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SPECIAL ISSUE

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A first assessment of the effect of storm climate trends and uncertainties on Dutch levee design

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Abstract

For the safety assessment and design of levees in the Netherlands probabilistic tools are used, which account for both statistical and model uncertainties in the determination of hydraulic loads. However, climate change induced uncertainties in extreme wind climate or storminess are not yet accounted for. This paper presents a first assessment of the effect of uncertainties in storminess on Dutch levee design. An expert panel was consulted to define a range of plausible trends and uncertainties in extreme wind climate. Three scenarios were defined with variations of the current wind climate, including changes in wind speed high percentiles and in wind direction. For the defined scenarios probabilistic computations were carried out to determine the effect of the wind statistics variations on the water level, wave loads, and required levee height along the Dutch lakes and coast. In the case of an increase in wind percentiles (mean + 5%, standard deviation 12%), the required levee height increases significantly: up to 1.5–4 m along the Dutch coast and up to 1–2 m along the Dutch lakes. Given the large impact of the considered changes, it is first recommended to carry out a more robust assessment of the uncertainties in future storm climate and to measure and monitor evolution of future wind speeds.

KEYWORDS

climate change, hydraulic loads, levee design, scenarios, storm climate, trends, uncertainty

1 | INTRODUCTION

The design and assessment of the Dutch levees are carried out with official probabilistic tools, which have been developed in the legal assessment and design instrumentation. According to these new risk-based assessment practices (Slomp et al., 2016), uncertainties in hydraulic loads must now explicitly be accounted for, since they can have a major effect on the design and assessment of the water defences. However, although ample attention has been devoted to (climate change induced) sea level rise and how it can affect the hydraulic loads, the probabilistic tools do not yet consider (climate change induced) uncertainties in storm intensity and storm frequency, here indicated as storm climate. Assessing the uncertainties in the storm climate can be of importance since the bandwidth of the extreme wind estimates due to climate variations of the past century and differences between climate models is in the order of 10% (Caires & Sterl, 2005). In addition, it is important to consider that a

1% extreme wind-speed increase can lead to a 2% increase in storm set-up and 1% increase in wave height. Consequently, the wave runup level and probability of levee overtopping will increase as well. This means that higher and stronger dikes are required to withstand the increased hydraulic load in case the addition of trends and uncertainties in wind leads to higher probabilities of certain wind speeds. Although the storm climate seems to have become slightly milder between 1990 and 2010, there are also reasons for alertness: the rather extreme Dollard storm floods of 1 November 2006 and 6 December 2013, the heavy summer storm of 25 July 2015 (an equally severe summer storm occurred a century ago) and signs of an extremer future storm climate. For example, Feser et al. (2015), Mölter et al. (2016) and Wolf et al. (2020) evaluated various storm-climate trend studies on storms over the North Atlantic and northwestern Europe. They report that most studies show an increase in future storm numbers and intensity for the North Sea. In addition, Haarsma et al. (2013) conclude that the increasing sea surface temperatures force hurricanes eastward. As a consequence, intense hurricanes are directed more frequently toward Europe, like Hurricane Ophelia in 2017, which had just lost its hurricane power before reaching Ireland. According to De Vries et al. (2018), with a slightly different path, Ophelia could have caused a near-normative event in one of the Dutch lakes. As noted above, storm-climate trends may lead to non-negligible impacts on hydraulic loads. Furthermore, uncertainty in the storm climate without a visible systematic trend may also lead to non-negligible impacts: it is expected that an uncertainty of 2%–7% in the storm-climate estimates (depending on the water system) is sufficient to be dominant in relation to the regular water level uncertainties, which are often some decimetres. Therefore, in this paper the magnitude of storm-climate trends and uncertainties are explored. Subsequently, a first assessment is presented of the impact of storm-climate trends and uncertainties on the Dutch levee design. As climate change affects storm-climate trends and uncertainties globally, the here presented method and conclusions could guide worldwide coastal adaptation problems.

2 | METHOD

2.1 | Overview

Two steps were distinguished to explore the effect of trends and uncertainties in the storm (namely, wind) climate on hydraulic loads:

- Storm-climate trends and uncertainties were identified.
- The trends and uncertainties were translated to hydraulic loads, in terms of water levels, wave conditions and requested crest heights at a number of locations along the Dutch lakes: Lake IJssel and Lake Marken and the Dutch coast: Wadden Sea, Holland coast and Western Scheldt, see Figure 1.

A distinction was made between lake levees and coastal levees in the translation of the effects on the hydraulic loads on the primary defences.

Use was made of the chain of methods and tools to determine Hydraulic loads (see Slomp et al., 2016). This is schematically presented in Figure 2. The hydraulic loads are determined with the probabilistic tool Hydra-NL (HKV, 2019). Hydra-NL translates the statistical distributions of stochastic variables, such as wind and river discharge, to probability exceedance curves of local hydraulic loads, in terms of water level, wave height, wave period and required crest height. In this translation the eventual correlation between the variables is taken into account. These exceedance curves are determined probabilistically, using the technique of Numerical Integration. The inverse computation is also possible with Hydra-NL: How large can one of the hydraulic load variables be, such that the probability of exceedance of that value equals a pre-defined probability.

