulic load level [m+NAP] for the critical overtopping discharges 5 and 10 l/s/m as calculated for dyke segments in the south of the Eastern Scheldt.

The occurrence of transgression

The southern side of the Eastern Scheldt experience similar load levels to the northern part though slightly lower; however, it does experience a substantially lower percentage of transgressed dyke heights rising to three per cent by 2100.

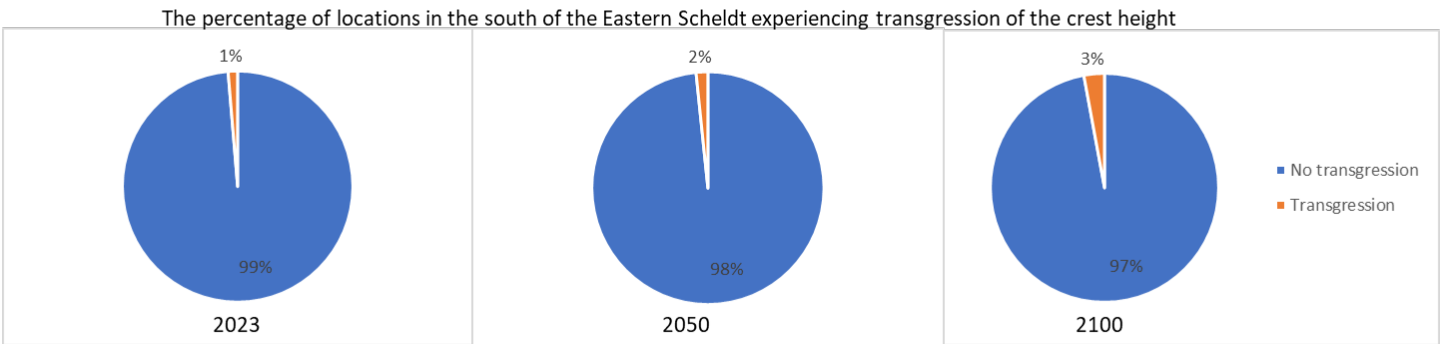
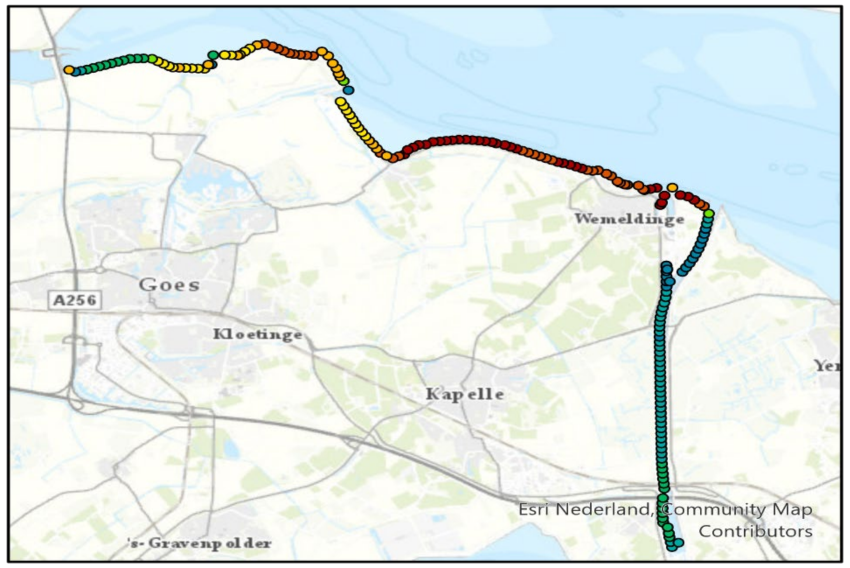
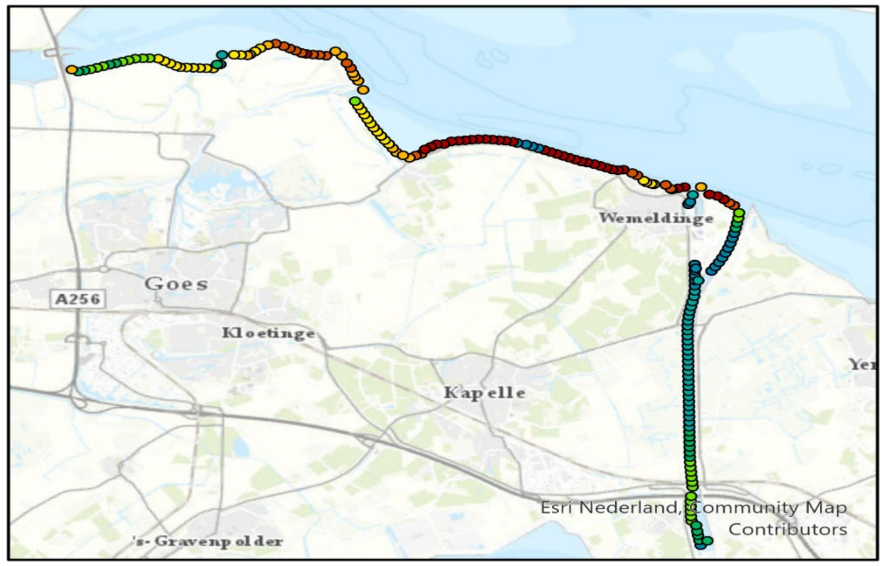


Figure 16 The fail and pass percentages of all locations on the south side of the Eastern Scheldt combined, for each of the calculated years

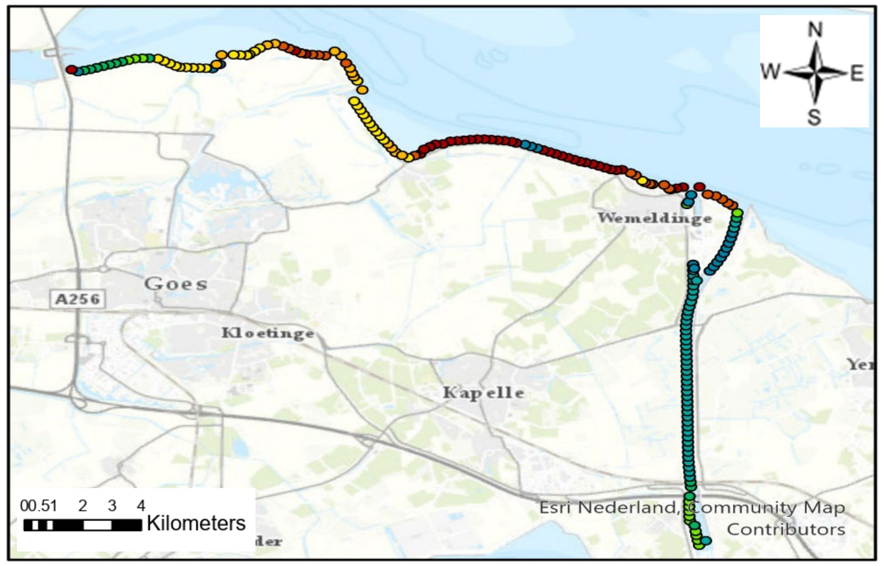
THE HYDRAULIC LOAD LEVEL RESULTS OF DYKE 30_1 FOR THE YEARS 2023, 2050 AND 2100



2023



2050

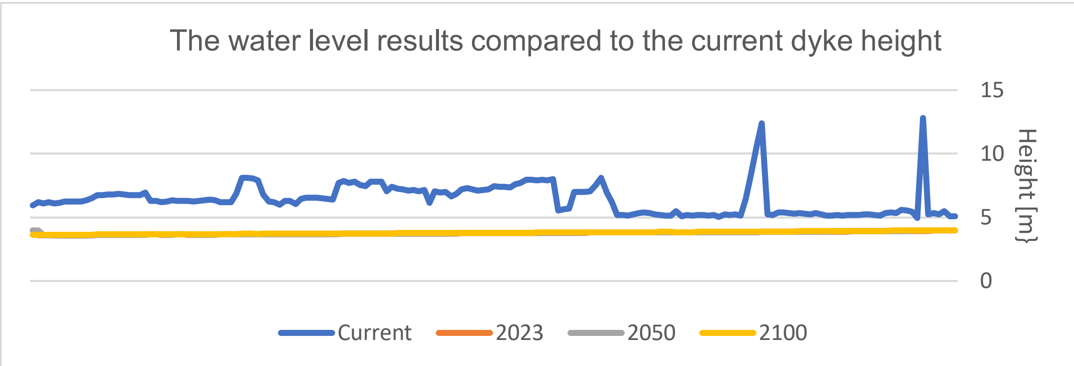


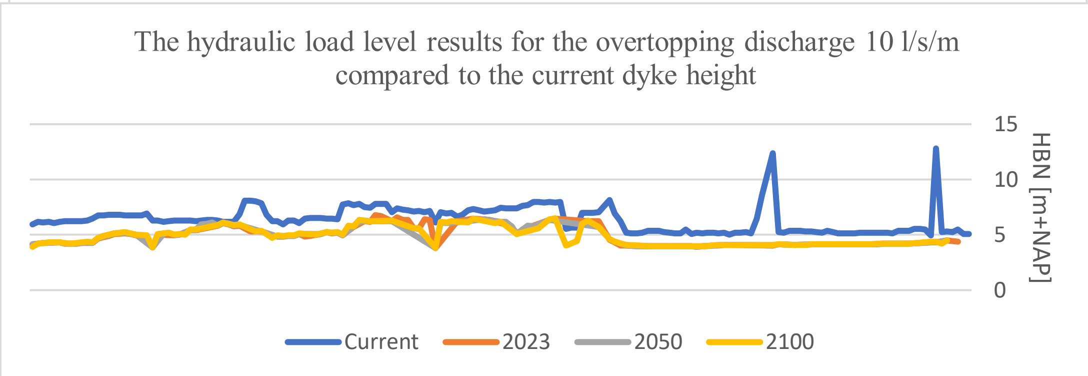
2100

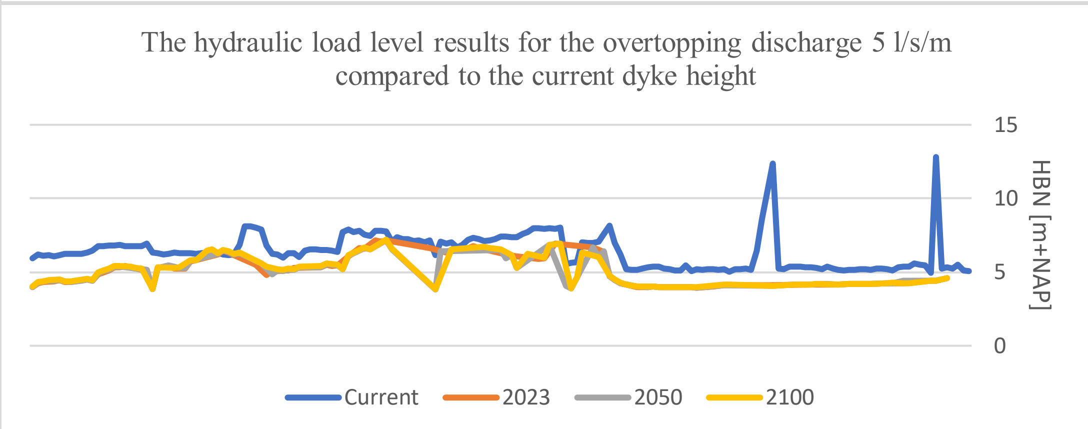
Map 17, 18, 19 The hydraulic load level results per location on dyke track 30_1, showing the results m+NAP

Legend

- ≤4.03
- ≤4.28
- ≤4.49
- ≤4.76
- ≤5.43
- ≤5.82
- ≤6.45
- ≤7.30



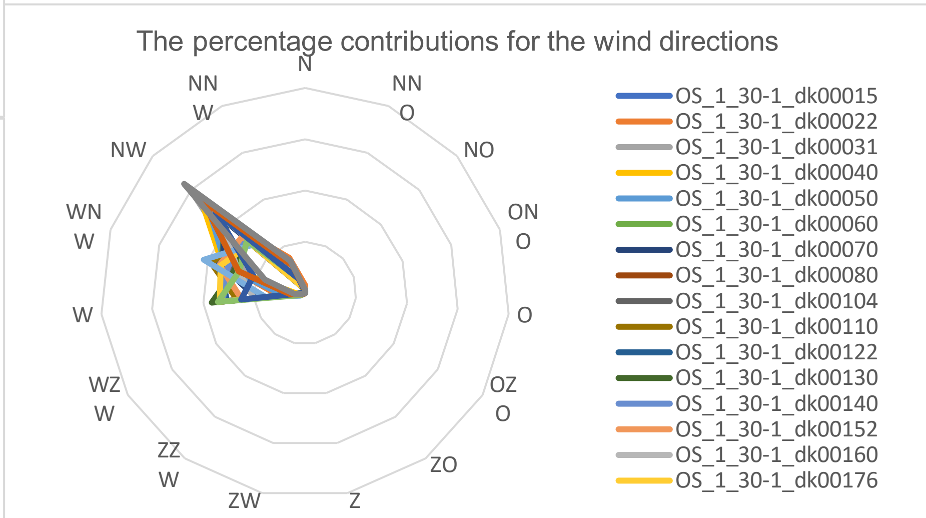




Each map represents one of the calculated years, showing the hydraulic load level in m+NAP based on the critical overflow rate of 5 l/s/m: The distance between locations is not entirely uniform as between some of the dyke sections; there are more significant gaps. The database of hydra-NL has a limited amount of points, using the shapefile of them as the maps layer, representing the estimated locations of the database. However, these locations do not encompass all of the locations provided by the waterboard. Thus, the result is a global overview of the hydraulic load levels.

As previously said, the water level calculations have little differences in results of all locations, compared to the highly varying results of the critical overtopping discharges. In the current situation (2023), 050 and 2100, there are no locations which experience transgression of their crests. At the moment, the highest experience load level is 7.153 m+NAP; with an average level of 4.949 m+NAP. By 2050 the maximum load level increases to 7.166 m+NAP, and the average increasing to 4.831 m+NAP. However, by 2100 the maximum experiences load level increases to 7.297 m+NAP, and the average to 4.979 m+NAP. The differences between the sight years are minimally throughout all locations; this is indicated within the graphs. The majority of locations do pass their norms for all sight years.

These results compared to the orientation of the dykes and the locations of the dyke section show more variation on which wind direction contributes the most significantly. Noord-Beveland shelters the stretch near lake Veere, the locations in the channel are also sheltered, therefore these experience the lower load levels. The highest load levels are experienced in the stretch indicated by the red colour, which is not sheltered and is oriented that the NW wind direction is almost perpendicular.



Graph 21, 22, 23, 24 The hydraulic load level results of several calculations in m+NAP compared to the current dyke heights with graph thirty-two represents the contribution of each wind direction [%].

Chapter 7. Discussion

The focus of the thesis was to research the effects of sea-level rise on the hydraulic load levels, relating the results to the required crest heights and whether a segment passes or fails its norm. A global overview was chosen instead of an in-depth one as it serves better to the requirements from Rijkswaterstaat, which needed an indication of the state. Setting a few boundaries, spatially, temporally, and calculation specific to answer the main question. Spatially the focus was on only the dykes along the estuary, therefore excluding the dunes of the coast, making another exclusion on the growth of sandbanks by assuming that they do not keep up with the changes. Temporally choosing to calculate 2050 and 2100 along with the base year 2023 and generating a worst-case scenario by testing the W+ scenario of KNMI'06. Within the calculations, a choice was made for the water level and hydraulic load level calculations, as the other calculation types stated in 1.4. did not serve a purpose towards the explanation of the results. Though these choices are explained in more detail in the corresponding sections below.

7.1. The method

The method used three software's to generate the final hydraulic load levels. As described in chapter 4, Riskeer is used to compare the locations provided by the waterboard to the Hydra-NL database, thus choosing the corresponding data. Importing them into the profile generator which results in a work folder in which each location has the same name as used by hydra-NL including the corresponding profiles. This method excludes quite some profiles, though, within the limitations of the database, it could not be prevented. The excluded profiles often were quite similar to the chosen one, so the exclusion has the little effect it is only not as in-depth as it would have been with all locations. The research worked with the software limitations toward the most comprehensive result within limits. The number of locations limits the in-depth; however, the number of locations does not substantially affect the results from the Hydra-NL software.

There was a choice between two software programs within the WBI2017, Riskeer and Hydra-NL. Even though Riskeer is used to find the corresponding profiles for hydra-NL, it is not used for further analysis. At the start of the thesis, a choice was made between Riskeer, which gives more in-depth analysis and hydra-NL, which simplifies the analysis. Comparing the learning curve of the two software and the period for the thesis, resulted in that hydra-NL was the better choice. As learning to work with the program proved to be simpler and would allow more time to analyse the results. Even though the analysis is somewhat simplified compared to what Riskeers calculations result in, Hydra-NLs results do fit the purpose of the research.

As stated in hydra-NL, a limited number of locations are present in the database; the corresponding profile data as provided by the waterboard is quite out-dated. As indicated by the waterboard, the last measurements were taken in 2010, since then steps towards strengthening and adjusting the dykes to meet standards have been taken. Though the magnitude of the changes is not known, so the locations are either still correct or not representative. Even though the profiles might not be entirely representative of the current situation, it sketches a worst-case scenario instead. Therefore, it is within the purpose of the research; the current state it presents is mostly correct though it will deviate from the actual state at some points, making it slightly less accurate.

The analyses of the output files used the safety norms from the *Water wet* as a way of assessing the results. Mostly by comparing the current dyke height to the results at the return period. Usually, within the WBI, the hydraulic load level results are tested for the cross-sectional requirement. These requirements are often quite a bit stricter than those given in the law, though the choice for the safety norms was made due to time constraints as the cross-sectional requirement is calculated per locations/section. In the theoretical framework, the cross-sectional requirement is briefly explained; this method is usually used during a detailed assessment. The method will be used in further wbi2017 assessments, instead of using the cross-sectional requirements, the safety requirements from the *Water wet* were used. The choice was based on the available time for the thesis research just like several other choices. As to correctly learn how to use the software and determine the cross-sectional requirements for all important failure mechanisms, would have been too much in the available time. Another reason for the choice was that the safety norms are more well-known to the public. Also, the safety norms are universal throughout a segment, whereas the cross-sectional requirements vary more between stretches. Thus, aiding in the comparisons within segments. However, the taken norm is specific to each segment, instead of choosing the same norm for all segments and comparing them that way, in order to generate the presented results.

The analysed results are presented in maps created using arc GIS pro, the inserted data corresponded with the highest load levels. These load levels were taken from the 5 l/s/m calculation when using Cadzand; therefore, the maps do not present the data from Vlissingen or the 10 l/s/m calculations. Another note on the maps is that they were made to be readable on their own, without needing to read the other maps or the presented results. This does, however, make the explanations below the maps quite repetitive, but this was a conscious choice. Having a map per segment which is readable on their own was chosen to be more critical than the repetitiveness of the maps.

7.2. Results

The first half of chapter 5 assess the results from the Western Scheldt, in which the water level and hydraulic load level calculations results are put next to the current dyke height. As well as putting the averages of calculated years and the two wind statistics next to each other. Within the water level calculation, the same pattern is seen, where the results are relatively uniform throughout entire segments, even showing limited variation between segments per sub-part of the estuary. The calculations do not take statistical data, dyke orientation and height into account, only the location within the database and the climate scenarios. Therefore, these results are accurate representations of the water level as a result of sea-level rise. Though they do no say anything about the hydraulic load levels, nor about the different wind statistics. In contrast, the hydraulic load level indicates high variability between location. However, the load level follows the same pattern throughout the segment for all years, only increasing in height. The height increase is not entirely uniform for all locations along a segment; however, this does not influence the conclusions of the specific segments.

Dyke segment 30_3 jumps out, the results for the first half do not follow the same pattern in their loads. Instead, they follow the same results as their water level calculations. Even re-running the calculations does not change the results. A similar event occurred in segment 223, where the first few locations did not calculate correctly, these were excluded though due

to the similarities between locations, a somewhat accurate estimation was made for the maps. The results of 223 must be taken with a grain of salt, where-as the first half of 30_3 is non-accurate.
The relative difference calculations showed similar patterns. As the wind statistic is not considered in the water level calculation, no deviation is observed between the two wind statistics. They are showing that the water level calculation gives a profoundly limited view and should only be used in combination with other calculations. The hydraulic load level calculations did show significant differences when comparing two wind statistics at the selected locations. In the representing tables, the averages of the relative difference in percentage.

The water level calculations show the same uniformity throughout locations in Eastern Scheldt's segments as those in the Western Scheldt. However, the increase with the sight years is substantially less than seen in the Western Scheldt. The limited increase is also seen in the hydraulic load level calculations. Though for the thesis, they served more as a control on that the water level rises, as these calculations are not affected by the wind statistic. These results were expected to experience lower impacts by the sea-level rise, only when the barrier fails or at higher return periods does hydra-NL show higher load level increases with the years. Thus, for the accuracy of the calculated locations, it can be said that these are within expectations and accurate.
However, the results are less accurate compared to the Western Scheldt, as within all segments, a limited number of locations were calculated. Though it is except for segments 27_2 and 31_2 where all locations were calculated. Even though the limited number of locations within each section of the segments representing dykes were calculated. This does, however, affect the accuracy of the presented load levels and required crest heights. Which by generalising of the load levels do not include the high variability as seen in the Western Scheldt. Therefore, the local variations are not shown, creating an even more global overview.

Going into more detail on the hydraulic load level calculation, the overtopping discharges of the 5 and 10 l/s/m, were chosen to make a good comparison, as briefly explained in chapter 4. The discharge variable was one which could be adjusted for the calculations; the choice was between 1, 2, 5, and 10 l/s/m. For a good comparison, 5 and 10 l/s/m were chosen, as they have an even increment of 5 between the two. The increment was expected to show a moderate difference, where for example 1 and 2 l/s/m would show a smaller difference between the two and 1 and 10 l/s/m would show a more substantial difference. Thus, for the comparison an even increment with overtopping discharges which were expected to show modest differences, or 5 and 10 l/s/m. These two discharges subsequently formed the basis of the tables and figures presented in chapter 5, though only the 5 l/s/m was chosen to be represented in the maps. The maps were representing the highest hydraulic load level in m+NAP for each location for each of the years. While both the water level and 10 l/s/m are presented in a graph below the maps, these only serve as extra context around the presented results.

The results presented in the maps and tables, do not give an insight into whether transgression occurs; instead, it is shown in Table 4, Table 6, as well as figure 15, 16 and Appendix 5. Figure 2. In the tables, the terms pass, and fail have been used to describe whether transgression occurs (fail) or if the crest height is high enough (pass). Whereas the figures do use transgression as the term, though they refer to the same data. These have been based on the safety norms of each segment, respectively. Though when failing a location in this research, it does not mean it would fail within the WBI. As a safety assessment of the WBI allows for higher overtopping discharges and even several decimetres of lower crest heights before it is failed. Therefore, the tables indicate whether transgression takes place

The alternative wind data from Cadzand showed in most locations higher results except a few on the northern side. This result was expected at the beginning of the thesis research. However, as indicated in the histograms of the northern side, there are a few locations which result in higher levels when using wind data from Vlissingen. The decrease is no more than 10 cm when using Cadzand for these locations. The decrease is limited to the northern side and a hand full of locations, whereas on the northern side no decrease is seen when using Cadzands data. The numbers from the histogram indicate that the effect of using alternative wind statistical data varies between the locations, just like the hydraulic load levels. The variations do not influence the conclusions which were made, in chapter 7.

The presented analysis is the first within the WBI2017, which means that there is little literature available for comparisons. The closest research to that performed in the thesis is in ''*Veiligheid Nederland in Kaart''* which assess the flood probability of all levee systems. The reports from the research are not comparable with any assessments based on the *water wet* as they do not consider the transgression probabilities used during assessments. Instead, they give the failure probability per section per year. The only comparison that could be made is looking at the sections with high failure probabilities and comparing them to the sections which experience high hydraulic load levels. Though there are a few similar pieces of research taking place using the WBI2017 on other water systems, these cannot be consulted to compare the results. However, the research for the VNK is debated as new information becomes available about, for example, tidal influences on dykes around the Scheldt estuary. The new information affects the interpretation and reliability of the presented flood probabilities. Therefore, there is almost no literature which could be used for comparison to validate the results.

In the conclusion of the discussion, it is essential to mention that the study focussed on giving a global overview of the worst-case scenario for the hydraulic load levels of the Scheldt Estuary. The report presented gives the first insight into the expected effects, there are several points discussed which affected the validity and the indebtedness of the results, though still falling within the focus of the thesis.

Chapter 6. Conclusion

This thesis aimed to understand, the impact of sea-level rise is on dyke safety along the Scheldt estuary for the years 2015-2050-2100, based on the required dyke heights and an alternative wind statistic for the Western Scheldt. Basing the conclusion on a quantitative software analysis calculating the hydraulic load levels of each dyke segment for nine return periods for the current situation and two sight years. Five sub-questions were created to answer the main research question accurately.

The first sub-question aimed to understand the current situation on the dykes, for the Western Scheldt this means that most dyke segments do not pass their norms, though this is not the case for each section within the individual dyke segments. The southern side experiences the highest maximum and average hydraulic load levels. The amount of locations experiencing transgression in the north is 56 of 236 and in the south 156 of 281. The Eastern Scheldt resulted in lower load levels, with only a few sections in 26_2; 26_3 and 27_2 experiencing transgression at the safety norm and within 31_ 2 coming close to the current crest height though not transgressing it. 86 of 553 locations on the north side of the Eastern Scheldt experience transgression, and 4 of 301 on the southern side.
Almost every dyke segment shows more variation between dyke sections for the overtopping discharges 5 and 10 l/s/m. In contrast, the water level calculation is uniform throughout all sections of a segment, with minimal deviation from others within the sub-area. Deriving one defined crest height for each section based on the water level calculation does not encompass the entire load level. Instead, a generalised required crest height per section derived from the hydraulic load level calculation for overtopping discharge 5 l/s/m. Therefore, the required crest height ranges between 7.0-10.0 m in the north and 7.7-13.0 m on the south side of the Western Scheldt. The crest heights of the Eastern Scheldt range between 4.0- 8.5 m in the north and between 4.0-7.0 m in the south.

By 2050 and 2100, an increase in the hydraulic load levels is expected as a result of sea-level rise; however, the amount by which it increases per locations varies widely. This increase in the required crest height is what the second sub-question addresses. The results follow the same pattern as 2023 in their differences between locations. Whether it is the uniformity of the water level results or the variable hydraulic load level results, the results indicate the same points to have high or low load levels. The locations already experiencing transgression keep facing it at higher load levels. Whereas, more locations start experiencing transgression, especially by 2100. In the Western Scheldt, only most segments 29, and 30-3 will not experience transgression at their norm. The number of locations that experience transgression is 125 of 236 in the north and 219 of 281 location in the south by 2100.
In contrast, the Eastern Scheldt resulted in a minimal increase, with the same segments experiencing transgression of the crest height. On the south side, a few small sections experience load levels close to the crest heights. In numbers, it means that about 108 of 543 location in the north and 9 of 309 in the south experience transgression.
As the load levels rise so does the required crest height. In the Western Scheldt, it ranges from 6.4-11.0 by 2050 and 6.5-11.5 by 2100 for the northern side. On the southern side, it increases to between 8.0-13.5 m by 2050 and 9.6-14.0 m by 2100. The Eastern Scheldt, on the other hand only increased to a range between 4.0-8.9 m by 2050 and 4.1-9.2 m by 2100 in the north side. On the southern side, the ranges increased to 4.2-7.2 m by 2050 and 4.4-7.4m by 2100.

Within each dyke segment, there are often significant deviations between the sections, though what are the segments and sections which experience the most substantial hydraulic loads and under which wind conditions? The dyke orientations play a significant role in the difference between sections within the locations. When comparing the dyke segments and sections on the northern side of the Western Scheldt, shows that dykes facing the mouth of the estuary experience the highest load levels, increasing in height as we move eastward. Segment 223 is an excellent example of this as it is perpendicular to the mouth of the estuary has a semi-open run-up area, and the water is funnelled. Most segments on this side are sheltered from northern wind directions, and only southwest to southern winds have perpendicular run-up to most dykes.
On the other hand, the south side of the Western Scheldt has dykes facing either perpendicular to the mouth of the estuary or at mostly acute angles in line with the contributing wind directions. A similar pattern also occurs in the northern side of the Eastern Scheldt. However, most southern side sections are also sheltered through facing away from the mouth of the estuary and the exceptions to this experience comparatively higher load levels. The dykes orientation compared to the contributing wind direction and mouth of the estuary are often leading in the hydraulic load levels. Both the Eastern and Western Scheldt's results show the same patterns in which orientations experience high load levels and which do not.

Moreover, the differences between the sight years 2023 (current), 2050 and 2100, vary between segments. Where in the Eastern Scheldt most locations see increases only by decimetres or even by centimetres. In contrast, the Western Scheldt experiences increases of up to a meter between 2050 and 2100. Comparing these increases to the presented sea-level rise as used by hydra-NL from table 2, are in-line with the results for the Western Scheldt. Though the Eastern Scheldt does not show the same comparison, as within the estuary the effect should only become apparent as the barrier fails or at the higher return periods; therefore, the results are substantially lower. Each location undergoes a different increase though all locations, even those with high loads follow similar degrees of increase throughout the segment.

The second part of the main question specific to the Western Scheldt presents a different wind statistic to use within hydra-NL. The final sub-question aims to indicate the significant difference in the calculated hydraulic loads of Western Scheldt if using the alternative statistical wind data. Just like the results for the hydraulic load levels, the relative difference per location is non-uniform. The average difference percentage was calculated between 4 and 40 cm on the northern side and 40 to 80 cm on the southern side. Though in Figure 11 and Figure 12 the distribution of the differences in the histogram indicates the most frequent differences on the northern side range between 10-30 cm up to 60 cm, and 30-60 cm up to 1.2 meters difference on the southern side.

In short, the Western Scheldt's dyke segments except for a few experience transgressions of over 50% of location on both sides by 2100. Whereas the Eastern Scheldt is less affected by sea-level rise experiencing transgression at 20% of its locations in the north and only 3% in the south. The required crest heights for the entire Scheldt estuary ranges from 4 to 14 meters. Then the alternative wind statistics follow the same patterns in their results, though using wind data from Cadzand resulted in an increase of up to 1.2 meters on the southern side. However, on average, the differences range from 10 to 60 cm throughout the Western Scheldt.

The results presented above were generated using a probabilistic approach within WBI2017 software, where for the Western Scheldt an alternative for the continuous stochasts wind speed was used. A worst-case scenario was generated by using the OI2014 scenario W+, as the basis within hydra-NL, for the failure mechanism of wave run-up and overtopping at discharge 5 and 10 l/s/m. The resulting hydraulic load levels of both the water level and the hydraulic load level calculations at each segment's norm compared to the current dyke height indicated which dykes pass and which fail. As expected, the alternative wind directions did generate higher load levels for the hydraulic load level calculations. Though the majority of results stay around the 0.5 meters or lower difference, only a limited amount of locations experience over 0.75 meters of difference. In the case that several decimetres of transgression are allowed before a dyke is failed, the difference is then not as substantial. Moreover, in tables Table *4* and Table ***6***, the comparison of location which would experience transgression is laid out, which results in only slightly higher results.

To conclude, as introduced at the start of the report, it serves as an indication of the current state of the Scheldt estuaries dykes. To support Rijkswaterstaat with their involvement in the knowledge program *''Zeespiegelstijging''*, even though the results give a more global overview. The new software for the on-going assessment round had not yet been used to assess the hydraulic load levels of the primary defences[8]. The analyses presented gives insight on the location within the database, which is rather global compared to the data used by the waterboard. However, this does fall within the limitations of the report. Thus, even by giving a global overview instead of an in-depth one, the results will be able to aid them in their advisory role within the program. The results show that in the worst-case scenario, a substantial number of dykes experience transgression at the norm, though this does not mean that they fail a wbi2017 assessment. Therefore, the results have to be taken as a global overview, which can support advice and needs further in-depth research to lead reinforcements. The second part of the question on the alternative wind statistic served to answer which statistic would be best to use, which indicated that Cadzand does result in slightly higher results.

The indications and overview given in this thesis are there to support and give a global first look into the current situation; it is now a task to go into more depth to assess and take action where needed to ensure the safety of the hinterlands.

[8] There are several other students working on other system, giving insight in the state of their primary defenses

Chapter 8. Recommendations

As the results indicate, most of the Western Scheldt's dykes do not pass their safety norms in the global sight set. Acting on adjusting them or their foreland is needed to ensure the safety of the hinterland. Whereas the Eastern Scheldt's dykes do pass their norms for the most part, though the dykes of the south are experiencing pressures reaching close to their crest. As this is a global overview, it is recommended for the governing body to perform a more in-depth test and act on the results.

As the profile data has been out-dated by the latest adjustments to several dyke segments, it would be recommended to apply the changes to the profiles. As the current assessment round using the WBI2017 and OI scenarios are in progress, checking the profiles by comparing them to the AHN is recommended. In the case that there are substantial differences, the profiles should be adjusted to get a more accurate assessment of the safety.

Next, the wind statistical data from Cadzand proved to generate higher load levels, especially for the south side of the Western Scheldt. Using it to double-check when assessing the results, is recommended. Such a double-check does not have to be a detailed assessment; instead, a simple test would suffice. Thus, validating the results and seeing if there are any points which would need a different conclusion to its assessment.

In the case of a repeat of the research, it is advisable to compare all segments on two return periods such as 1:1000 and 1:300.000 to definitively show how significant differences are between the segments. Another addition would be to compare the moderate and warm+ climate scenarios, as due to time the moderate climate scenario was excluded. These two additions would take more time, however, are advised to create a more encompassing conclusion. Whereas when additional research is performed, it would be advisable to go into more depth on the cross-sectional requirements. Using these instead of the safety requirements from the *Water wet* allows for more in-depth analysis of the flood probability. Further research using those requirements are planned for the current assessment round, and the global overview as presented is a basis on which further research can be built. In doing this, the result will become more accurate and be able to start reinforcements where needed.

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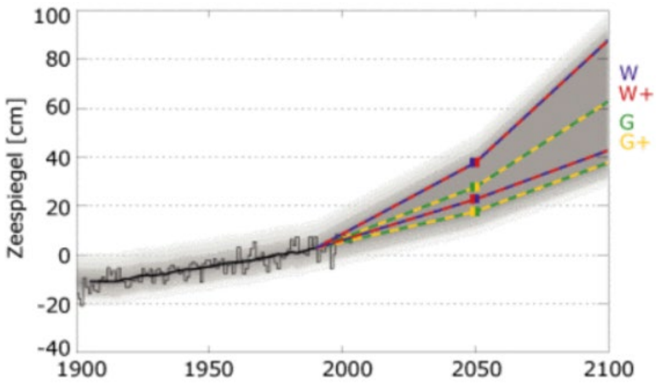
Appendix 1. ''Faalkanseisen''

Dyke tract	Length [km]	dyke ring	Norm [1/year]	max change of failure [1/year]	N_{HT} [-]	Required failure chance height	Signalling value	Bottom limit
26-1	*17,3*	*26*	*1/3000*	*1/3000*	*Dune*	*-*	*1/3000*	*1/1000*
26-2	*20,7*	*26*	*1/3000*	*1/1000*	*2*	*1/8330*	*1/3000*	*1/1000*
26-3	*21,9*	*26*	*1/10.000*	*1/3000*	*2*	*1/25.000*	*1/10.000*	*1/3000*
27-1	*16,2*	*27*	*1/3000*	*1/1000*	*2*	*1/8330*	*1/3000*	*1/3000*
27-2	*36,8*	*27*	*1/10.000*	*1/3000*	*2*	*1/25.000*	*1/10.000*	*1/10.000*
28-1	*23,9*	*28*	*1/1000*	*1/300*	*2*	*1/2500*	*1/1000*	*1/300*
29-1	*38,9*	*29*	*1/10.000*	*1/10.000*	*Dune*	*-*	*1/3000*	*1/1000*
29-2	*7,1*	*29*	*1/100.000*	*1/30.000*	*3*	*1/375.000*	*1/10.000*	*1/3000*
29-3	*12,5*	*29*	*1/1000*	*1/300*	*3*	*1/3750*	*1/100.000*	*1/30.000*
30-1	*22,6*	*30*	*1/3000*	*1/1000*	*2*	*1/8330*	*1/3000*	*1/1000*
30-2	*4,5*	*30*	*1/100.000*	*1/30.000*	*2*	*1/250.000*	*1/100.000*	*1/100.000*
30-3	*27,5*	*30*	*1/3000*	*1/1000*	*2*	*1/83.330*	*1/3000*	*1/1000*
30-4	*2,1*	*30*	*1/1.000.000*	*1/300.000*	*2*	*1/2.500.000*	*1/1.000.000*	*1/1.000.000*
31-1	*19,3*	*31*	*1/30.000*	*1/10.000*	*2*	*1/83.330*	*1/30.000*	*1/10.000*
31-2	*28,7*	*31*	*1/10.000*	*1/3000*	*2*	*1/25.000*	*1/10.000*	*1/3000*
32-1	*20,8*	*31*	*1/1000*	*1/300*	*2*	*1/2500*	*1/1000*	*1/300*
32-2	*11,6*	*32*	*1/1000*	*1/300*	*2*	*1/2500*	*1/1000*	*1/300*
32-3	*15,2*	*32*	*1/1000*	*1/300*	*2*	*1/2500*	*1/3000*	*1/1000*
32-4	*37,9*	*32*	*1/3000*	*1/1000*	*2*	*1/8330*	*1/3000*	*1/1000*

Appendix 1. Table 1 The norm for the chance of failure per Dyke track, focused on the failure mechanism of height, based on the flood risk norm at a fixed chance of failure, the red background colour shows the two tracts that will not be tested as these are a dune system. (Rijkswaterstaat, 2015) *The signalling value bottom limit based on the Water Wet 1-1-2020*

Appendix. 2. The climate scenarios

2.1. KNMI’06

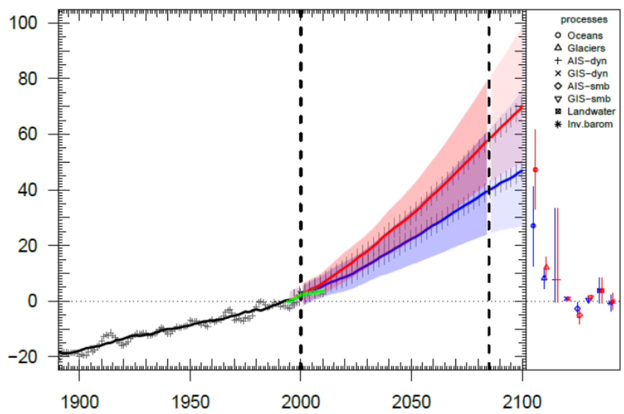


Appendix 2. Graph 1 The yearly average water level at the Dutch coast from 1900 to 2004 compared to the NAP, with the four climate scenarios for 2100. (KNMI, 2006)