As indicated in Figure 2, Hydra-NL requires statistical distributions for various stochastic variables, such as lake level, sea water level, wind speed and wind direction. The statistical distributions include statistical uncertainty intervals. In Hydra-NL statistical uncertainty is not modelled as a separate stochastic variable. Instead, and for user's convenience, it is integrated in the point estimates, or average statistics, following the method described in Geerse (2016). For a large number of combinations values of stochastic variables the wave conditions and water levels at locations in front of the dike levees have been determined using process-based models. These are stored in a so-called translation database. For each sample of values of stochastic variables, the local water level and wave conditions are determined by interpolating between the values in the translation database. To determine the required crest height, the local water level and wave conditions are translated to wave runup and wave overtopping discharge levels. The levee height for which the probability of exceedance of a user-defined critical wave overtopping discharge level (related to the strength of the revetment of the inner slope) equals the maximum allowable failure probability is defined as the required crest height. In other words, the levee is assumed to fail as soon as the user-defined overtopping threshold is reached. The wave runup and wave overtopping levels

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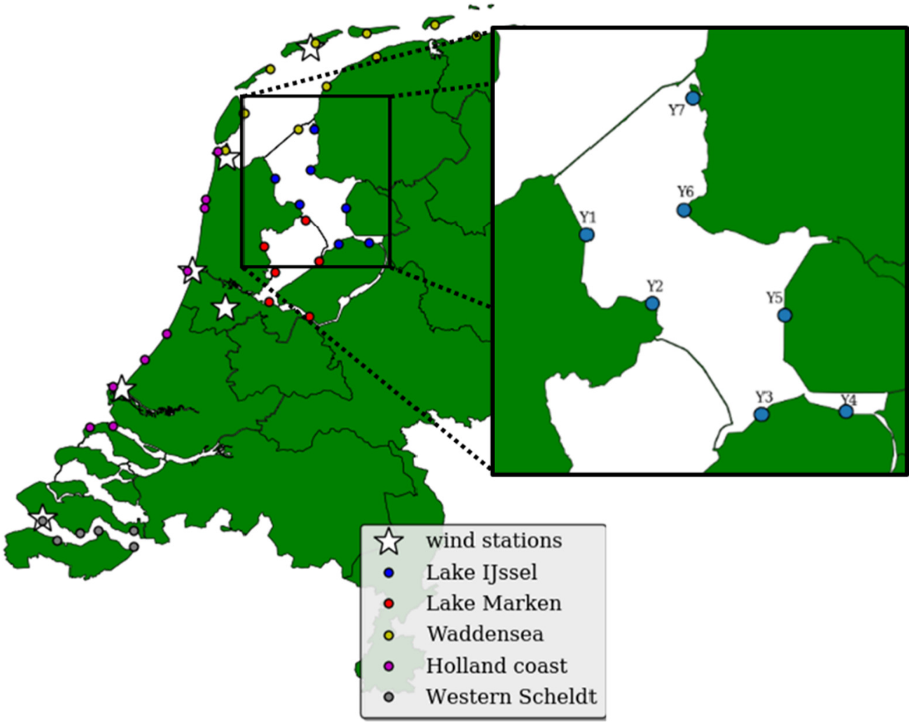

FIGURE 1 Locations along Lake IJssel and Lake Marken (outlined, including the names of the locations in Lake IJssel), Wadden Sea, Holland coast and Western Scheldt for which hydraulic loads have been determined

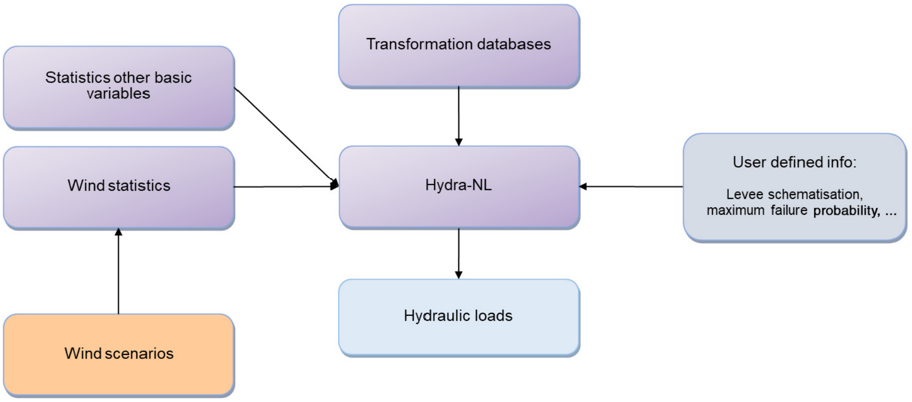

FIGURE 2 Chain of tools and methods to determine hydraulic loads: Probabilistic model Hydra-NL and required input of statistics of stochastic variables, transformation database and user-defined information. Wind scenarios are not part of this chain, but have been defined in this paper and adapted into new distributions of the wind statistics.

depend on the levee schematisation, whereas the normative water level and wave height do not.

2.2 | Storm-climate trends and uncertainties

The extreme wind statistics used in the design and assessment of the safety of the Dutch primary water defences have been determined based on KNMI[1] homogenised (exposure corrected or so-called potential) wind observations in the period between 1979 and 2008 (Wever & Groen, 2009). The considered extreme wind statistics were determined for 12 directional sectors and comprise the average values and the 95% confidence intervals for statistical uncertainty for arbitrary return values, see Caires (2009).