2.2. KNMI’14

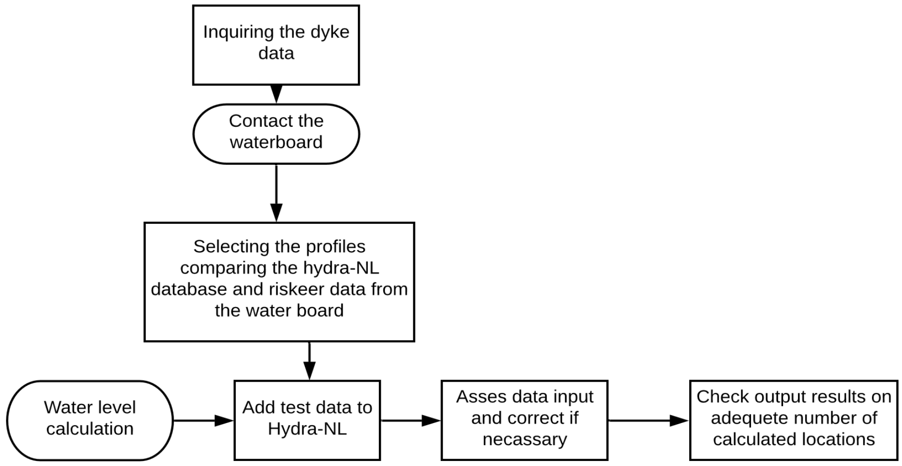
NORTHSEA	Low (2050)	Low (2085)	High (2050)	High (2085)
Oceans	07 to 20 cm	13 to 34 cm	14 to 27 cm	29 to 50 cm
Glaciers	02 to 05 cm	04 to 10 cm	04 to 07 cm	07 to 13 cm
AIS-dyn	01 to 11 cm	00 to 26 cm	01 to 11 cm	00 to 26 cm
GIS-dyn	00 to 00 cm	00 to 01 cm	00 to 00 cm	00 to 01 cm
AIS-smb	-2 to 00 cm	-4 to 00 cm	-2 to -1 cm	-6 to -2 cm
GIS-smb	00 to 00 cm	00 to 01 cm	00 to 00 cm	00 to 02 cm
Landwater	00 to 03 cm	00 to 07 cm	00 to 03 cm	00 to 07 cm
Inv.barom	-1 to 00 cm	-1 to 01 cm	-1 to 01 cm	-1 to 01 cm
Total	**14 to 32 cm**	**25 to 62 cm**	**22 to 40 cm**	**43 to 80 cm**

Appendix 2. Table 1 The processes contribution for the North Sea sea-level change concerning 1995, indicated by a range of 5-95%. The ranges do not include natural variability on the time-scales smaller than 30 years. The contribution termed "oceans" includes the ocean expansion and dynamic changes. (Hurk, et al., 2014)

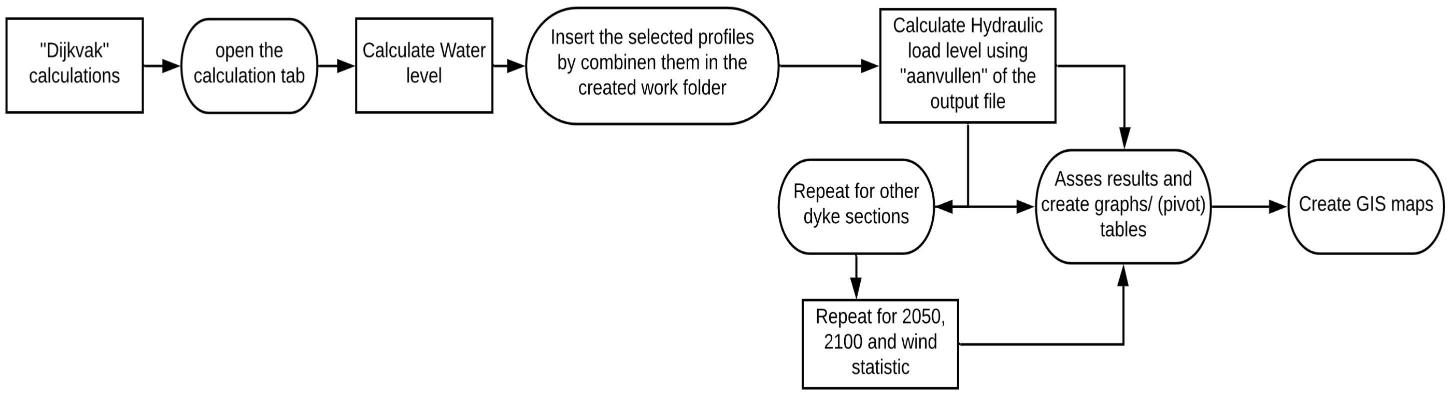


Appendix 2. Graph 2 KNMI'14 scenarios for the North Sea on mean sea-level rise and the range (shaded), compared to the reference period 1986-2005.. (Permanent Service for Mean Sea Level, www.psmsl.org) & (Hurk, et al., 2014)

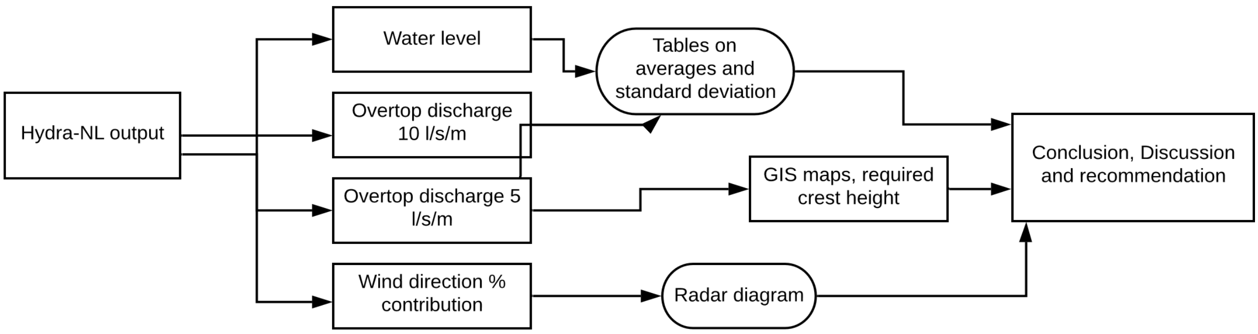
Appendix 3. Workflow diagram



Appendix 3. Figure 1 Flow diagram on profile data



Appendix 3. Figure 2 Flow diagram on the calculations and their visualisation



Appendix 3. Figure 3 Flow diagram on the process and parts leading to the conclusion, discussion and recommendation

Appendix 4. The water level calculation results

In the following appendix, the tables summarising the water level calculation results for each segment are shown starting with the northern part of the Western Scheldt and ending with the southern side of the Eastern Scheldt.

	29			***30_2***			***31_1***			***223***		
Return period	**2023**	**2050**	**2100**	**2023**	**2050**	**2100**	**2023**	**2050**	**2100**	**2023**	**2050**	**2100**
10	3.873	4.122	4.622	4.202	4.433	4.933	4.517	4.767	5.267	4.711	4.959	5.459
100	4.450	4.698	5.198	4.829	5.056	5.556	5.193	5.443	5.943	5.419	5.667	6.167
300	4.727	4.976	5.476	5.135	5.360	5.860	5.526	5.776	6.276	5.770	6.018	6.518
1000	5.034	5.282	5.782	5.474	5.697	6.197	5.897	6.147	6.647	6.161	6.409	6.909
3000	5.319	5.567	6.067	5.791	6.012	6.512	6.247	6.497	6.997	6.531	6.779	7.279
10000	5.639	5.887	6.387	6.148	6.367	6.867	6.642	6.892	7.392	6.949	7.197	7.697
30000	5.939	6.187	6.687	6.485	6.702	7.202	7.014	7.264	7.764	7.343	7.592	8.092
100000	6.279	6.528	7.028	6.868	7.083	7.583	7.438	7.688	8.188	7.788	8.036	8.536
300000	6.598	6.847	7.347	7.227	7.439	7.939	7.829	8.079	8.579	8.187	8.435	8.935

Appendix 4. Table 1 *The calculated average water level results [m] as calculated for the dyke segments in the north of the Western Scheldt, comparing both wind statistics*

	32_2			***32_3***			***32_4***		
Return period	**2023**	**2050**	**2100**	**2023**	**2050**	**2100**	**2023**	**2050**	**2100**
10	3.989	4.239	4.739	4.200	4.449	4.949	4.486	4.738	5.237
100	4.582	4.833	5.333	4.826	5.075	5.575	5.158	5.409	5.908
300	4.869	5.120	5.620	5.131	5.380	5.880	5.488	5.740	6.238
1000	5.187	5.438	5.938	5.469	5.718	6.218	5.856	6.108	6.606
3000	5.483	5.734	6.234	5.786	6.035	6.535	6.203	6.454	6.953
10000	5.816	6.066	6.566	6.143	6.392	6.892	6.594	6.846	7.344
30000	6.128	6.379	6.879	6.479	6.728	7.228	6.963	7.215	7.713
100000	6.484	6.734	7.234	6.862	7.111	7.611	7.382	7.634	8.132
300000	6.816	7.067	7.567	7.221	7.470	7.970	7.769	8.021	8.519

Appendix 4. Table 2 *The calculated average water level results [m] as calculated for the dyke segments in the south of the Western Scheldt, comparing both wind statistics*

	26_2			***26_3***			***27_1***			***27_2***		
Return period	**2023**	**2050**	**2100**	**2023**	**2050**	**2100**	**2023**	**2050**	**2100**	**2023**	**2050**	**2100**
10	3.090	3.162	3.286	3.327	3.296	3.471	3.535	3.596	3.655	3.439	3.502	3.590
100	3.277	3.332	3.394	3.532	3.464	3.584	3.796	3.815	3.810	3.662	3.689	3.720
300	3.354	3.388	3.420	3.609	3.521	3.623	3.902	3.910	3.890	3.746	3.760	3.774
1000	3.406	3.426	3.465	3.675	3.564	3.671	4.012	4.017	3.991	3.827	3.833	3.843

3000	3.445	3.463	3.539	3.734	3.603	3.730	4.110	4.113	4.090	3.900	3.904	3.922
10000	3.490	3.522	3.724	3.799	3.651	3.867	4.211	4.216	4.214	3.981	3.987	4.043
30000	3.547	3.610	4.025	3.858	3.714	4.148	4.295	4.306	4.395	4.056	4.070	4.255
100000	3.660	3.846	4.440	3.948	3.919	4.563	4.391	4.423	4.784	4.145	4.194	4.644
300000	3.895	4.196	4.765	4.132	4.282	4.877	4.498	4.642	5.099	4.262	4.458	4.958

Appendix 4. Table 3 *The calculated average water level results [m] as calculated for the dyke segments in the north of the Eastern Scheldt.*

Return period	*2023*	*2050*	*2100*	*2023*	*2050*	*2100*	*2023*	*2050*	*2100*
	28_1				**30_1**			**31_2**	
10	3.120	3.185	3.303	3.372	3.437	3.527	3.524	3.583	3.655
100	3.305	3.347	3.405	3.575	3.605	3.636	3.755	3.774	3.794
300	3.377	3.405	3.427	3.648	3.664	3.678	3.841	3.851	3.860
1000	3.423	3.433	3.462	3.712	3.718	3.727	3.931	3.934	3.942
3000	3.448	3.456	3.537	3.766	3.770	3.791	4.015	4.017	4.032
10000	3.479	3.509	3.736	3.831	3.839	3.924	4.110	4.115	4.159
30000	3.534	3.611	4.039	3.893	3.913	4.189	4.198	4.210	4.349
100000	3.667	3.865	4.461	3.976	4.065	4.606	4.298	4.334	4.706
300000	3.919	4.218	4.789	4.126	4.390	4.919	4.408	4.559	5.012

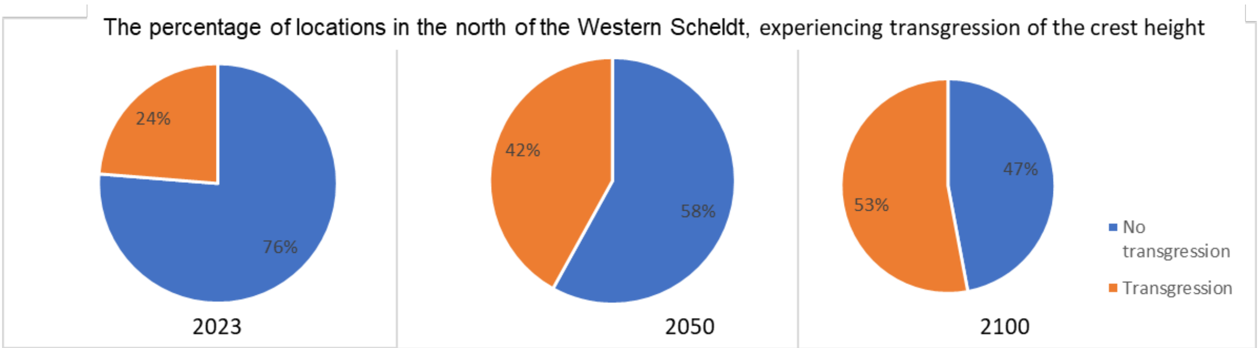
Appendix 4. Table 4 *The calculated average water level results [m] as calculated for the dyke segments in the north of the Eastern Scheldt*

Appendix 5. The required crest height tables.

In the following appendix, the tables with the required crest heights for each sight year of the sections are shown, with new figures of transgression for the Western Scheldt.

Name dyke segment	*2023*	*2050*	*2100*
	29		
Buitenhaven Vlissingen	6.8	7.4	7.8
Zuidwatering	8.5	8.8	9.4
Westelijke Sloehaven	5.2	5.5	6.5
Oostelijke Sloehavendam			7.6
	30_2,3,4		
Van Citterspolder	10.75	11	11.5
Borsselepolder West	-	9	9.9
Borsselepolder lage tafel	-	6.7	7
Borsselepolder Oost	-	7	7.5
Ellewoutsdijkpolder	-	8	9.1
Ellewoutsdijk fort	-	7.9	8.2
Everingepolder Van Hattumpolder	-	8.8	9.3
Zuidpolder	-	9	9.8
Baarlandpolder	-	7.4	8.3
Hoedenskerke Restant	-	7.6	8.4
Hoedenskerke fase 1	-	7.7	8.6
Biezelingse ham	-	6.4	6.9
Willem-Annapolder	7	7.6	8.4
Breede Wateringen bewesten Yerseke	9.8	10.1	10.7
Hansweert	10.0	10.4	11.2
	31_1		
Kruiningenpolder	7.0	7.0	10.0
Oost-Inkelenpolder	8.3	8.8	9.5
Waarde- en Westveerpolder	9.7	10.3	11.0
Emanuelpolder	9.5	9.7	10.2
Zimmermanpolder	8.2	9.1	10.4
Reigersbergschepolder	8.7	9	9.8
	223		
PaviljoenPolder	10.0	10.3	11.5

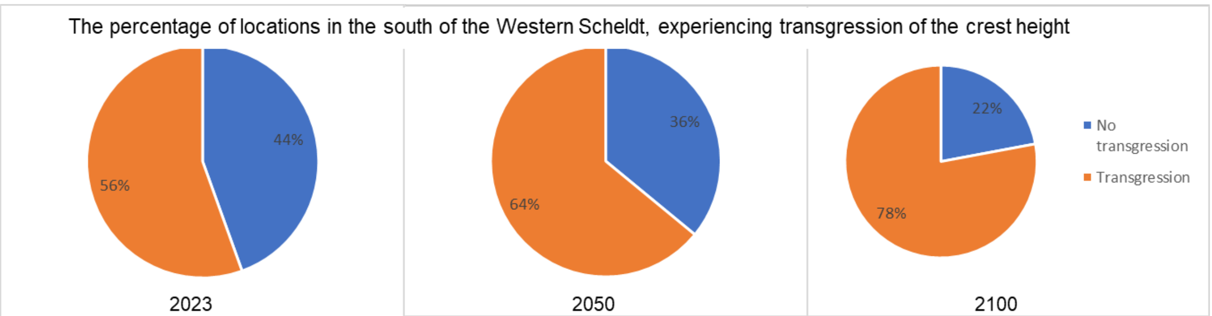
Appendix 5. Table 1 *The required crest height based on the generalised hydraulic load level per dyke section for the segments safety norm in the current situation, 2050 and 2100*



Appendix 5. Figure 1 *The fail and pass percentages of all locations on the north side of the Western Scheldt combined, for each of the calculated years, using Cadzands wind statistic*

Name dyke section	***2023***	***2050***	***2100***
	32_2		
Hand van Kruiningenpolder	10.0	10.4	11.3
Voorland Nummer een	8.9	9.3	10.2
Hoofdplaatpolder	7.7	8	8.7
	32_3		
Paulinapolder	10.7	11.2	12.1
Mosselbanken	11.4	11.9	12.7
Braakmanpolder	10.9	11.3	12.0
Nieuw Neuzen	12	12.4	13.3
Terneuzen havens	9.6	10.0	10.7
Terneuzen boulevard	11.0	11.3	12.0
Ser Lippenspolder	11.2	11.5	12.3
	32_4		
Nieuw Othenepolder	12.7	13.3	14.0
Overlagingen Zeeuws-vlaandered	11.8	12.8	12.9
Eendragtpolder	12.5	12.9	13.7
Hellegatpolder	12.0	12.4	13.3
Ser Arendspolder	12.8	13.2	14.0
Kop van Ossenisse	12.3	12.6	13.3
Perkpolder	9.2	9.4	9.9
Noorddijkpolder	8.5	8.8	9.4
Walsoorden Havendammen	10.4	10.7	11.5
Wilhelmus- en Kruispolders	10.0	10.4	11.2
Saeftinghe 2	7.9	8.3	8.9
Saeftinghe 1	9.3	9.8	10.8
Emmapolder	7.7	8.0	8.6

Appendix 5. Table 2 *The required crest height based on the generalised hydraulic load level per dyke section for the segments safety norm in the current situation, 2050 and 2100*



Appendix 5. Figure 2 The fail and pass percentages of all locations on the south side of the Western Scheldt combined, for each of the calculated years using Cadzand

Name dyke section	***2023***	***2050***	***2100***
	26_2		
Polder Burgh- en Westland	4.6	4.6	5.2
Burgsluis	5.4	5.3	5.4
Schelphoek West	4.3	4.0	4.5
Schelphoek Oost	5.2	5.5	5.7
Polder Schouwen	4.0	5.3	5.5
Kisters of Suzannas Inlaag	8.4	8.9	9.2
Zierikzee	8.0	8.9	9.2
	26_3		
Zuidhoek Zierikzee	7.1	7.9	7.9
Haven de val	7.1	7.1	7.1
Polder vierbannen	6.1	6.2	6.2
Viane	6.7	6.8	6.8
Oosterlandpolder	5.5	5.6	5.9
Bruinisse polder	5.4	5.5	5.5
Bruinisse	4.0	4.0	4.1
	27_1		
Anna Jacoba- en Prins Hendrikpolder	5.0	5.0	5.0
Anna Jacobapolder	5.0	5.2	5.2
Abraham Wissepolder	5.5	5.7	5.8
St. Phillipsland	5.2	5.2	5.2
Krabbenkreekdam	5.6	5.7	5.7
	27_2		
Van Haaftenpolder	5.3	5.3	5.4
Hollarepolder	5.5	5.5	5.6
Sint-Annaland	4.1	4.1	4.2
Moggershil	5.9	5.9	5.9
Oud Kempenshofstedepolder	6.5	6.5	6.6
Stavenissepolder	6.3	6.4	6.4
Stavenisse	5.7	5.7	5.7
Tholen 1	5.8	5.8	5.8
Geertrui- en Scherpenissepolder	6.5	6.6	6.6
Tholen 2	7.1	7.1	7.2

Appendix 5. Table 3 *The required crest height based on the generalised hydraulic load level per dyke section for the segments safety norm in the current situation, 2050 and 2100*

Name dyke section	***2023***	***2050***	***2100***
28_1			
Roompot	4.9	5.0	5.1
Sophiastrant	5.0	5.1	5.2
Vliete- en Thoornpolder	4.7	4.8	4.9
Nieuw Noord-Bevelandpolder	5.5	5.6	5.7
Oud Noord-Bevelandpolder	4.9	6.5	6.5
Alteklein	5.5	5.5	5.6
Leenderd abrahampolder	5.0	5.5	5.5
Zandkreekdam Wilhelminapolder west	4.0	4.2	4.4
30_1			
Wilhelminapolder Oost-Bevelandpolder	5.3	5.4	5.6
Stormesandepolder	7.1	7.2	7.2
Snoodijkpolder	6.6	6.6	7.1
Kanaal door Zuid-Beveland west	4.2	4.2	4.2
31_2			
Kanaal door Zuid-Beveland west	4.4	4.5	4.4
Koude en Kaarspolder	6.1	6.5	6.5
Yerseke	6.8	6.8	7.4
Sint Pieterspolder	6.3	6.5	6.5
Krabbendijke	6.7	6.8	7.4
Tweede Bathpolder	7.0	7.0	7.0
Bathpolder	6.5	6.5	6.5

Appendix 5. Table 4 *The required crest height based on the generalised hydraulic load level per dyke section for the segments safety norm in the current situation, 2050 and 2100*

Appendix 6. The average difference between wind statistics

The following two tables summarise the average difference for each segment, comparing the results of Cadzand and Vlissingen. The results are in meters, in chapter 5, the results these are highlighted in the text.