In order to apply in some sense "realistic" parameter variations in the uncertainty analysis, wind statistics and climate-change, experts were asked for their opinion and recommendations. This led to various scenarios that could lead to changes in the storm climate. These scenarios have been translated into adaptations for the currently used wind statistics. The various scenarios and resulting distributions of the winds statistics have been elaborated below.

2.3 | Translation to hydraulic loads for the lakes

For the lakes, that is, Lake IJssel and Lake Marken, the wind direction dependent extreme wind speed statistics of Schiphol, including statistical uncertainty, were adjusted

TABLE 1 Safety requirements (maximum failure probability per year) for Lake IJssel

Location	Safety standard (for levee stretch in Water Act)	Cross-sectional requirement for overtopping
Y1	1/1.000	1/8.330
Y2	1/1.000	1/8.330
Y3	1/10.000	1/125.000
Y4	1/10.000	1/125.000
Y5	1/1.000	1/12.500
Y6	1/1.000	1/12.500
Y7	1/1.000	1/12.500

according to the defined scenarios. Subsequently, the probabilistic assessment tool Hydra-NL was used to determine the hydraulic loads: water level, required crest height and wave conditions for the various scenarios. Waves will not be considered here separately, but only as a hydraulic component leading contributing to wave overtopping and therefore determining the required crest height. The concept in Figure 2 is followed straightforwardly for each scenario.

Besides wind speed and wind direction the lake level is the third stochastic variable in Hydra-NL for the lakes. In the case of the lakes it is assumed that the impact of the changing storm climate on extreme lake levels is small. Therefore, the statistical distribution of the lake levels is assumed to be unaffected by the change in storm climate. Sea level rise has not been considered in this storm-climate sensitivity study to assure an unambiguous analysis of the effect of storm climate uncertainty. Therefore, the defined scenarios only require adjustment of the wind-speed statistics, as indicated in Figure 2. Both the point estimates and the statistical uncertainty were changed.

The required crest height was determined for a critical wave overtopping discharge of 5 L/s/m. The in situ levee cross sections available in Hydra-NL were used. Furthermore, the hydraulic loads were determined for the maximum allowable failure probabilities, which are different for each trajectory. Two safety requirements were considered, the formal safety standard for levee stretches as defined in the Dutch Water Act, and an overtopping-related cross-sectional safety requirement. For the latter, it is assumed that 24% of the levee failure probability can be ascribed to overtopping, and thus 76% to other mechanisms such as erosion of the outer slope revetment, (macro) instability of the dike core and piping under the dike (Slomp et al., 2016), and that the length effect factors, accounting for inhomogeneity along the stretch, are according to those in the Water Act. The resulting cross-sectional requirement is typically a factor 8–12.5 smaller than the overall levee-stretch safety standard. Contributions of other failure mechanisms have not been considered here. Adding the probability of failure due to these failure mechanisms to the failure probability due to overtopping results in the total failure probability of the cross-section considered. The sum over all cross-sections within the stretch results in the failure probability of the entire stretch. In Table 1 both the formal safety standard and the cross-sectional safety requirement are given for seven locations in Lake IJssel. The locations Y1, …, Y7 are given in Figure 1.

2.4 | Pragmatic approach for the coastal area

For the coastal region, that is, Wadden Sea, Western Scheldt and the Holland coast, no straightforward approach is possible, because in Hydra-NL the water level is a stochastic variable by itself. The local water level in the current probabilistic load model of Hydra-NL is determined from measured sea level statistics of some reference stations. Despite the strong correlation in the load model, changing the wind statistics will not affect the calculated normative water level. A direct approach as for the lakes is therefore not possible. Here we present a detour, based on simple calculation rules. This means that a rough estimate of the impact on the hydraulic loads at a number of coastal locations was made.

Along the coast, the wind statistics at five stations are relevant, that is, Terschelling-West, De Kooij, IJmuiden, Hoek van Holland and Vlissingen, see Figure 1. For each scenario an input file was generated for each of these five stations.

The storm surge depends on various factors, such as wind speed, fetch length of the wind, wind direction, water depth, geometry of the coast and the location (see, e.g., Fagherazzi & Wiberg, 2009). The storm surge is roughly proportional to the square of the wind speed and inversely proportional to the water depth. For the North Sea the relation between wind speed and storm surge for various wind directions, was used. The quadratic relationship can be written as:

$$h = aU^2 \tag{1}$$

with h the storm surge, U the wind speed and a a coefficient depending on different factors, for example, depth and fetch. The relative change in storm surge as a function of the relative change in wind speed is then:

$$\Delta h/h = 2\Delta U/U \tag{2}$$

In other words, a relative change of 1% in wind speed results in a relative change of 2% in storm surge.

For each location again the chain in Figure 2 is used for the reference scenario. This also holds for the other scenarios, except that the absolute change in surge level Δh is determined and added as input to Hydra-NL. The determination of Δh requires the following steps:

1. A reference scenario is defined with the current wind statistics. For this scenario, we determine the required crest height with Hydra-NL, together with the corresponding values for water level, wind speed U and wind direction resulting into this crest height;
2. We calculate the storm surge h by subtracting the tide from the water level determined in step (1). Note that the normative temporal variation of the water level in the assessment and design framework are location dependent and are determined by adding the average astronomical tide to a storm surge evolution, including a phase lag between both. The storm surge evolutions have a trapezoidal shape with a basic period of 30–44 h and top period of 2–4 h, and are available for five coastal stations (Vlissingen, Hoek van Holland, Den Helder, Harlingen, Lauwersoog) see Chbab (2015). The statistically determined values for maximum surge level, maximum tide and phase lag are given in Table 2 for those five locations. The resulting difference between maximum water level and maximum surge level, assumed to be valid for an entire region around the five stations, was subtracted from the local water level from step (1) to determine the local storm surge h;
3. For each scenario we make an estimate for the relative change in wind speed, that is, the combined effect of change in point estimate and uncertainty. This is illustrated in Figure 3. The probability of the wind speed U given the wind direction, both from Step 1 is determined (reference scenario). For the other scenarios the wind speed with that probability of exceedance is determined, resulting in a value of ΔU;
4. For each scenario we determine the correction $\Delta h = 2 \Delta U/U\, h$;
5. For each scenario we perform Hydra-NL computations with a water level correction Δh and wind statistics corresponding to the specific scenarios to calculate the required crest height. The required crest height was determined for a critical wave overtopping discharge of 5 L/s/m. The in-situ cross sections available in Hydra-NL were used. Again, the computations were carried out for both the overall safety standard (for a levee stretch) and for the cross-sectional requirement for overtopping respectively. For example, for the Holland coast the required crest height levels for Scenario 0, corresponding to the cross-sectional requirement for overtopping, along with the values of water level, wind speed and wind direction are given in Table 3.

3 | SCENARIOS

During a workshop with wind statistics and climate-change experts various scenarios were defined that reflect possible trends and uncertainties in the storm climate. These scenarios were translated into point estimates of the wind speed and direction and the standard deviation of the statistical uncertainty. The scenarios were chosen based on the main conclusions from the expert workshop:

- Scenario 0 is defined as the reference scenario. The current wind speed and direction estimates (point estimates and standard deviation) are used in this scenario. These values differ per location. The standard deviations of the statistical uncertainty of the wind speed are approximately 5%.

TABLE 2 Phase lag between astro tide and surge peaks, the maximum values and the resulting maximum water level (WL) at five main stations. This normative condition depends on the location dependent safety standards. NAP stands for Amsterdam ordnance datum

Location	Safety standards (per year)	Phase lag (h)	Peak astro. tide (m + NAP)	Peak surge (m)	Max. wl (m + NAP)
Vlissingen	1/3.000	2.5	2	5	6
Hoek van Holland	1/10.000	−4.5	1.1	4.5	5
Den Helder	1/1.000	2.5	0.6	5	5.5
Harlingen	1/1.000	5.5	1.1	5	4.6
Lauwersoog	1/1.000	5.5	1	5	4.6