Calculation type	*Year*	29	30_4	30_3	30_2	31_1	223
Overtopping discharge 5 l/s/m	2023	0.0581	0.143	0.019	0.175	0.232	0.287
	2050	0.0669	0.0167	0.0194	0.183	0.231	0.348
	2100	0.0858	0.188	0.0201	0.206	0.256	0.384
Overtopping discharge 10 l/s/m	2023	0.0562	0.128	0.016	0.174	0.213	0.271
	2050	0.0444	0.123	0.154	0.176	0.212	0.325
	2100	0.0811	0.195	0.173	0.213	0.235	0.357

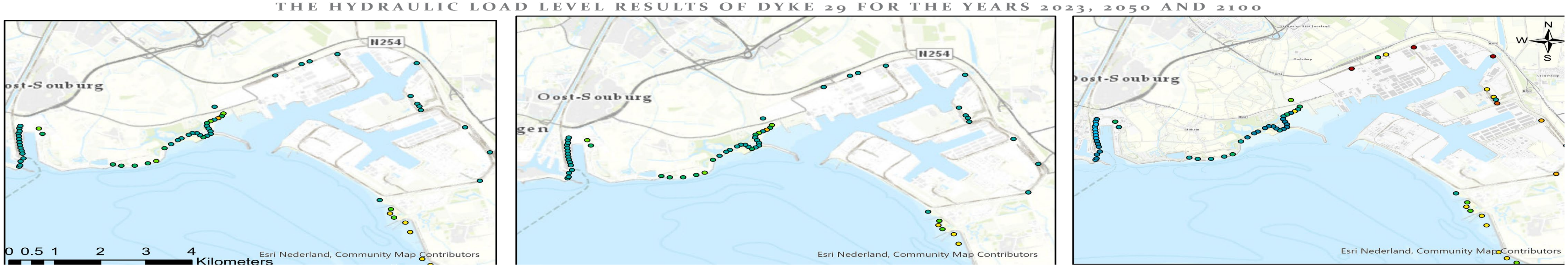
Appendix 6. Table 1 *The average relative difference between Cadzand and Vlissingen, of the dyke segments in the north of the Western Scheldt, for the years 2023, 2050 and 2100 at their safety norms*

Calculation type	*Year*	*Location*		
		32_2	32_3	32_4
Overtopping discharge 5 l/s/m	2023	0.387	0.695	0.525
	2050	0.403	0.716	0.614
	2100	0.435	0.760	0.588
Overtopping discharge 10 l/s/m	2023	0.342	0.619	0.510
	2050	0.355	0.639	0.540
	2100	0.385	0.679	0.584

Appendix 6. Table 2 *The average difference in meters of the results between Cadzand and Vlissingen, for selected locations at the dyke segments for the south Western Scheldt, at years 2023, 2050 and 2100 at their safety norms*

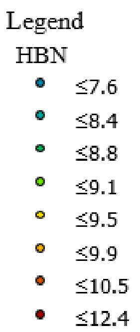
Appendix 7. The remaining maps

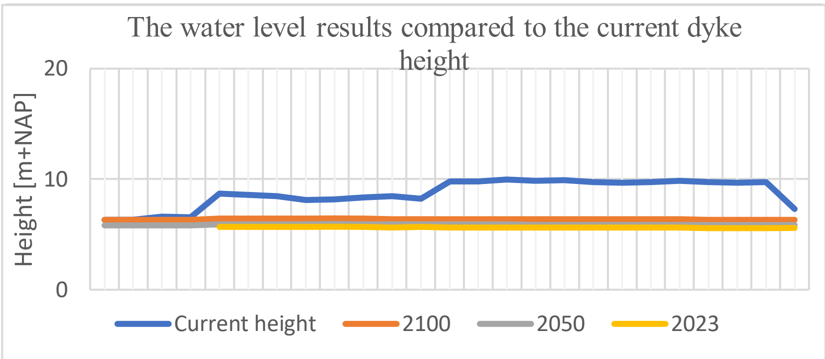
THE HYDRAULIC LOAD LEVEL RESULTS OF DYKE 29 FOR THE YEARS 2023, 2050 AND 2100

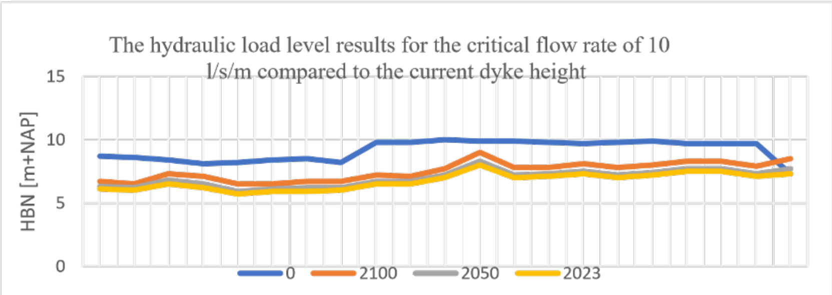


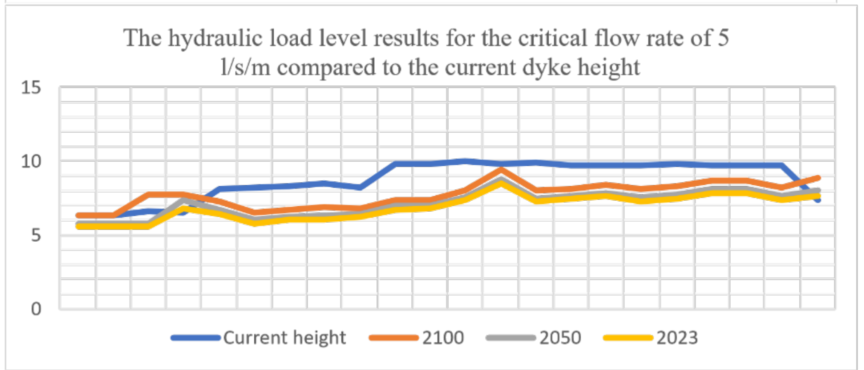
2023 2050 2100

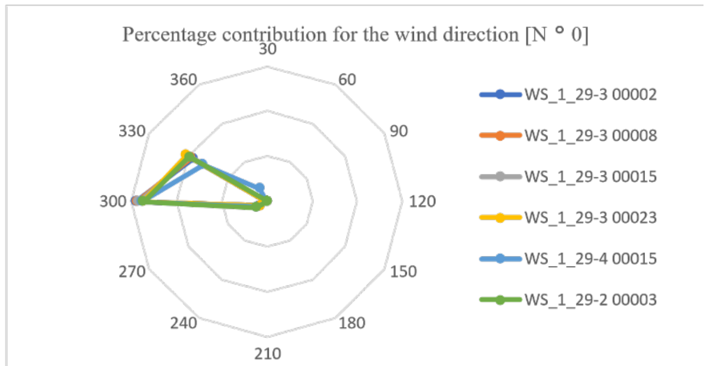
Appendix 7. Maps 1 2 and 3. The hydraulic load level results per location on dyke track 29, showing the results m+NAP











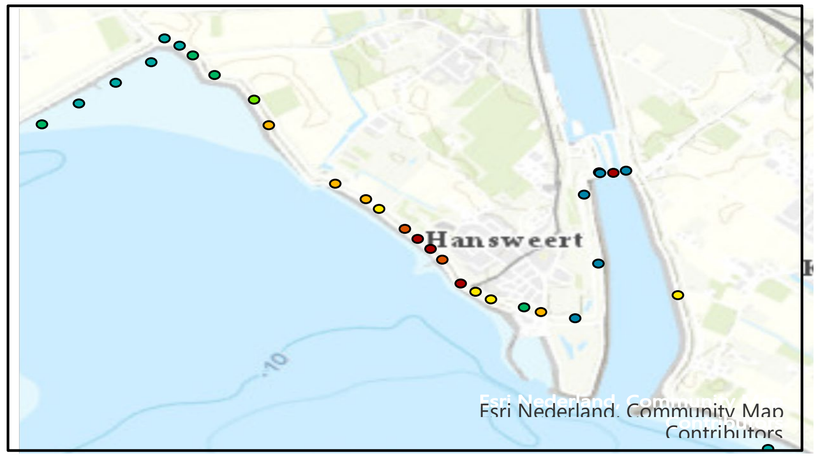
Appendix 7. Graphs 1 2,3 4. The hydraulic load level results of several calculations in m+NAP compared to the current dyke heights, graph four represents the contribution of each wind direction [%]

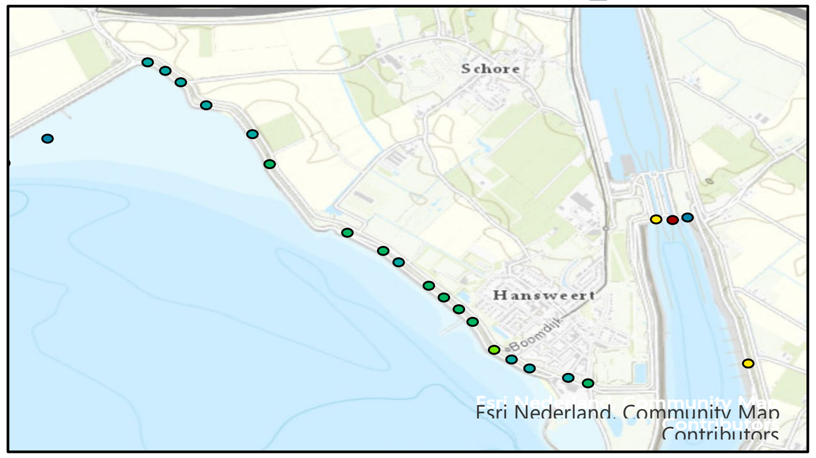
Each of the maps represents one of the calculated years, showing the hydraulic load level in m+NAP based on the critical overflow rate of 5 l/s/m. The locations are not at a uniform distance, x-axis, with the majority of points in the graph belonging to 29_3. This difference is caused by the limitation of a database within hydra-NL, as for 29_4, only one location was present. However, for 29_2, there was a more expansive database; only 1 location represented the data from the waterboard. Therefore, the results show a global point of view on the transgression locations. The two locations where transgression occurs in the graphs are at the front of the Sloehaven, and in Vlissingen Oost (29_4). Section *Zuidwateringen*

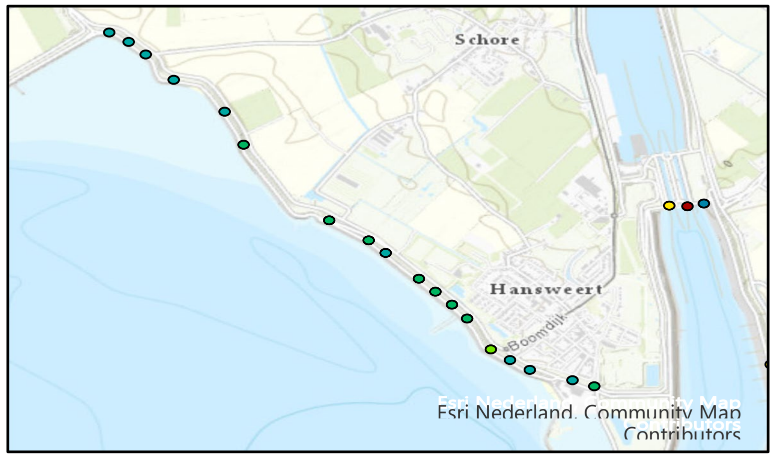
As previously stated, the water level calculations have uniform results of all locations. Whereas the hydraulic load level results show more significant differences between locations, even transgressing the current dyke height at a few points. In 2023 the highest experience load level is 11.526 m+NAP, however the transgression locations of the Sloehaven experience 6.8 m+NAP at most. 2050 increases the maximum load level to 11.940 m+NAP, though for the Sloehaven the dykes experience 7.4 m+NAP. However, in 2100 the maximum experiences load level is about 7.8 m+NAP, and the other points experience 6.3 m+NAP. The differences between the time frames are at most 0.5 meters; Between the two wind statistics, the difference also varies between locations though the average ranges between -5 to 30 cm.

Comparing the dyke orientations to the wind contributions show that the transgression points are less shielded, these dykes are oriented more towards the mouth of the estuary, whereas 29_3 or the middle of the maps are more shielded and therefore experience lower hydraulic loading.

THE HYDRAULIC LOAD LEVEL RESULTS OF DYKE 30_2 FOR THE YEARS 2023, 2050 AND 2100







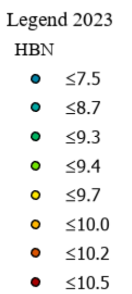
Appendix 7. Maps 4,5,6 The hydraulic load level results per location on dyke track 30_2, showing the results m+NAP

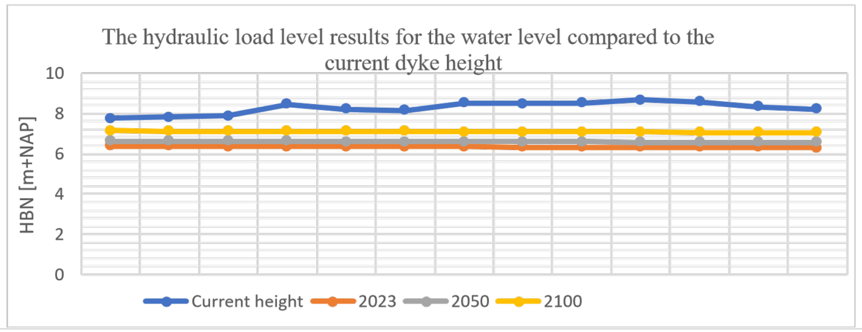
2023 2050 2100

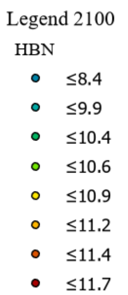
Each of the maps represents a calculated sight year, basing the shown hydraulic load level on the critical flow rate of 5 l/s/m. The locations are not entirely at uniform distances, with some locations close together and others further away. This difference is also present on the x-axis of the graphs, though the graph presents it as a uniform. The difference is in part due to the limitation of the database within hydra-NL, as these locations are not uniform. The database also encompasses fewer locations than the provided data set; therefore, the results show a global point of view on the transgression locations. As previously referenced, the water level calculations have uniform results of all locations. When comparing the results presented in graph 6 and 7 then all locations would experience transgression of the dyke.

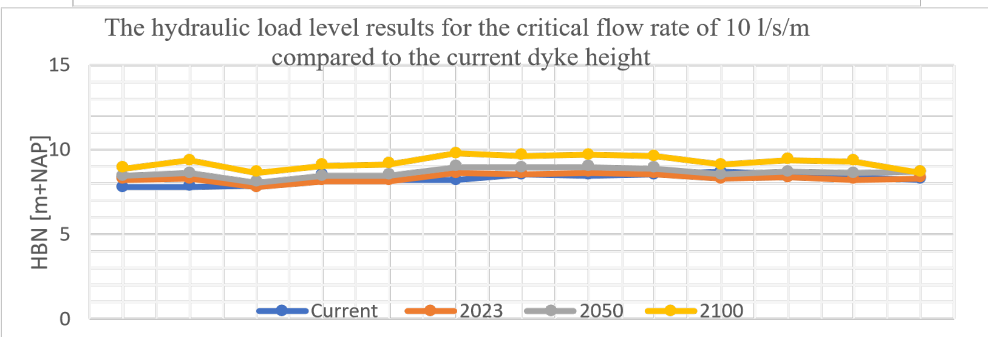
In the current situation (2023), there are a few locations that are either at or only just above the crest height. The highest experience load level is 10.498 m+NAP; however, the average experienced load level is 8.584 m+NAP. By 2050 the maximum load level increases to 10.892 m+NAP, and the average increases by 0.340 m to 8.930 m+NAP. However, by 2100 the maximum experiences load level increases to 11.689 m+NAP, and on average to 9.625 m+NAP. For all three time frames is the result that the current crest heights are insufficient. When comparing the differences between the time frames, then the highest increased overtime is 0.7 meters, between 2050 and 2100. This increase is quite significant though expected as a large amount of time has passed between the two. In contrast, between the two wind statistics, the significant difference varies between locations, from 0 to 50 cm.

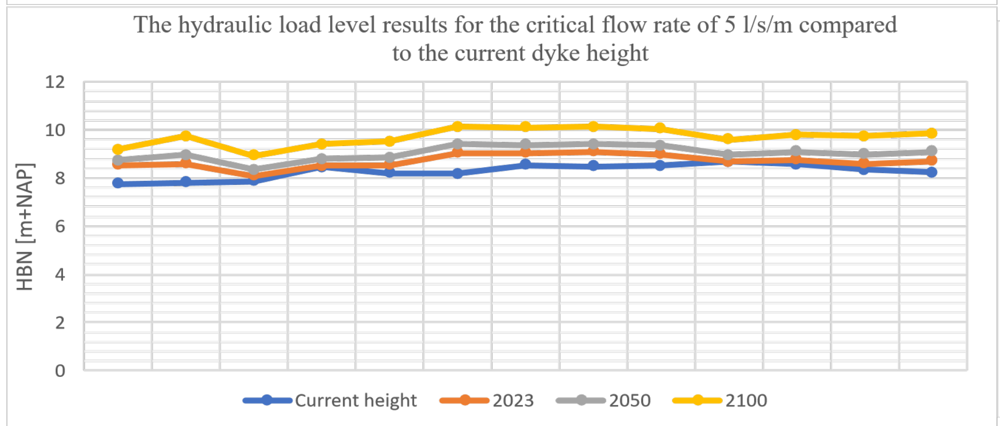
The dyke orientation compared to the wind directions contributions shows that the most significant contributing wind direction is at 300°. Which, together with the dyke orientation almost perpendicular to the bend creating an open area causing the higher hydraulic load levels.

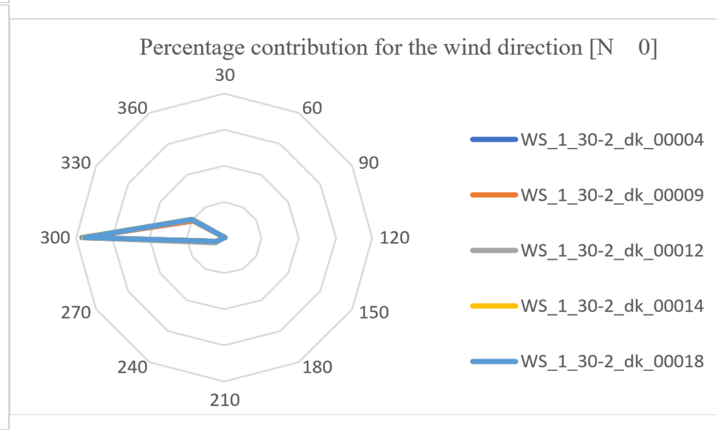












Appendix 7. Graphs 5, 6, 7, 8 The hydraulic load level results of several calculations in m+NAP compared to the current dyke heights, graph eight represents the contribution of each wind direction [%].