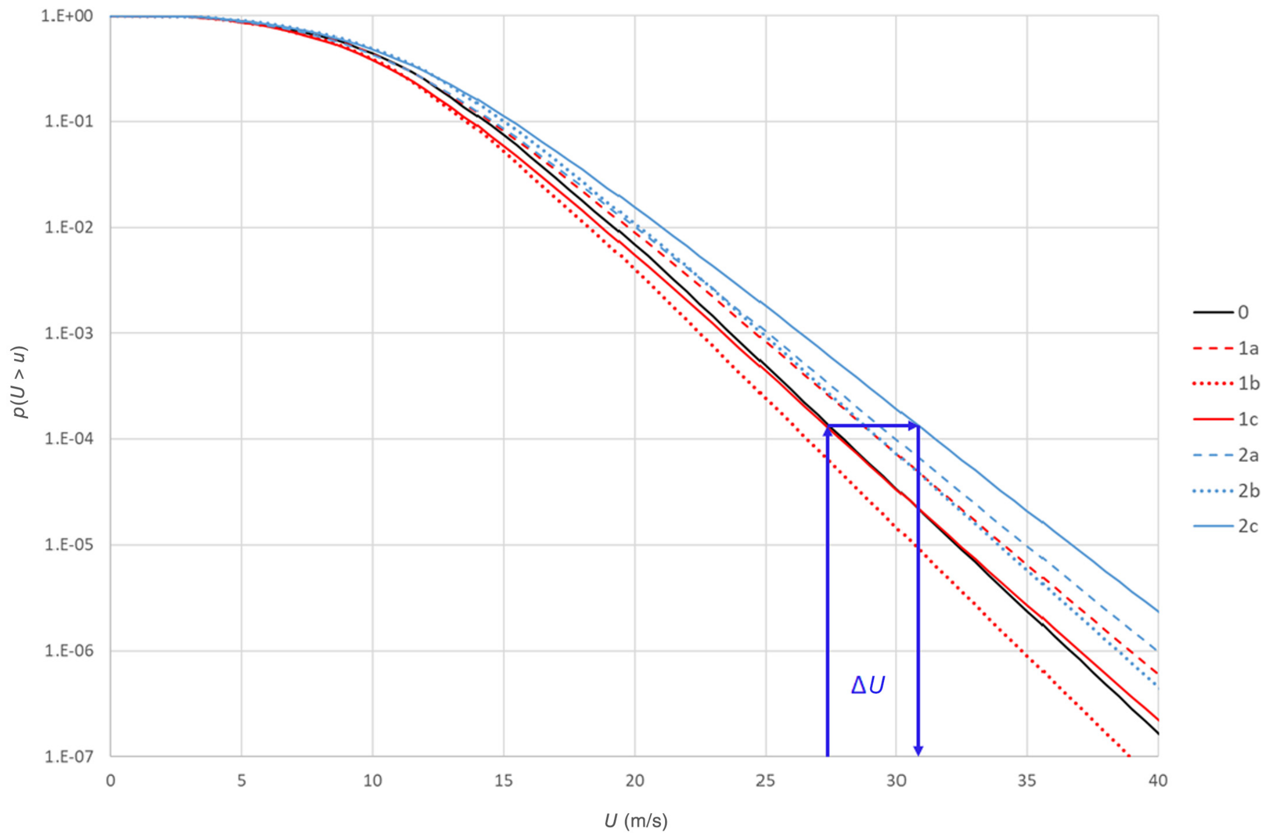

FIGURE 3 Probability of exceedance curves for the reference wind climate (Scenario 0) and the other scenarios at IJmuiden for wind direction 330° N. How ΔU is determined for coastal regions is indicated for Scenario 2c.

TABLE 3 Safety requirements for the Holland coast (maximum failure probability per year). For the reference wind climate the required crest heights, corresponding to the cross-sectional requirement for overtopping, are given along with the values of water level (WL), wind speed and wind direction

Location	Safety standard (levee stretch)	Cross-section req. (overtopping)	HBN (m + NAP)	Normative conditions wl (m + NAP)	Wind speed (m/s)	Wind dir. (°N)
H1	1/1.000	1/4.170	7.11	3.74	32.7	270
H2	1/3.000	1/12.500	13.71	4.34	31.1	330
H3	1/3.000	1/12.500	13.75	4.36	31.1	330
H4	1/10.000	1/41.670	14.05	4.91	35.2	300
H5	1/10.000	1/41.670	13.87	5.46	33.2	330
H6	1/10.000	1/41.670	12.94	5.54	33.8	330
H8	1/1.000	1/8.330	10.34	4.54	32.3	330

- In the determination of current estimates (Scenario 0), the applied exponential distributions may have led to conservative point estimates and an underestimation of the standard deviation of the point estimates. These expert views have led to the definition of Scenario 1. The experts concluded that the current values might be decreased by 5%, since the current values of the point estimates are considered to be overestimates and historical observations show a slightly decreasing trend in the wind speeds above the Netherlands. Because the current values of the statistical uncertainties are considered to be low, it is recommended to increase the standard deviations (by approximately a factor 2) to 10%.
- It cannot be excluded that with the advance of new and higher-resolution climate models, projected future

TABLE 4 Expert recommendations for the uncertainty analysis scenarios. The standard deviations of the statistical uncertainty of the wind speed are approximately 5%, as indicated in Scenario 0 between brackets

Scenario	Point estimate wind speed	Standard deviation wind speed	Point estimate wind dir.
0	Current	Current (5%)	Current
1a	Current	10%	Current
1b	Current – 5%	Current	Current
1c	Current – 5%	10%	Current
2a	Current	12%	Current
2b	Current + 5%	Current	Current
2c	Current + 5%	12%	Current
3	Current	Current	+10°

storminess will increase (see Feser et al., 2015), for example due to an increased probability of active tropical cyclones reaching the North Sea and the Netherlands. Although there is still low confidence in these climate projections, the opinion of the experts is that this effect should be considered since the impact can be large. This case was translated into Scenario 2. For the future (say 2100-scenario) a net increase of 5% of the current values is therefore recommended. This +5% net increase results from +10% gross increase in storminess, and 5% decrease resulting from improved statistical estimates (Scenario 0). The standard deviation is increased to 12% to account for the increased uncertainty in storm climate projections, compared to the current storm climate estimate.

- It is also possible that typical wind directions change due to a changing storm climate. Therefore, Scenario 3 was added, in which the wind direction changes 10° in clockwise direction and the wind speed stays unchanged.
- Until recently, there were no clear signs of an increase in the activity of extratropical cyclones. Therefore, no separate scenario was defined for this. However, Feser et al. (2015) give indications that extratropical storms might intensity after all. For now, it is assumed that this feature has been sufficiently covered by Scenario 2.

The standard deviation and point estimate adjustments mentioned above have been summarised in Table 4. For the Scenarios 2 and 3 three combinations of adjustments in point estimate and standard deviation were made, leading to the variations *a*, *b* and *c*. The values in Table 4 were agreed upon by the experts and are given with the disclaimer that they are very rough. Therefore, they should only be used for the purposes of the uncertainty analysis of this study, and not for, for example, design purposes. As indicated above the standard deviations are integrated into the point estimates. The resulting distributions for all scenarios have been given in Figure 3. Some distributions are very close, such as for Scenarios 0 and 1c.

Given the approximate character of the expert advice, the recommended changes in point estimates and standard deviations are for now applied for all locations, return periods and wind direction sectors.

4 | IMPACT ANALYSIS ON HYDRAULIC LOADS

4.1 | Lake IJsseland Lake Marken

By changing the wind statistics, the Hydraulic Loads, in terms of water level, required crest height and wave conditions will change. The changes in water level and required crest height (which comprise the changes in water level and wave conditions) were determined with Hydra-NL for all scenarios and been compared to the reference scenario.

Seven locations distributed in Lake IJssel and six locations in Lake Marken (see Figure 1) were considered. The locations for Lake IJssel are also shown in Figure 1.

The local water levels obtained for the seven scenarios were compared to the water levels obtained with the reference wind statistics at the seven locations in Lake IJssel and six locations in Lake Marken. The comparison is presented in Figure 4 for Lake IJssel.

Locations Y1, Y2 and Y6 are close to the centre of the lake and are therefore lake level dominated, see Figure 1. This means that impact of the wind on their local water level is modest. The water levels at these three locations are almost the same and show hardly any variation over the various scenarios. Also, location Y5 is lake-level dominated, but the influence of the wind cannot be fully neglected. For the most severe scenario, Scenario 2c, the water level at this location increases by 10%, compared to the reference situation.

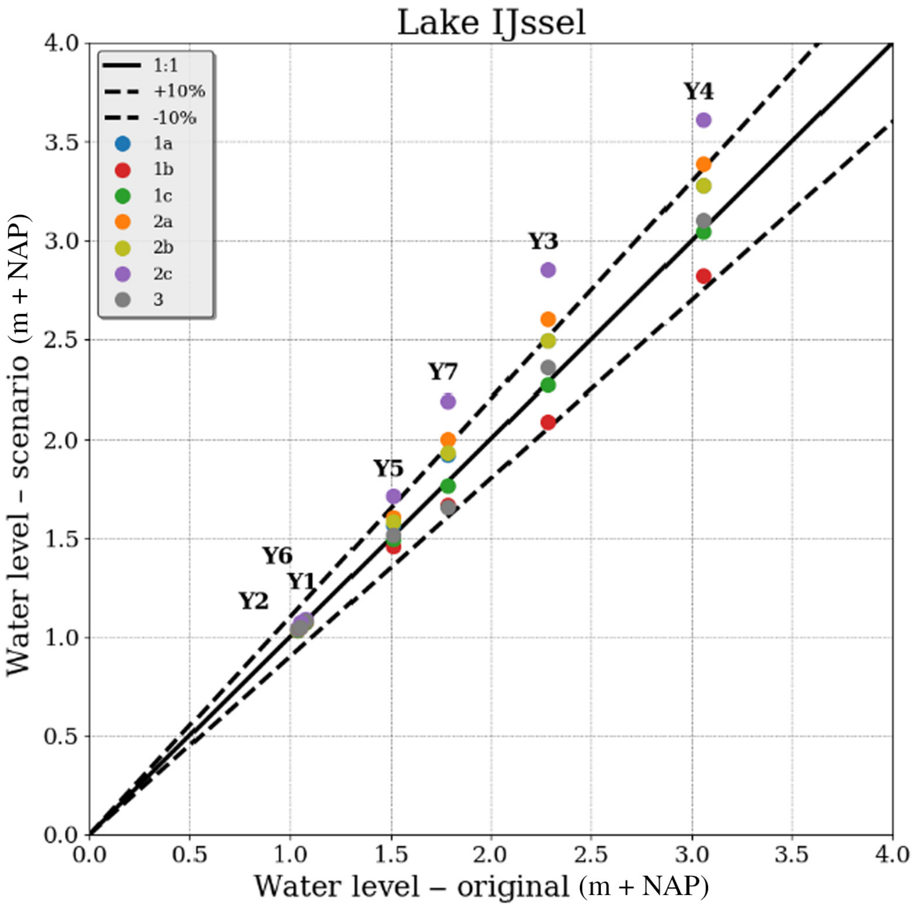

FIGURE 4 Comparison of local water levels for reference scenario (horizontal axis) versus defined scenarios (vertical axis) at all locations at Lake IJssel. Scenario 1a (blue) almost gives identical results as Scenario 2b. The solid black line is the 1:1 line, the dashed lines 10% lower and higher values.

Locations Y3, Y4 and Y7 are strongly wind dominated. The long fetches cause a surface slope from northwest to southeast. For Scenarios 1b and 2b, in which only the wind speed point estimates change with ±5%, the water level changes by 10% at these locations.

Scenario 1c, which entails a decrease of the point estimates of 5% and an increase of the standard deviation to 10%, leads to almost identical results as for reference Scenario 0. This is due to the fact that the resulting statistical distributions are almost similar (see Figure 3). The most severe scenario, Scenario 2c, leads to increases of the water level of 20%, which implies an increase in water level between 0.4 and 0.6 m at locations Y3, Y4 and Y7.

A change in wind direction, Scenario 3, hardly affects the water level. Only for the wind dominated north-easterly location Y7, the change in direction causes a decrease in wind speed. This results in a decrease in water level of approximately 0.15 m, which means a decrease of almost 10%.

In Lake Marken, the effect of the scenarios is similar to the effect observed for Lake IJssel. For the most severe scenario, Scenario 2c, an increase of water level of about 20% was observed, which is a 0.4–0.5 m water level increase at the wind-dominated location.