THE HYDRAULIC LOAD LEVEL RESULTS OF DYKE 30_4 FOR THE YEARS 2023, 2050 AND 2100

Legend 2023
- ≤6.9
- ≤7.3
- ≤7.7
- ≤8.0
- ≤8.3
- ≤8.8
- ≤9.4
- ≤10.4

Legend 2050 and 2100
- ≤7.6
- ≤8.4
- ≤8.8
- ≤9.1
- ≤9.5
- ≤9.9
- ≤10.5
- ≤12.4

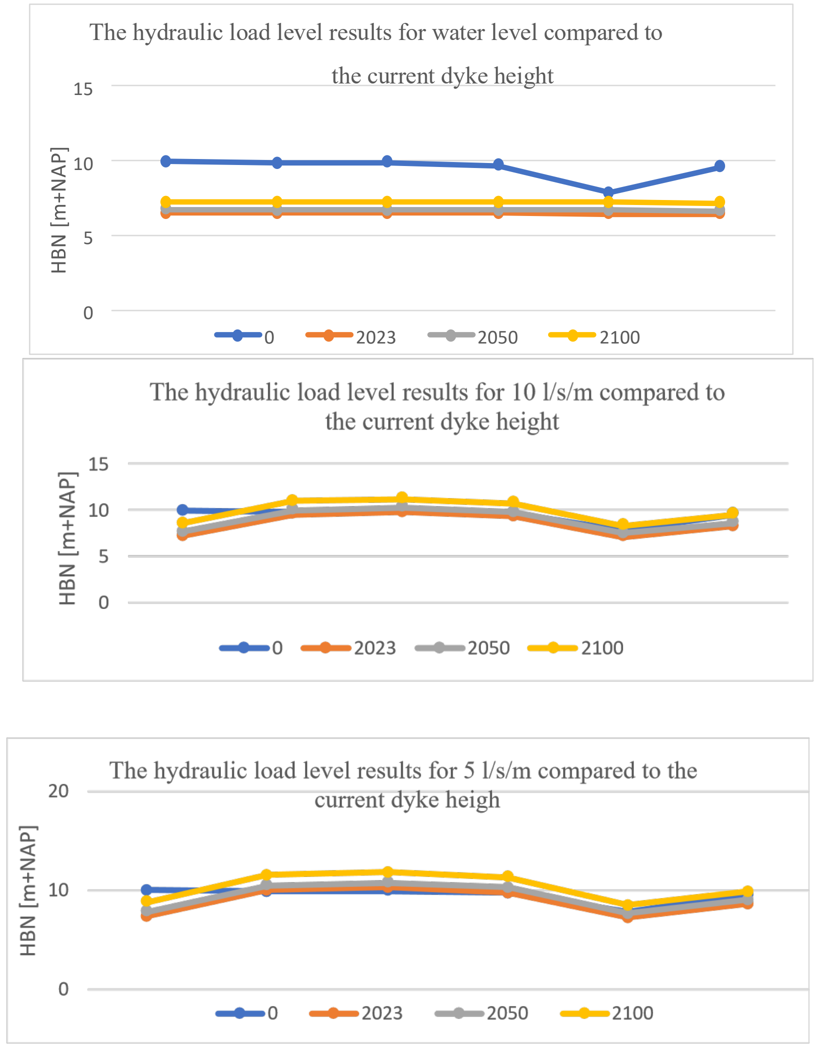
Appendix 7. Maps 7,8,9 The hydraulic load level results per location on dyke track 30_4, showing the results m+NAP

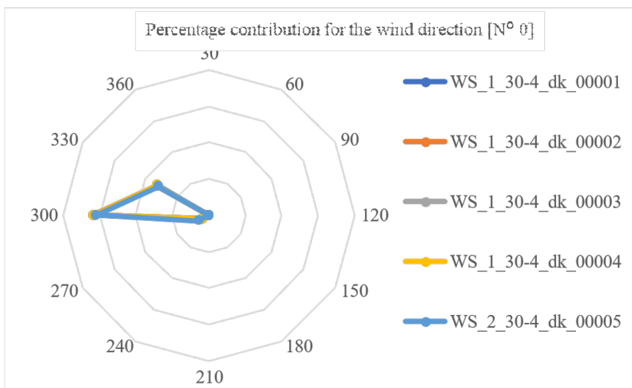
2023 2050 2100

Each of the maps represents one of the calculated years, showing the hydraulic load level in m+NAP based on the critical overflow rate of 5 l/s/m. Dyke section 30_4 is a small but not sheltered section. The distance between locations is not entirely uniform, though still closer to each other compared to other dyke sections. The non-uniform distance is presented as uniform by the x-axis affecting the comparison of the graphs to the map. Within the database of hydra-NL, there is a limited amount of points using them as the map layer. The maps represent all calculated locations, but these do not encompass all of the locations provided by the waterboard. Therefore, the results show a global point of view on the transgression locations. The shown legends vary slightly in the ranges, causing the difference in colours.

As previously said, the water level calculations have little differences in results of all locations, compared to the varying results of the critical overtopping discharges. Comparing the graphs 14 and 15 show that for both discharge location 2, 3, 4 and 6 would experience transgression of the crest height. In the current situation (2023), the highest experience load level is 10.955 m+NAP; with an average level of 8.957 m+NAP. By 2050 the maximum load level increases to 11.475 m+NAP, and the average increases by 0.50 m to 9.418 m+NAP. However, by 2100 the maximum experiences load level increases to 12.509 m+NAP, and on average to 10.306 m+NAP. The majority of the locations of dyke section 30_4 do not pass their safety norms now and in the future. The difference between the two flow rates is when the transgression takes place in time. Where for 5 l/s/m the load levels transgress the crest for all three years, it will only transgress in 2100 and be on edge for 2050 when looking at 10 l/s/m. When comparing the differences between the time frames, then the highest increase in overtime is 0.7 meters, between 2050 and 2100. In contrast, the two wind statistics, the significant difference varies between locations form -5 to 70 cm.

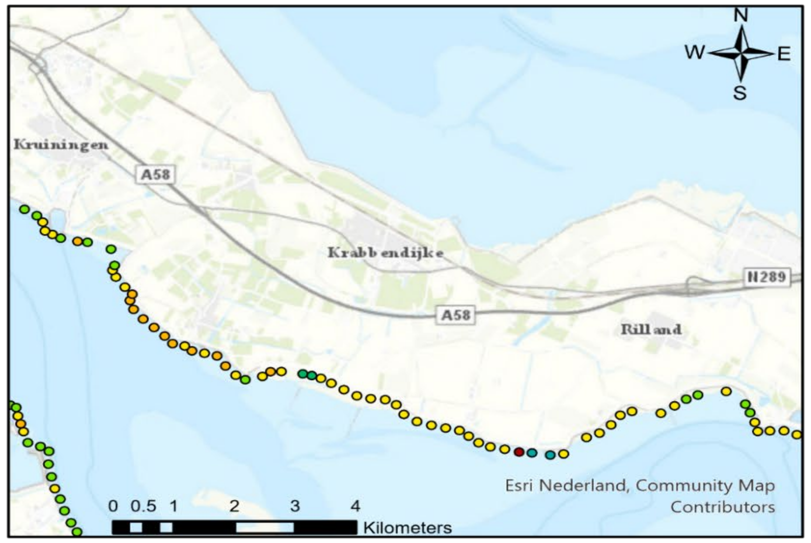
Dyke section 30_4 is right next to Vlissingen East, connecting to dyke 29. Comparing the wind direction to the dyke orientations supports the results as the most significant contributor is a north-western west wind which pushed vast quantities of water from the north down along the Dutch coast, the section experiences high loads by facing the mouth of the Western Scheldt.

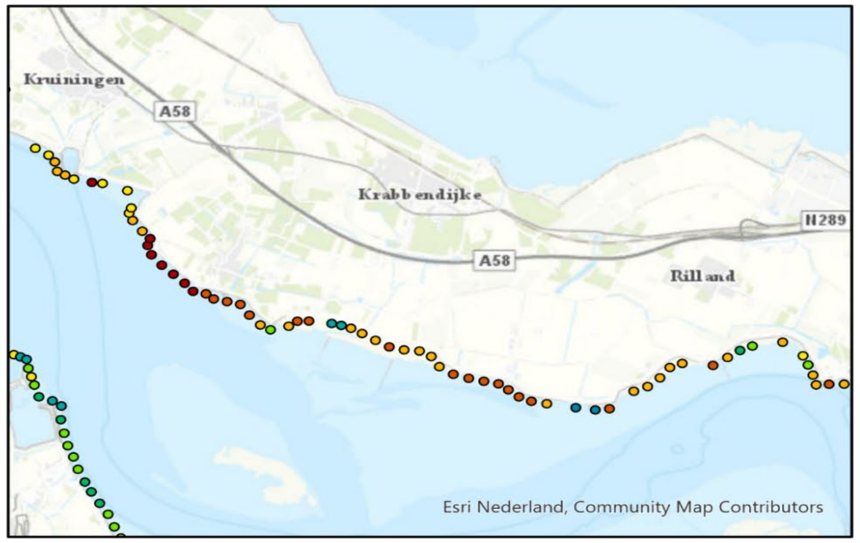


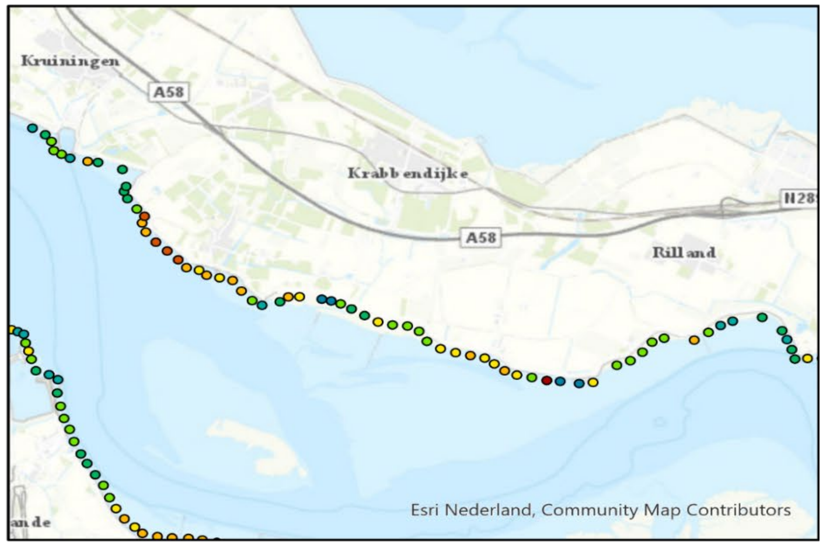


Appendix 7. Graphs 9, 10 , 11, 12 The hydraulic load level results of several calculations in m+NAP compared to the current dyke heights, graph twelve represents the contribution of each wind direction [%].

The hydraulic load level results for dyke segment 31_1 for the years 2023, 2050 and 2100



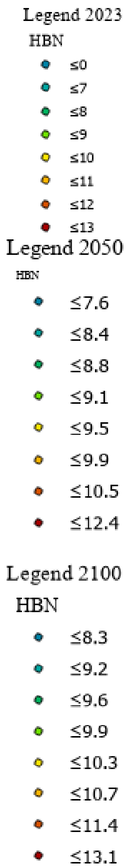


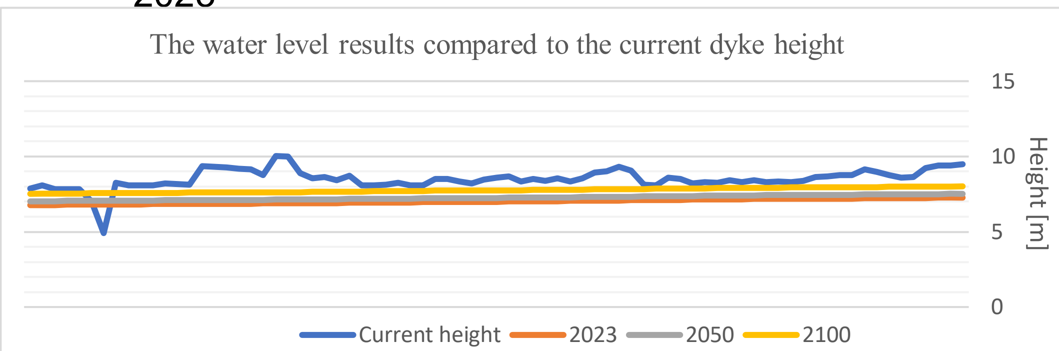


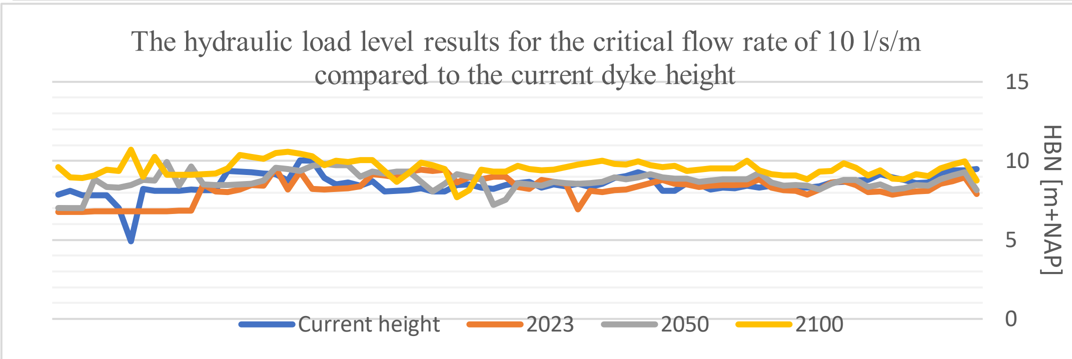
2023

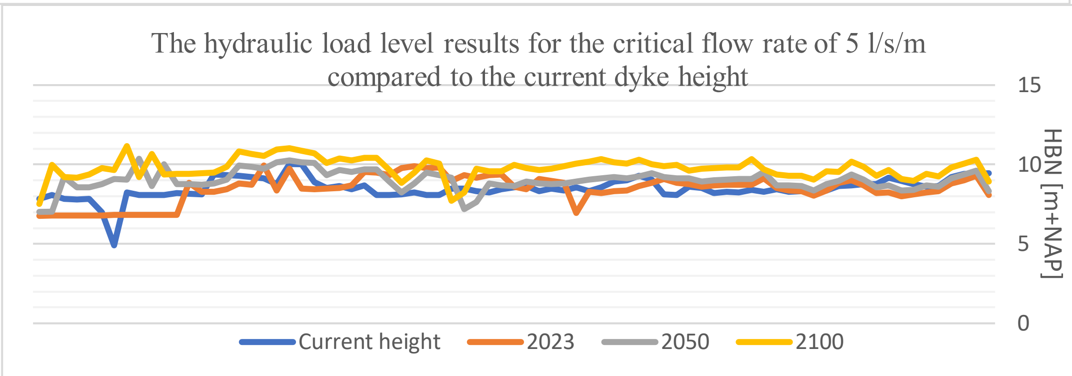
2050

2100





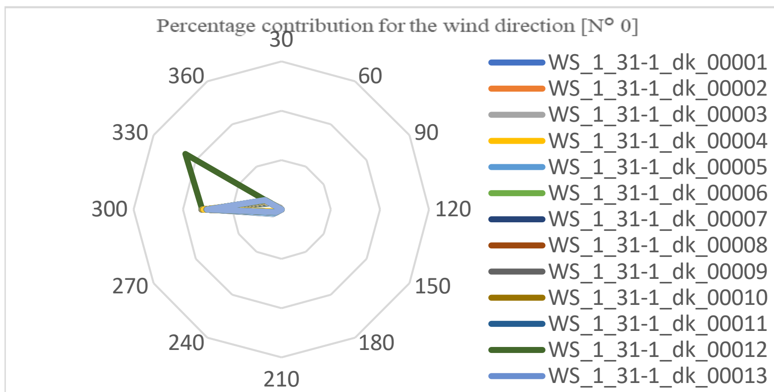




Each map represents one of the calculated years, showing the hydraulic load level in m+NAP based on the critical overflow rate of 5 l/s/m. Dyke section 31_1 is one of the larger segments of the Western Scheldt in which both sheltered and not sheltered locations are present. The distance between locations is not entirely uniform, though the different orientations are represented. The x-axis of the graphs does show the distance between locations as uniform, and the harbour near Kruiningen only has one point representing it. The used database of hydra-NL has a limited amount of points, using the shapefile of them as the maps layer, thus representing the calculated locations of the database. However, these locations do not encompass all of the locations provided by the waterboard. Therefore, the results show a global point of view on the transgression locations.

As previously said, the water level calculations have little differences in results of all locations, compared to the varying results of the critical overtopping discharges. The hydraulic load does decrease very minimally towards the right side of the map. In the current situation (2023), there some locations that experience transgression of the crest. The highest experience load level is 11.386 m+NAP; with an average level of 8.758 m+NAP. By 2050 the maximum load level increases to 11.737 m+NAP, and the average increasing to 9.078 m+NAP. However, by 2100 the maximum experiences load level increases to 12.434 m+NAP, and the average to 9.813 m+NAP. The majority of the locations do not pass their safety norms in the future. In the current situation, 44 out of 78 locations experience transgression, by 2100, 74 out of 78 experience transgression. When comparing the differences between the time frames, then the highest increase in overtime is 0.735 meters, between 2050 and 2100. On average, the relative difference caused by an alternative wind statistic ranges from 10 to 70 cm.

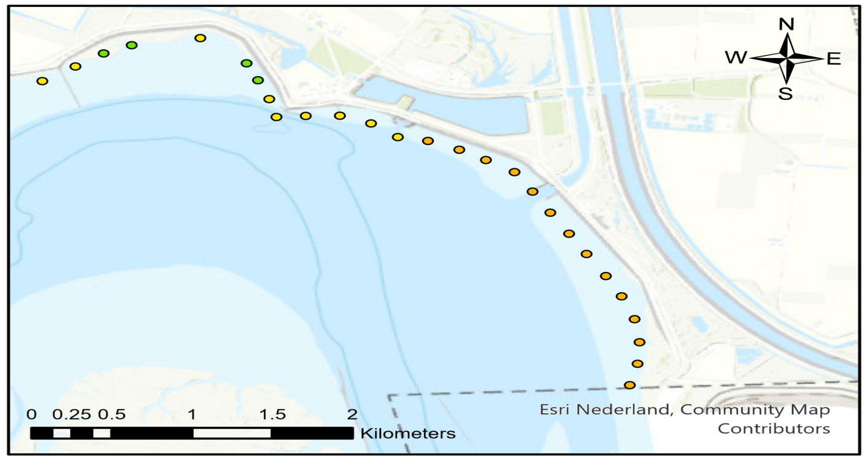
The most substantial wind directions contribution is at 300°, with some experiencing the most at 330°. Looking at the orientation and how it changes between points, shows that the non-sheltered locations experience higher load levels. The sections experiencing the highest loads are *Waarde- en Westveerpolder, and Emanuelpolder*. These are the non-sheltered sections.

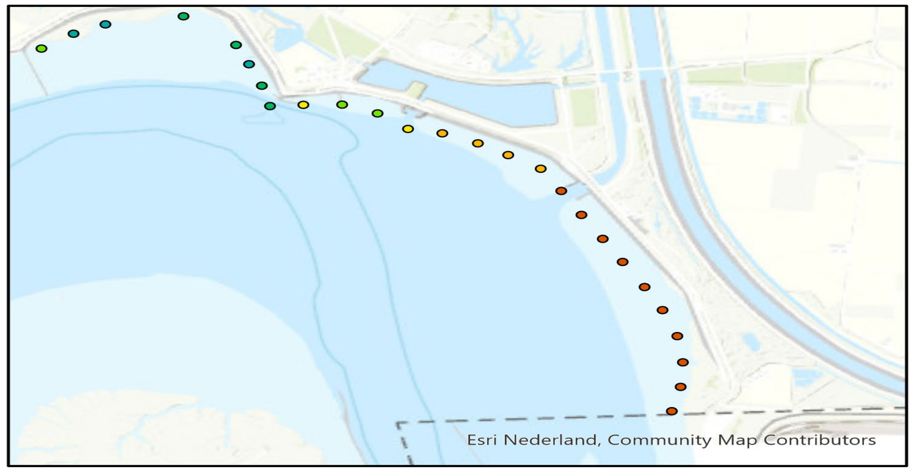


Appendix 7. Graph 13, 14, 15 and 16 The hydraulic load level results of several calculations in m+NAP compared to the current dyke heights, graph sixteen represents the contribution of each wind direction [%].