The required crest height is presented in Figure 5 for Lake IJssel. For Scenarios 1b and 2b, in which the point estimates change by 5%, the lake-level dominated locations Y1, Y2 and Y6 show a variation of approximately 5%. The water level is hardly affected by the wind changes, but the wave height, and successively the wave runup and wave overtopping, is. For the wind-dominated locations Y4, Y5 and Y7 a 5% change in wind speed (and unchanged standard deviation, see Scenarios 1b and 2b) results in a 10% change in required crest height, since both the wave height and the water level contribute to a change in required crest height. A similar change is obtained when only the standard deviation is increased to 10%, without changing the point estimates (Scenario 1a). For the most extreme scenario, Scenario 2c, the increase in required crest height varies between 1 and 2 m.

Finally, a change of wind direction over 10° in Scenario 3 leads to an increase of required crest height of at most 0.2 m. This is a secondary effect compared to the effect caused by the most severe scenario, Scenario 2c. For the wind-dominated locations in Lake Marken similar conclusions hold as for Lake IJssel. The required crest heights increase by 1.2–1.8 m for Scenario 2c. The cost of dike reinforcements varies significantly from typically 2000 euros per

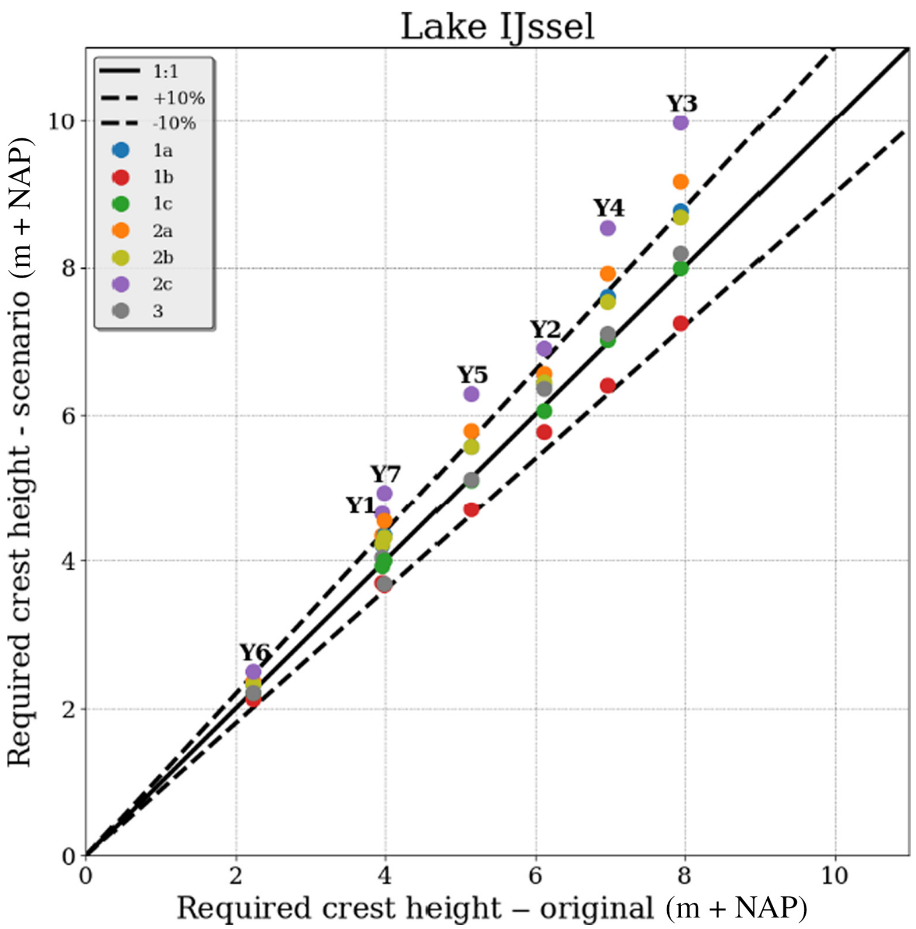

FIGURE 5 Comparison of required crest height for reference scenario versus defined scenarios at all locations at Lake IJssel

metre dike length per metre dike elevation for a rural dike to 10000 euros for more complex situations. A rough cost estimate for elevating a dike by 1 m over a distance of 10 km is 50 million euros, assuming an average cost of 5000 euro per m elevation per m dike length.

From the water level and required crest height computations at the lakes we can conclude that the water level hardly changes for the "adapted statistics" Scenario 1c. The same holds for required crest height. For Scenario 2c the water level changes by 0.4–0.6 m and required crest height by 1–2 m at wind-dominated locations (costing roughly 75 million euro for a stretch of 10 km). This is only due to changes in wind speed. The effect of a change in wind direction of 10° (Scenario 3) is small for the lakes, compared to the potential future climate impacts on wind speed.

4.2 | Coastal area

The local normative water levels in the coastal area are determined by the measured water level statistics at a number of water level stations, and therefore no wind statistics information is used. As a consequence, it is not possible to determine the effect of the changes in wind, indicated in Table 4, on the water level for the coastal region. Only the effect of the scenarios on the required crest height was considered in the analysis. Figure 1 gives an overview of the locations in the three coastal areas, Wadden Sea, Western Scheldt and Holland coast. A more detailed overview of the locations along Holland coast is given in Figure 6.