Appendix 7. Map 10, 11, 12 The hydraulic load level results per location on dyke track 31_1, showing the results m+NAP

THE HYDRAULIC LOAD LEVEL RESULTS OF DYKE 223 FOR THE YEARS 2023, 2050 AND 2100





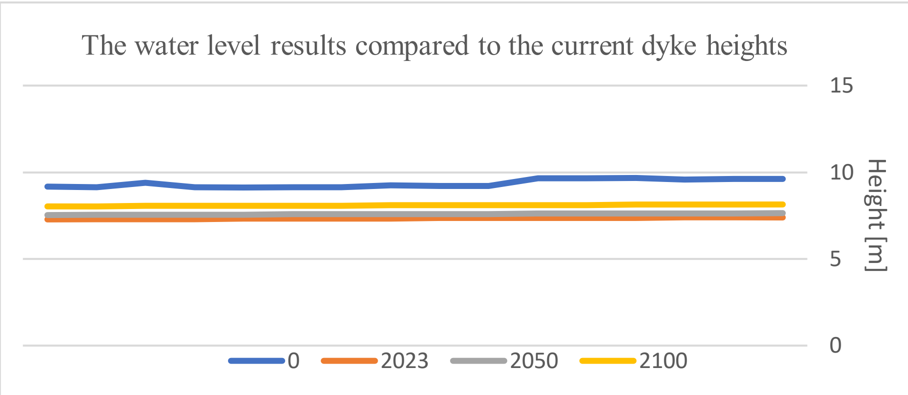
Appendix 7. Maps 13, 14, 15 The hydraulic load level results per location on dyke track 223, showing the results m+NAP

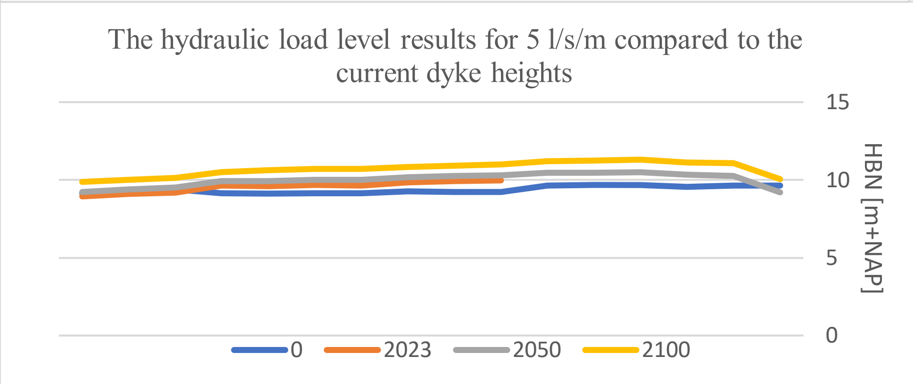
2023 2050 2100

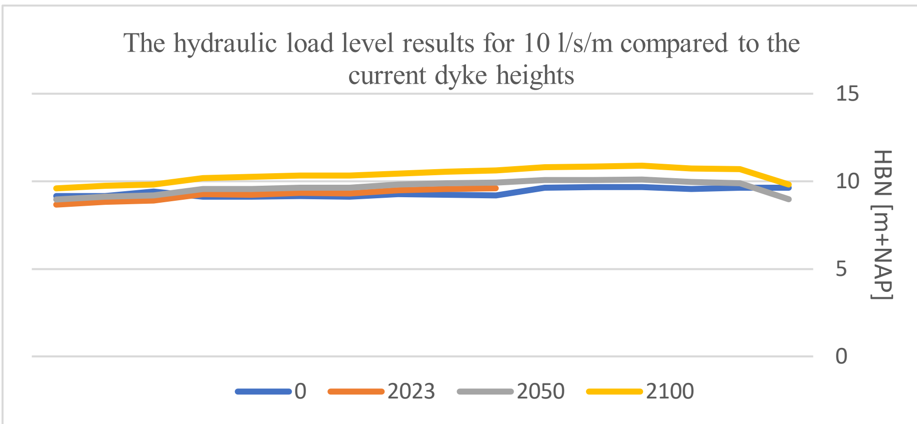
Legend 2023
HBN
≤0
≤7
≤8
≤9
≤10
≤11
≤12
≤13

Legend 2050
HBN
≤7.6
≤8.4
≤8.8
≤9.1
≤9.5
≤9.9
≤10.5
≤12.4

Legend 2100
HBN
≤8.3
≤9.2
≤9.6
≤9.9
≤10.3
≤10.7
≤11.4
≤13.1



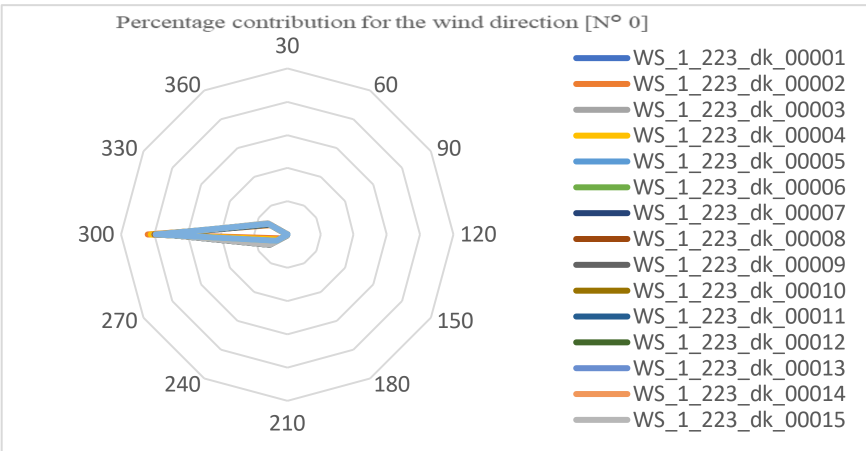




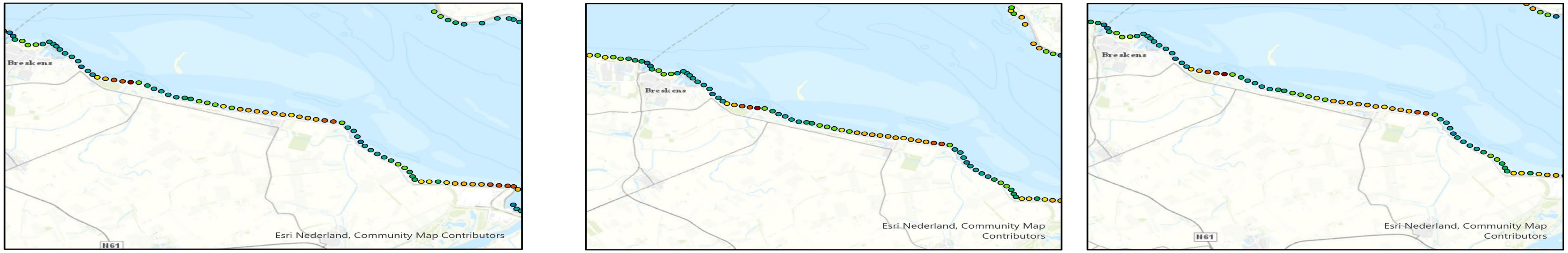
Appendix 7. Graphs 17, 18, 19 and 20 The hydraulic load level results of several calculations in m+NAP compared to the current dyke heights, graph twenty represents the contribution of each wind direction [%].

The maps represent a calculated sight year, basing the shown hydraulic load level on the critical flow rate of 5 l/s/m. The locations are relatively uniform in the maps as well as on the x-axis of the graphs. The database within hydra-NL encompasses fewer locations than the provided data set, but for this dyke segment, it includes the majority of them. Though the results still give a global point of view on the transgression locations. The water level calculations have uniform results of all locations, with no decrease or increase, whereas the hydraulic load level calculations show a slight variation between the locations. Both of the critical overtopping discharges result in transgression of the current crest heights. However, for 2023 there were a few points that resulted in an error, looking at the other dyke sections does show that the years follow roughly the same pattern. The current situation (2023), the highest experience load level is 9.969 m+NAP; with an average level of 9.459 m+NAP. By 2050 the maximum load level increases to 10.738 m+NAP, and the average increases to 9.904 m+NAP. However, by 2100 the maximum experiences load level increases to 11.450 m+NAP, and on average to 10.604m+NAP. By 2100 all dykes experience transgression based on the safety norms. When comparing the differences between the time frames, then the highest increase in overtime is 0.7 meters, between 2050 and 2100. The relative difference between the two wind statistics ranges between 0 to 50 cm.

The orientation of the dykes linked to the contribution of wind direction shows that the section is not sheltered whatsoever; instead, it experiences relatively high hydraulic loads. The section is located at the beginning of the estuary at the border with Belgium. It is facing perpendicular to the mouth even with the bends blocking a straight wave run-up



THE HYDRAULIC LOAD LEVEL RESULTS OF DYKE 32_2 FOR THE YEARS 2023, 2050 AND 2100



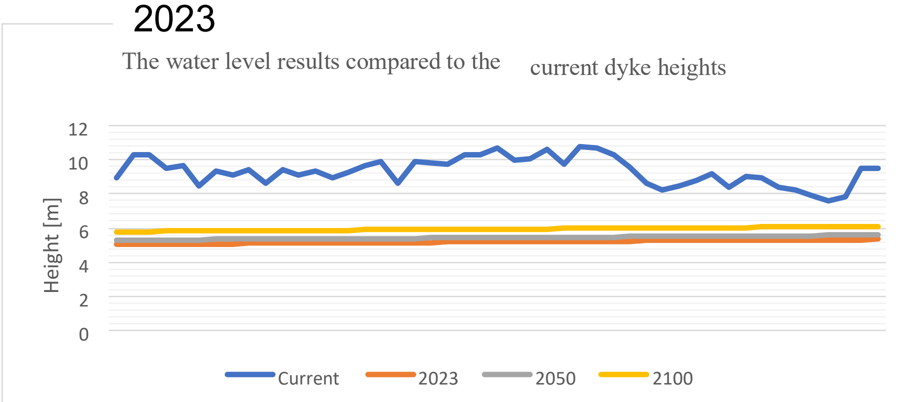
Appendix 4. Maps 16,17, and18 The hydraulic load level results per location on dyke track 32_2, showing the results

2023 2050 2100

Legend

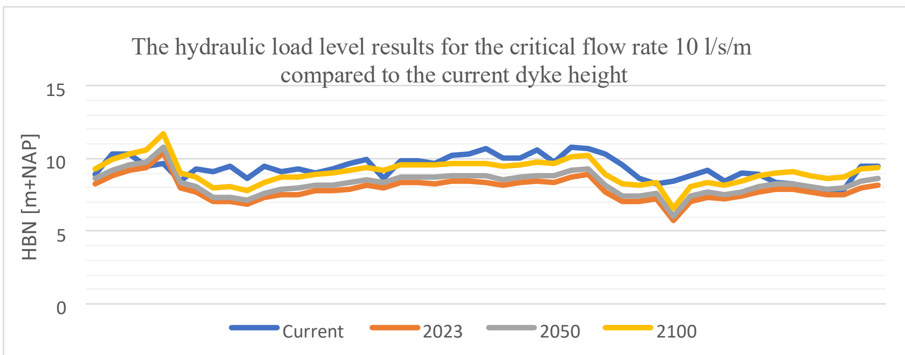
HBN

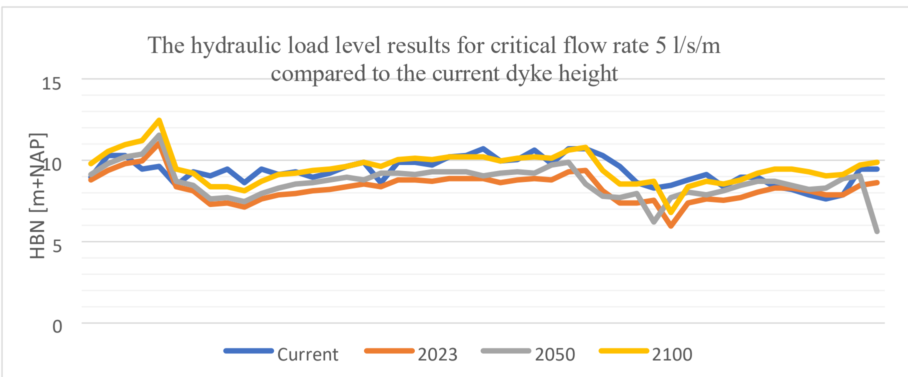
- ≤6.8
- ≤8.8
- ≤9.3
- ≤9.6
- ≤9.9
- ≤10.5
- ≤11.2
- ≤12.4

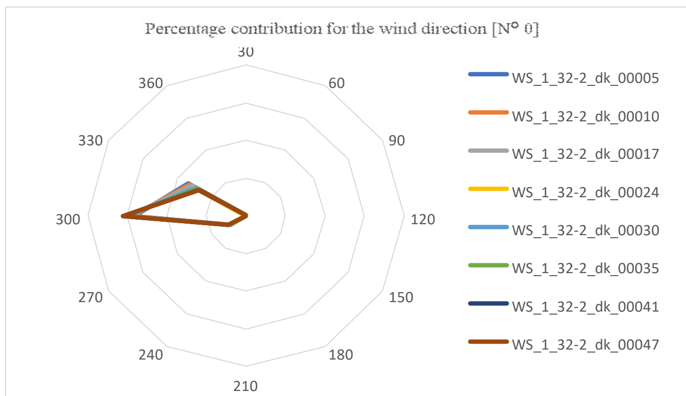


The maps represent a calculated sight year, basing the shown hydraulic load level on the critical flow rate of 5 l/s/m. The locations are relatively uniform in the maps as well as on the x-axis of the graphs. The database within hydra-NL encompasses fewer locations than the provided data set, but for this dyke segment, it includes the majority of them. Though the results still give a global point of view on the transgression locations. The water level calculations have uniform results of all locations, with no decrease or increase, whereas the hydraulic load level calculations show a slight variation between the locations. Both of the critical overtopping discharges result in transgression of the current crest heights. At the moment (2023), the highest experience load level is 11.071 m+NAP; with an average level of 8.326 m+NAP. Whereas by 2050, the maximum load level increases to 11.534 m+NAP, and the average increases to 8.735 m+NAP. However, by 2100 the maximum experiences load level increases to 12.447 m+NAP, and on average to 9.533 m+NAP. The majority of the locations of dyke segment 32_2 3 experience transgression at their safety norms by 2100, for 26 out of 47 dykes. As seen in the graphs, the beginning of the section experiences higher hydraulic loads that even in 2023 and 2050 transgresses the crest heights. When comparing the differences between the time frames, then the highest increase in overtime is 0.8 meters, between 2050 and 2100. The highest load level is experienced by section *Hand van Kruiningenpolder*. Though the difference between locations varies, the average relative difference of the two wind statistics range between 10 to 120 cm.

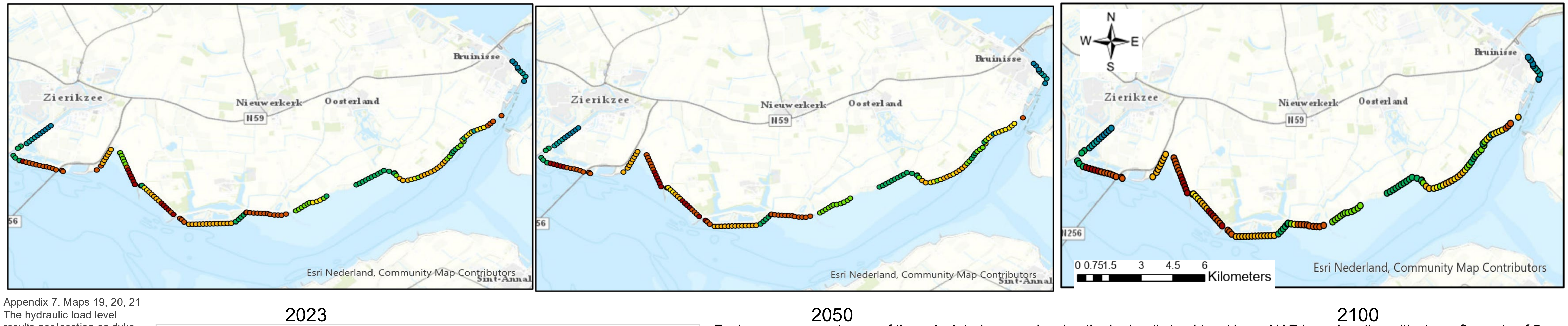
In the maps there two stretches experiencing higher hydraulic load levels. Comparing their orientation to the wind direction contributions show that they are not perpendicular to the north western west wind instead at a slight angle of it. These dykes do experience higher level compared to the protective dykes. As the dykes facing more towards the east have lower hydraulic, these face away from the mouth of the Western Scheldt.







Appendix 4. Graphs 20, 21, 22, 24 The hydraulic load level results of several calculations in m+NAP compared to the current dyke heights with graph twenty-four represents the contribution of each wind direction [%].

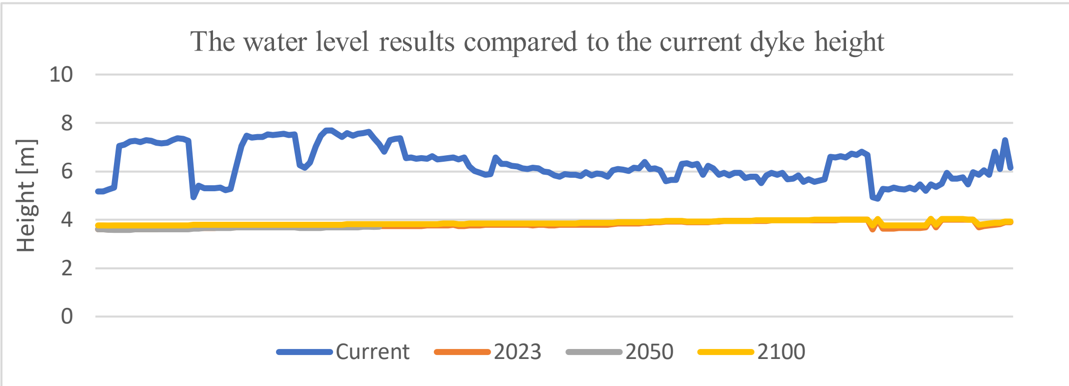


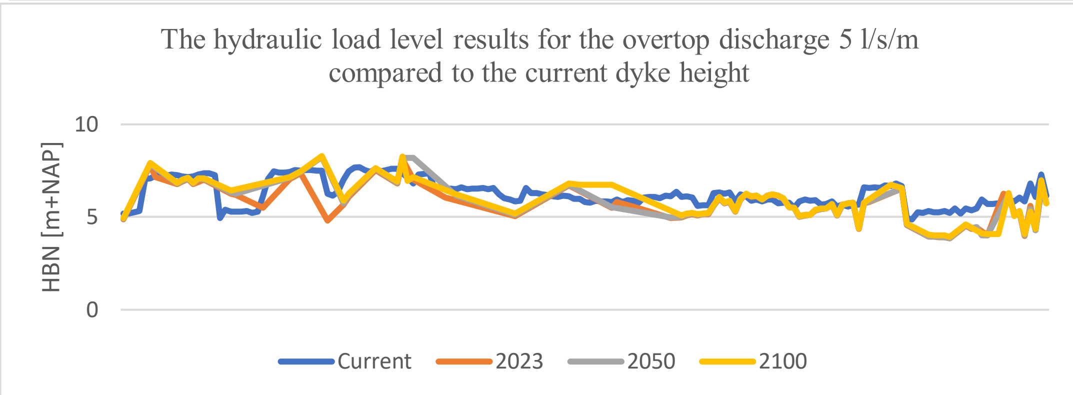
Appendix 7. Maps 19, 20, 21 The hydraulic load level results per location on dyke track 26_3, showing the results m+NAP

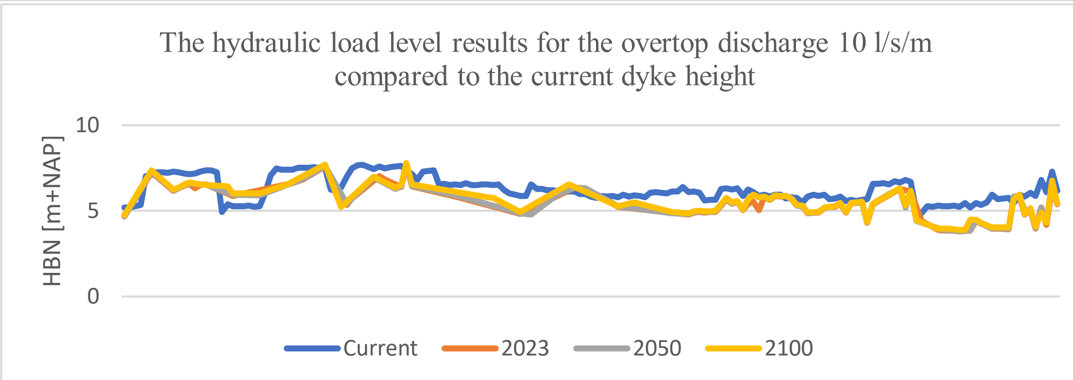
HBN
- ≤4.10
- ≤4.63
- ≤5.30
- ≤5.70
- ≤6.01
- ≤6.58
- ≤7.17
- ≤8.29

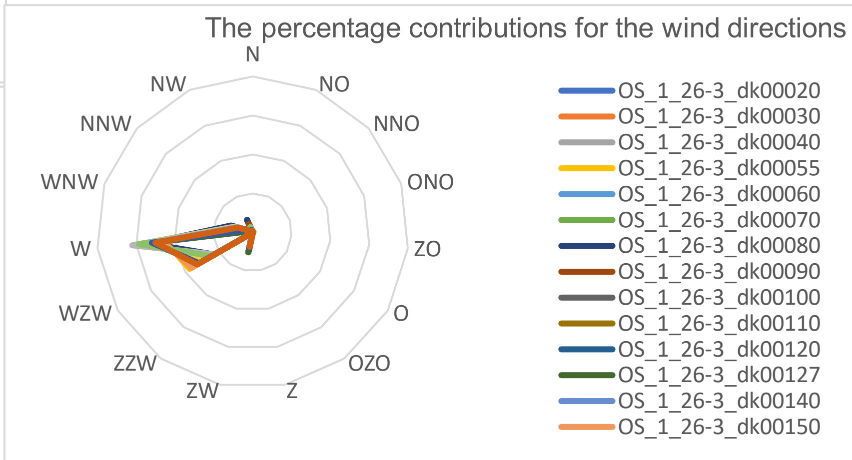
Each map represents one of the calculated years, showing the hydraulic load level in m+NAP based on the critical overflow rate of 5 l/s/m. Dyke section 26_3 is the first section in the north of the Eastern Scheldt, representing both sheltered and non-sheltered dyke sections. The distance between locations is not entirely uniform as between some of the dyke sections; there are more significant gaps. The x-axis does show the range as uniform, also indicates that not all locations were calculated towards the end. The database of hydra-NL has a limited amount of points, using the shapefile of them as the maps layer, thus representing the estimated locations of the database. However, these locations do not encompass all of the locations provided by the waterboard. Even though the majority of locations were calculated, some of them were still missing, though every dyke section and orientation had at least 1 point calculated. Therefore, the results show a global point of view on the transgression locations.
As previously said, the water level calculations have little differences in results of all locations, compared to the varying results of the critical overtopping discharges. In the current situation (2023), there some locations that experience transgression of the crest, though the majority does not. The highest experience load level is 8.623 m+NAP; with an average level of 6.008 m+NAP. By 2050 the maximum load level increases to 8.667 m+NAP, and the average increasing to 6.056 m+NAP. However, by 2100 the maximum experiences load level increases to 8.846 m+NAP, and the average to 6.256 m+NAP. The majority of locations experience hydraulic load levels are similar to the crest heights; some do transgress it for 2050 and 2100.

The most substantial wind directions contribution occurs between the west and west-southwest directions. Looking at the orientation and how it changes between points, shows that locations on would be sheltered from the west northwestern side though not from the W and WZW directions. Throughout the section, the dykes become increasingly sheltered. However, even the more sheltered dykes experience relatively high load levels as the water is funnelled between Tholen and Schouwen-Duivenland.







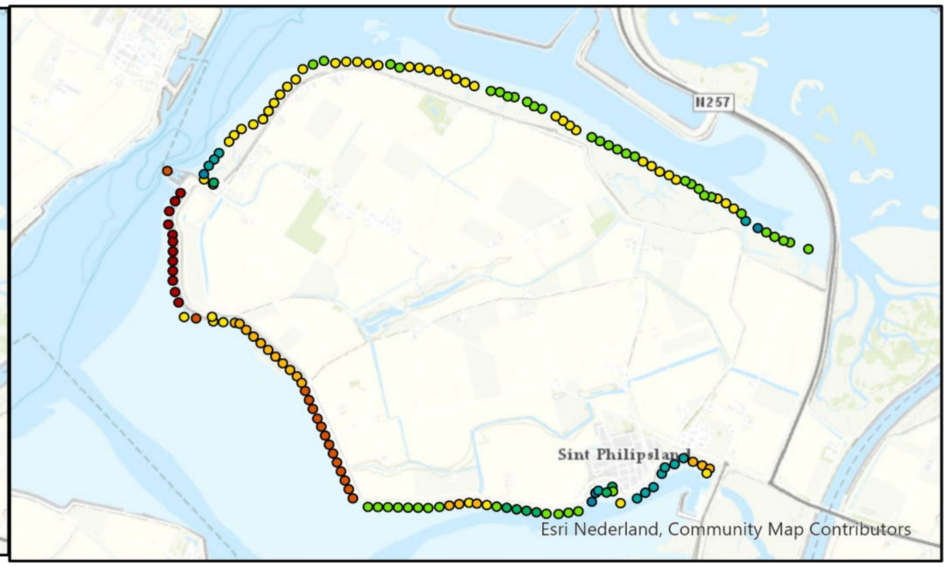


Appendix 7. Graphs 25, 26, 27 and 28 The hydraulic load level results of several calculations in m+NAP compared to the current dyke heights with graph twenty-eight represents the contribution of each wind direction [%]

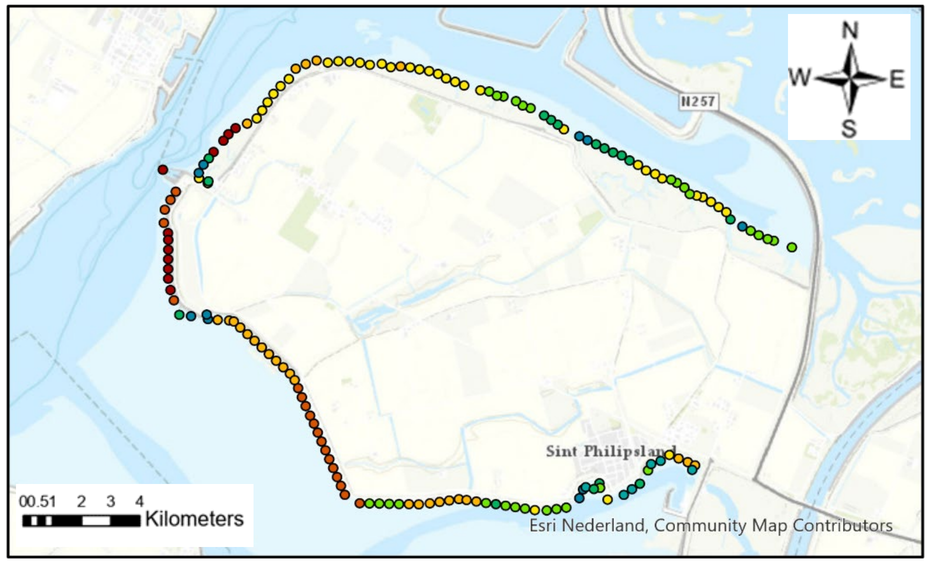
THE HYDRAULIC LOAD LEVEL RESULTS OF DYKE 27_1 FOR THE YEARS 2023, 2050 AND 2100

Appendix 7. Maps 22, 23, 24 The hydraulic load level results per location on dyke track 27_1, showing the results m+NAP

2023



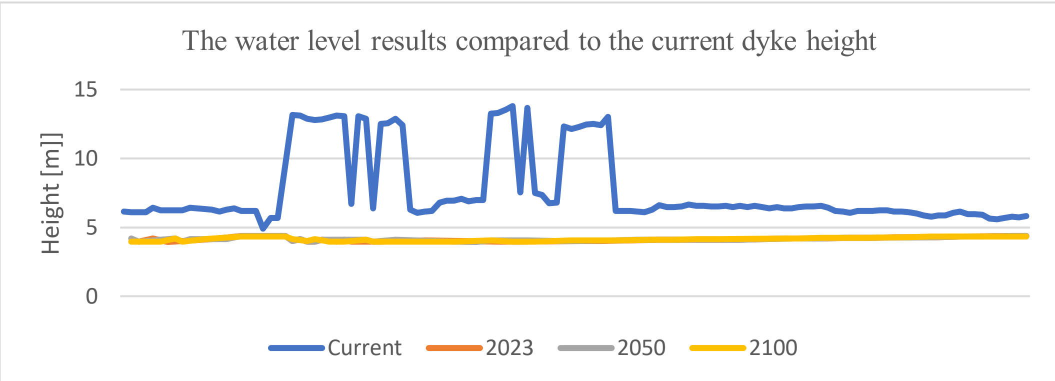
2050

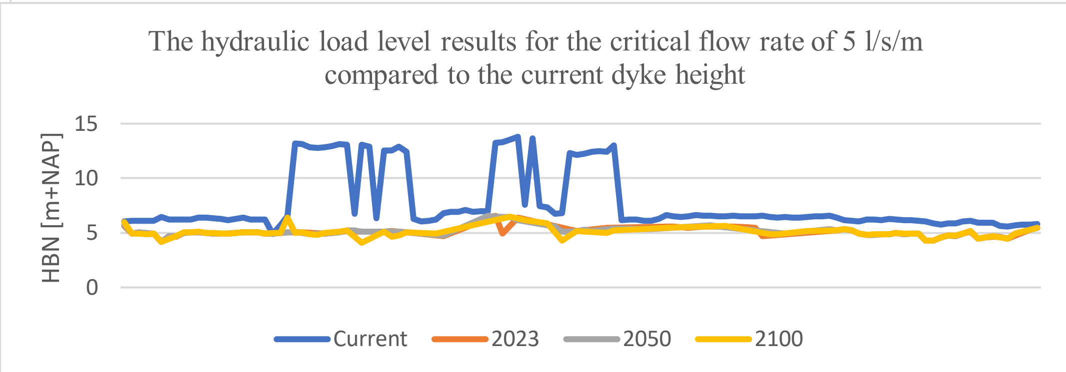


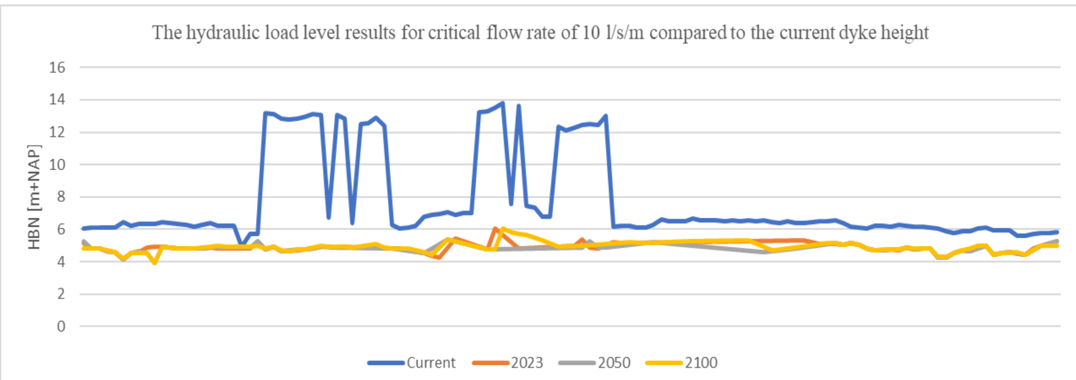
2100

HBN

- ≤4.29
- ≤4.70
- ≤4.85
- ≤5.02
- ≤5.21
- ≤5.45
- ≤5.94
- ≤6.56





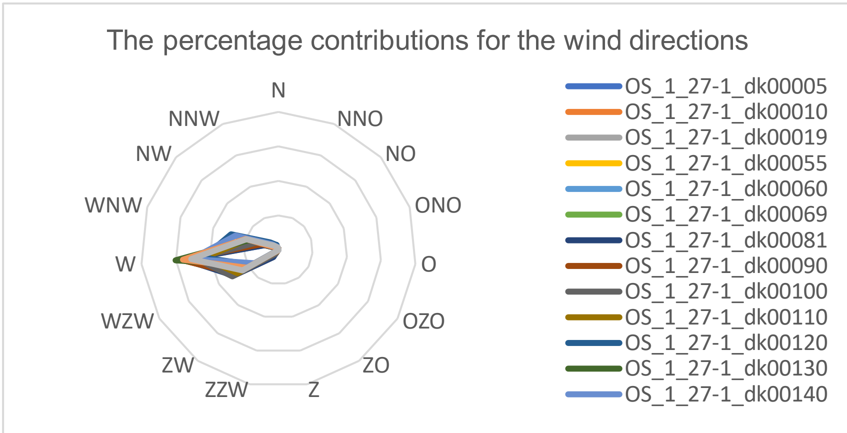


Appendix 7. Graphs 29, 30, 31,and 32 hydraulic load level results of several calculations in m+NAP compared to the current dyke heights with graph thirty-two represents the contribution of each wind direction [%].

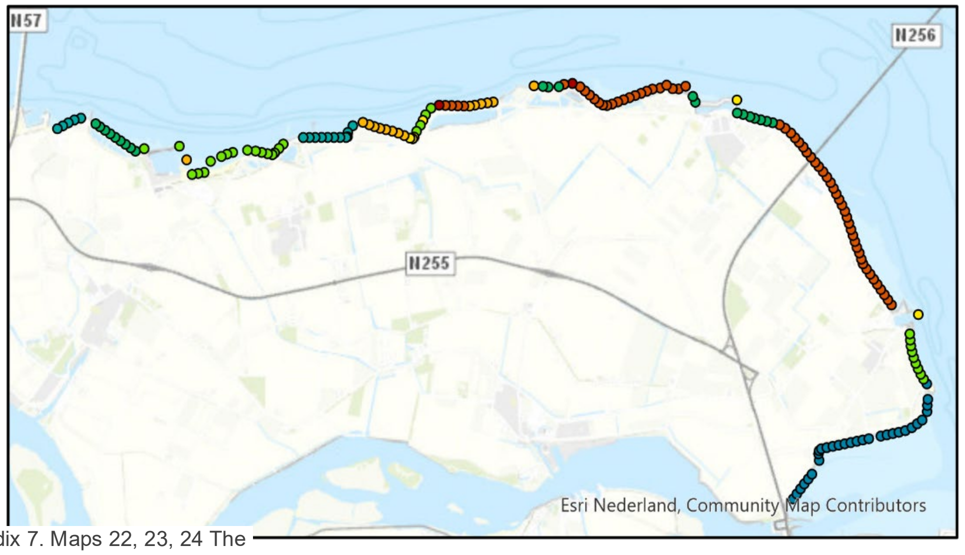
Each map represents one of the calculated years, showing the hydraulic load level in m+NAP based on the critical overflow rate of 5 l/s/m. Dyke section 27_1 in the northeast of the Eastern Scheldt is one of the most sheltered dyke sections. The distance between locations is not entirely uniform as between some of the dyke sections; there are more significant gaps. The x-axis does show the range as uniform. The database of hydra-NL has a limited amount of points, using the shapefile of them as the maps layer, thus representing the estimated locations of the database. However, these locations do not encompass all of the locations provided by the waterboard. Thus, the result is a global overview of the hydraulic load levels.

As previously said, the water level calculations have little differences in results of all locations, compared to the varying results of the critical overtopping discharges. In the current situation (2023), 2050 and 2100, there are no locations which experience transgression of their crests. At the moment, the highest experience load level is 6.561m+NAP; with an average level of 5.016 m+NAP. By 2050 the maximum load level increases to 6.557 m+NAP, and the average increasing to 5.059 m+NAP. However, by 2100 the maximum experiences load level increases to 6.478 m+NAP, and the average to 4.998 m+NAP. The differences between the sight years are minimally and even throughout all locations; the variations are again minimally.

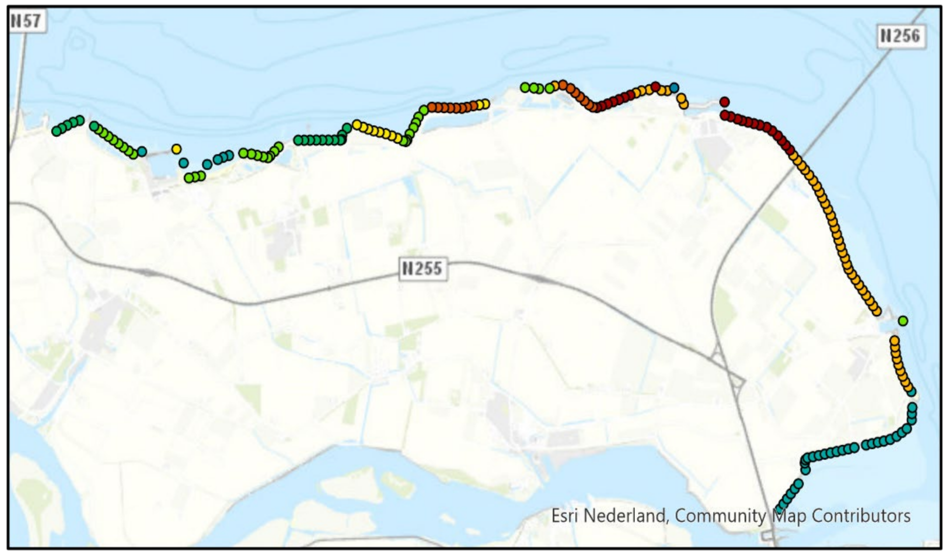
These results compared to the orientation of the dykes and the locations of the dyke section show that the majority is highly sheltered. The only locations which are not sheltered are those facing southwest which is where the water is pushed up from the Eastern Scheldt whereas the northern part is very sheltered, just like the right stretch towards Sint Phillipsland.



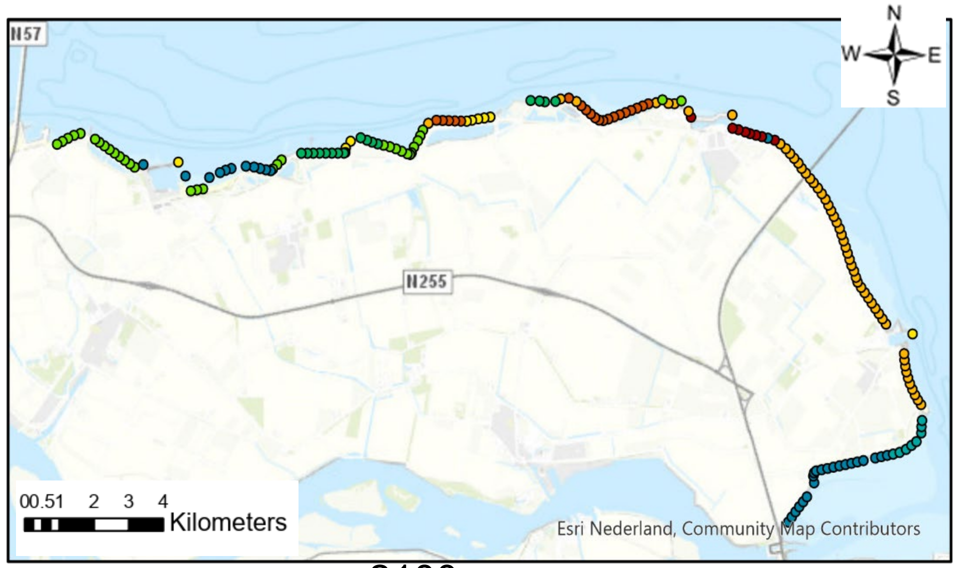
THE HYDRAULIC LOAD LEVEL RESULTS OF DYKE 28_1 FOR THE YEARS 2023, 2050 AND 2100



2023

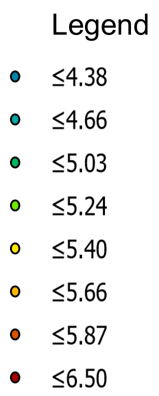


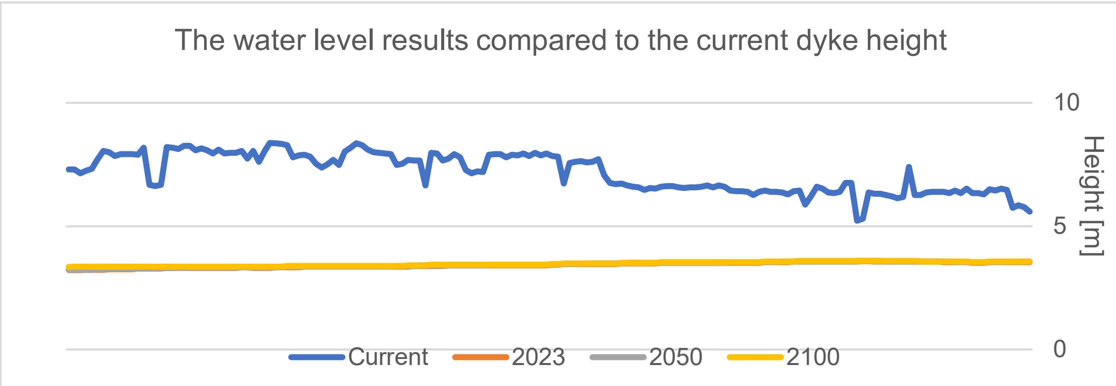
2050

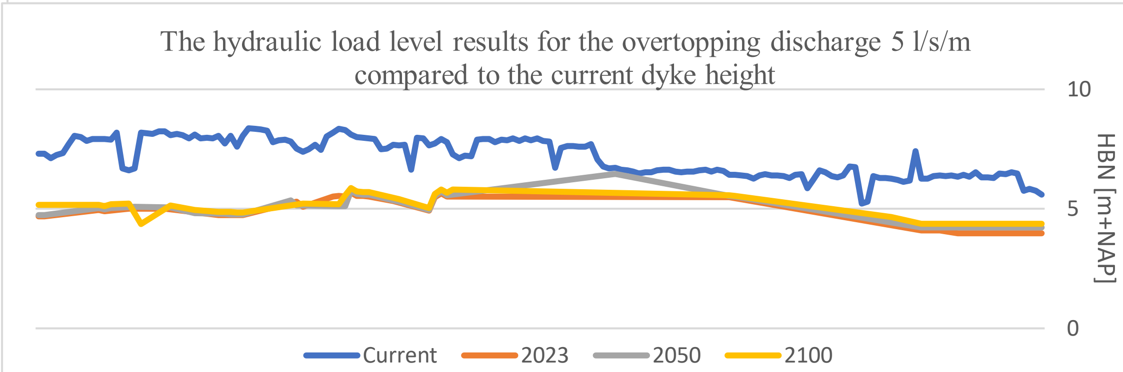


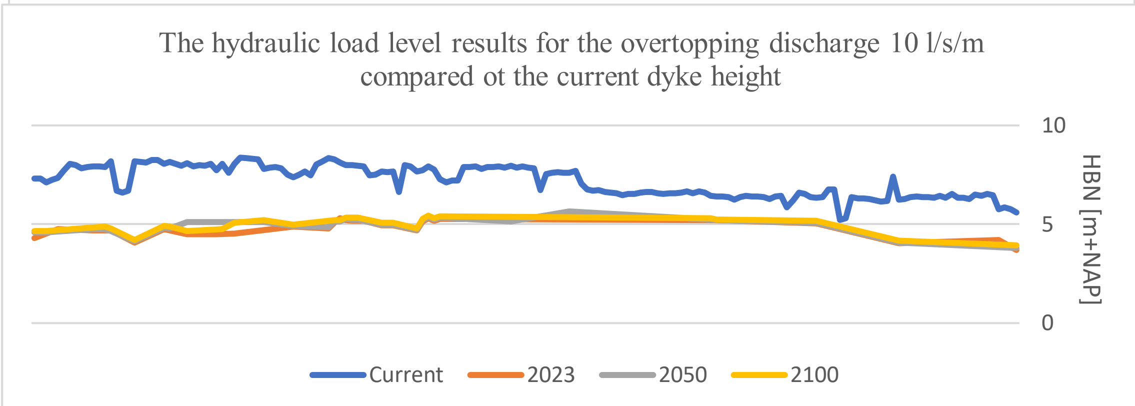
2100

Appendix 7. Maps 22, 23, 24 The hydraulic load level results per location on dyke track 31_2, showing the results m+NAP





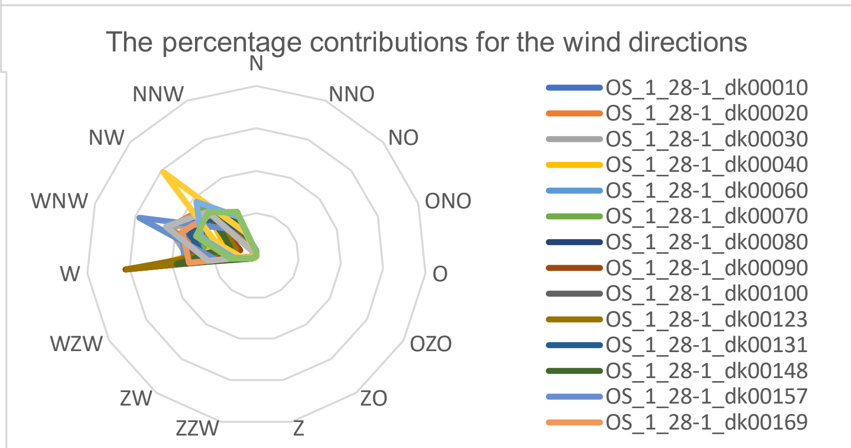




Each map represents one of the calculated years, showing the hydraulic load level in m+NAP based on the critical overflow rate of 5 l/s/m: Dyke section 28_1, the first dyke section on the south side of the Eastern Scheldt. The distance between locations is not entirely uniform as between some of the dyke sections; there are more significant gaps. The x-axis does show the range as uniform. The database of hydra-NL has a limited amount of points, using the shapefile of them as the maps layer, representing the estimated locations of the database. However, these locations do not encompass all of the locations provided by the waterboard. Thus, the result is a global overview of the hydraulic load levels.

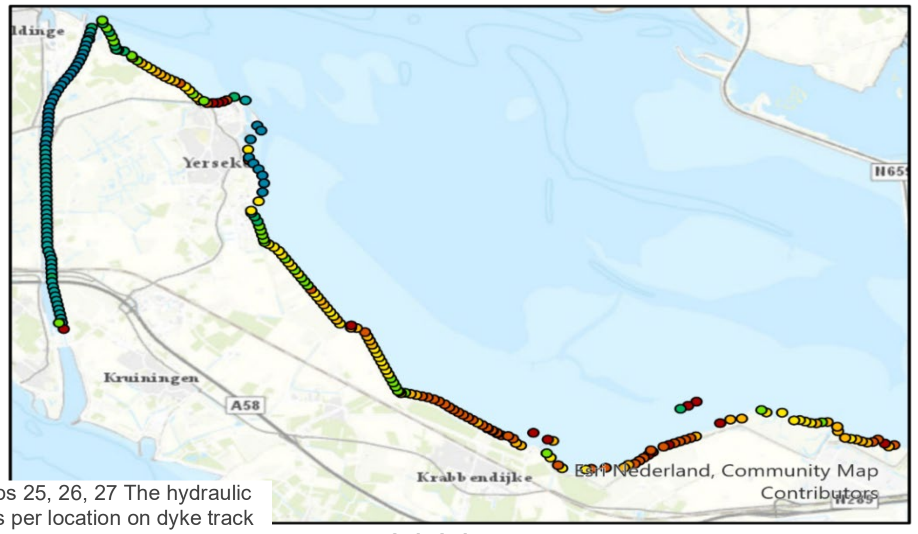
As previously said, the water level calculations have little differences in results of all locations, compared to the varying results of the critical overtopping discharges. In the current situation (2023), 2050 and 2100, there are no locations which experience transgression of their crests. At the moment, the highest experience load level is 6.027 m+NAP; with an average level of 5.009 m+NAP. By 2050 the maximum load level increases to 6.461 m+NAP, and the average increasing to 5.211 m+NAP. However, by 2100 the maximum experiences load level increases to 6.156 m+NAP, and the average to 5.222 m+NAP. The differences between the sight years are minimally throughout all locations; this is indicated within the graphs. The majority of locations do pass their norms for all sight years.

These results compared to the orientation of the dykes and the locations of the dyke section show more variation on which wind direction contributes the most significantly. The storm surge barrier shelters the dykes at the mouth of the Eastern Scheldt, and the dykes near lake Vere face away from the contributing wind directions.

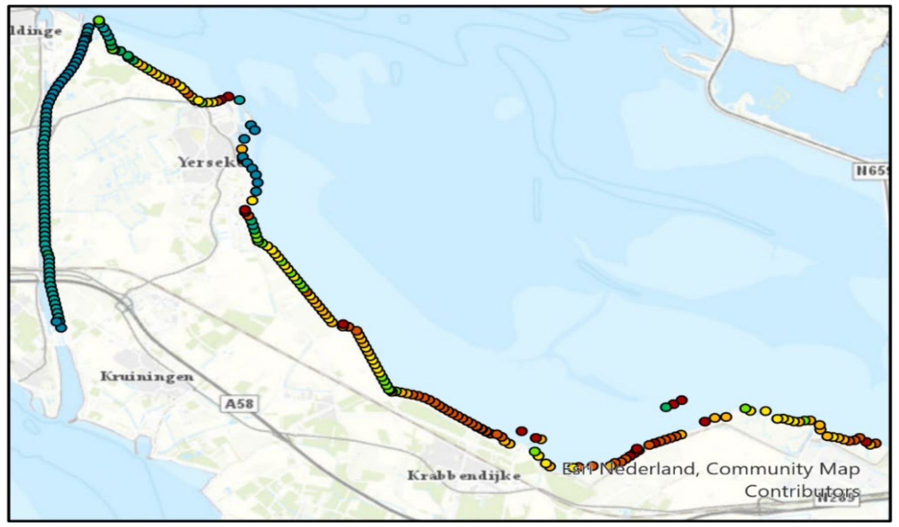


Appendix 7. Graphs 29, 30 , 31, and 32 The hydraulic load level results of several calculations in m+NAP compared to the current dyke heights with graph thirty-two represents the contribution of each wind direction [%]

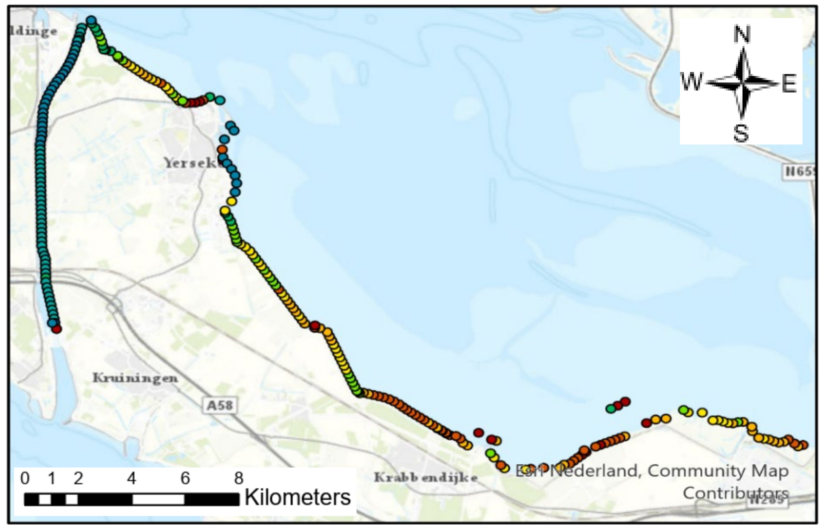
THE HYDRAULIC LOAD LEVEL RESULTS OF DYKE 31_2 FOR THE YEARS 2023, 2050 AND 2100



2023

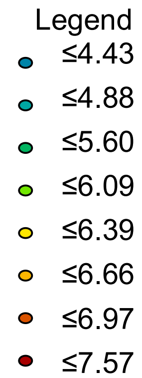


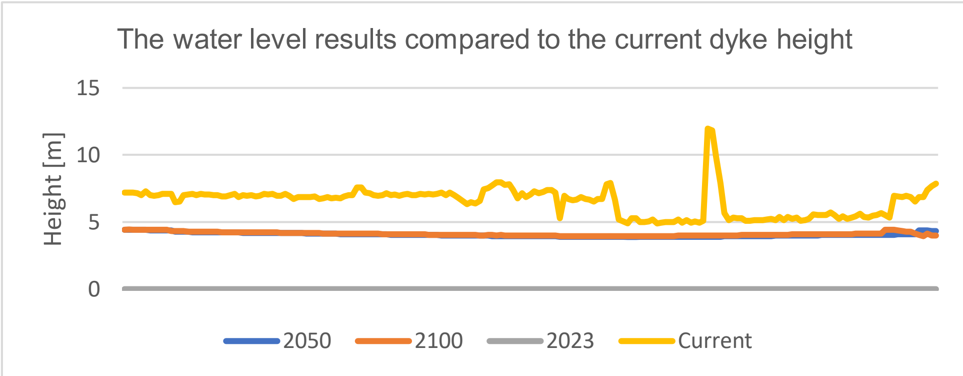
2050

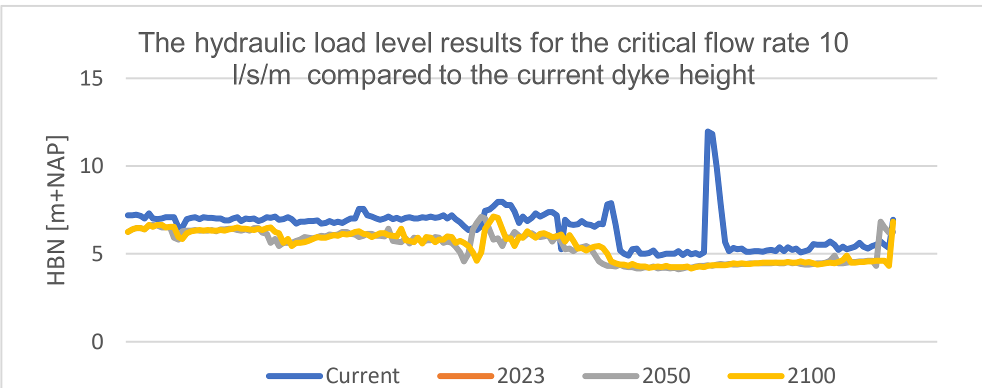


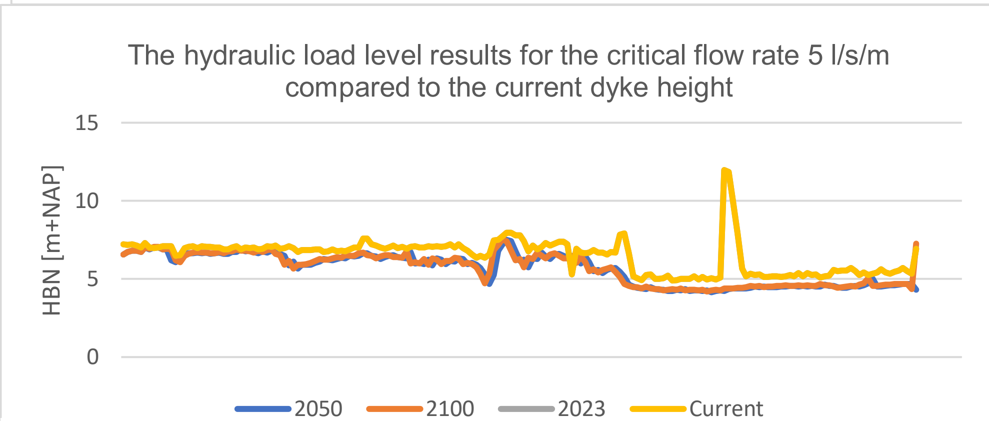
2100

Appendix 6. Maps 25, 26, 27 The hydraulic load level results per location on dyke track 31_2, showing the results m+NAP

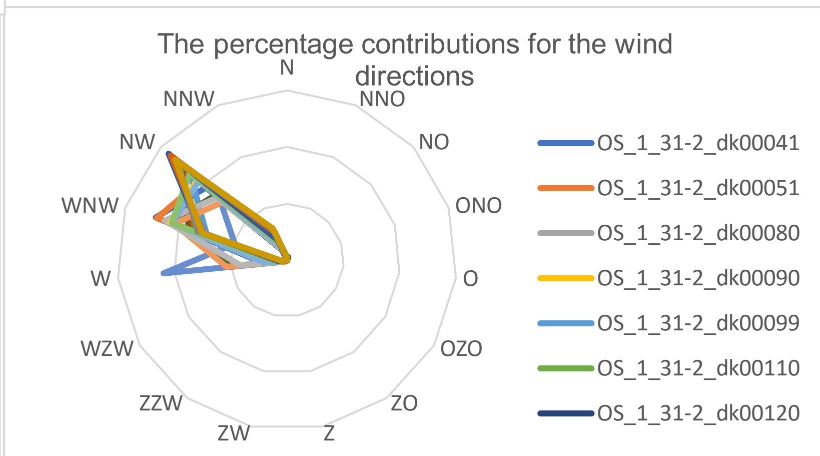








Appendix 7. Graphs 33, 34 , 35, and 36 The hydraulic load level results of several calculations in m+NAP compared to the current dyke heights with graph thirty-six represents the contribution of each wind direction [%]



Each map represents one of the calculated years, showing the hydraulic load level in m+NAP based on the critical overflow rate of 5 l/s/m: The distance between locations is not entirely uniform as between some of the dyke sections; there are more significant gaps. The x-axis does show the range as uniform. The database of hydra-NL has a limited amount of points, using the shapefile of them as the maps layer, representing the estimated locations of the database. However, these locations do not encompass all of the locations provided by the waterboard. Thus, the result is a global overview of the hydraulic load levels.
As previously said, the water level calculations have little differences in results of all locations, compared to the highly varying results of the critical overtopping discharges. In the current situation (2023), 2050 and 2100, there are a few locations which experience transgression of their crests. At the moment, the highest experience load level is 7.487 m+NAP; with an average level of 5.207 m+NAP. By 2050 the maximum load level increases to 7.503 m+NAP, and the average increasing to 5.187 m+NAP. However, by 2100 the maximum experiences load level increases to 7.571 m+NAP, and the average to 5.207 m+NAP. The differences between the sight years are minimally throughout all locations; this is indicated within the graphs. The majority of locations do pass their norms for all sight years, with a few coming close to the crest heights though not transgressing it.

These results compared to the orientation of the dykes and the locations of the dyke section show more variation on which wind direction contributes the most significantly. The locations in the channel are sheltered and therefore, these experience the lower load levels though the remaining locations experience little to no sheltering from the WNW and NW wind directions.

Appendix 8. The pivot tables of raw hydra-NL data

Separate excel file by the same name.