The required crest heights were determined for Scenarios 1a–c and 2a–c and compared to the required crest heights of Scenario 0. As the results are similar for the entire coastal area, only the results for Holland coast are presented (see Figure 7). The trends are unambiguous. At all locations the wind is the main source for large required crest heights. An increase in wind leads to an increase in both water level (actually storm surge) and wave heights, and therefore to an increase in required crest height. Due to the applied pragmatic approach, the relative effect of wind changes on storm surge is more or less uniform over all locations. Dike cross sections vary in slope and height and width of the berm, or do not have a berm at all. Consequently, the wave run up and wave overtopping discharges vary per location and explain part of the variation in the increase of the required crest height.

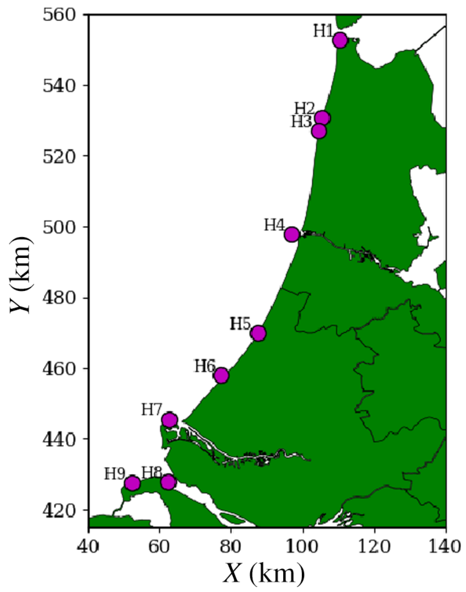

FIGURE 6 Locations along the Holland coast (magenta) for which the required crest heights were determined. Since H7 and H9 are dune locations, they have not been included in the analysis

From the computed required crest heights we can conclude that they hardly change for the "adapted statistics" Scenario 1c. For Scenario 1a, where the point estimates remain unchanged, and Scenario 1b, with unchanged standard deviation, a 10% change in required crest height is obtained (up to 1.5 m). For the most severe Scenario 2c, however, the required crest height changes of 1.5 m to even 4 m were observed. Figure 7 shows that an increase to 12% uncertainty (Scenario 2a) has more impact than a 5% increase of point estimate (Scenario 2b). However, since these percentages are different the conclusion that increase in uncertainty has more impact than increase in point estimate, cannot be not justified.

The 4 m change in required crest height was observed for locations H3, H4 and H6, see Figure 7. The reference scenario, Scenario 0, resulted in a wind speed of 35.2 m/s from 300° N and surge estimate of 4.9 m. Going from the basic Scenario 0 to Scenario 2c provides a relative change in wind speed of 15% and consequently an absolute change in surge of $\sim$1.5 m ($= 2 \times 15\% \times 4.9$ m), explaining almost 40% of the increase of required crest height. The increase in wind speed results in an increase in wave height from 4.0 to 5.0 m. The spectral wave period $T_{m-1,0}$ increases slightly by 0.3 to 10 s. The increase in wave height and period explain the remaining 60% increase of required crest height. For the Scenarios 2a and 2c the increase at locations H3, H4 and H6 is significantly more than at the other locations. In contrast, for Scenario 2b the increase is approximately the same (10%) at all locations. This can be explained by the difference in curvature of the point estimate distribution, or exceedance curve, of the wind speed. This curvature is defined as $\Delta P(U > u)/\Delta U$. Figure 3 shows that the curvature of Scenario 2b is close to the curvature of Scenario 0, for Scenarios 2a and 2c the curvatures are different. Since the maximum failure probability for locations H3, H4 and H6 is smaller than at the other locations (Table 3), a larger ΔU, and thus a larger Δh is found for Scenarios 2a and 2c at locations H3, H4 and H6, compared to the other locations. The smaller curvature for Scenario 2b results in values for Δh that are comparable for all locations. Larger values for Δh, as input to Hydra-NL, lead to higher requested crest heights.

The effect of Scenario 3 was not calculated for the coastal areas, as it is not useful to change the wind statistics due to the definition of the load model. The effect can only be estimated qualitatively. Given the orientation of the North Sea the normative direction is NNW. With a rotation of the wind over 10° the maximum wind speed turns more toward NNW and leads to higher surge levels. As can be seen in Figure 8 the wind speed increases approximately 1 m/s in the northwestern sector, so let us say 3%. A 3% increase in wind speed leads to a 6% increase in storm surge level. For a 30 m/s wind speed from NNW this is almost a 0.2 m (6% of 3 m) change in surge level. For the normative wind speeds this will be approximately 0.25 m. Compared to the change in storm surge level due to future Scenario 2c (approximately $20\% \times 5$ m $= 1$ m) this is a secondary effect, as for the lakes.

From the required crest height computations at the coastal locations we can conclude that the required crest height hardly changes for the "adapted statistics" Scenario 1c. For "the potential future climate" scenario (Scenario 2c) the required crest height increases by 1.5–4 m (roughly 75–200 million euro for 10 km dike reinforcement, assuming an average cost of 5000 euro per m elevation per m dike length). As for the lakes, the effect of a change in wind direction of 10° (Scenario 3) is small, compared to the potential future climate impacts on wind speed.

5 | DISCUSSION

An evaluation of different storm climate studies has been given by Feser et al. (2015) and Mölter et al. (2016). They show that there are still substantial differences between different climate models and large uncertainties exist, for example, scenario- and modelling uncertainties overshadowed by a large internal climate variability. This means that deducting storm trends and uncertainties is a challenge. In this paper we present a simple method to

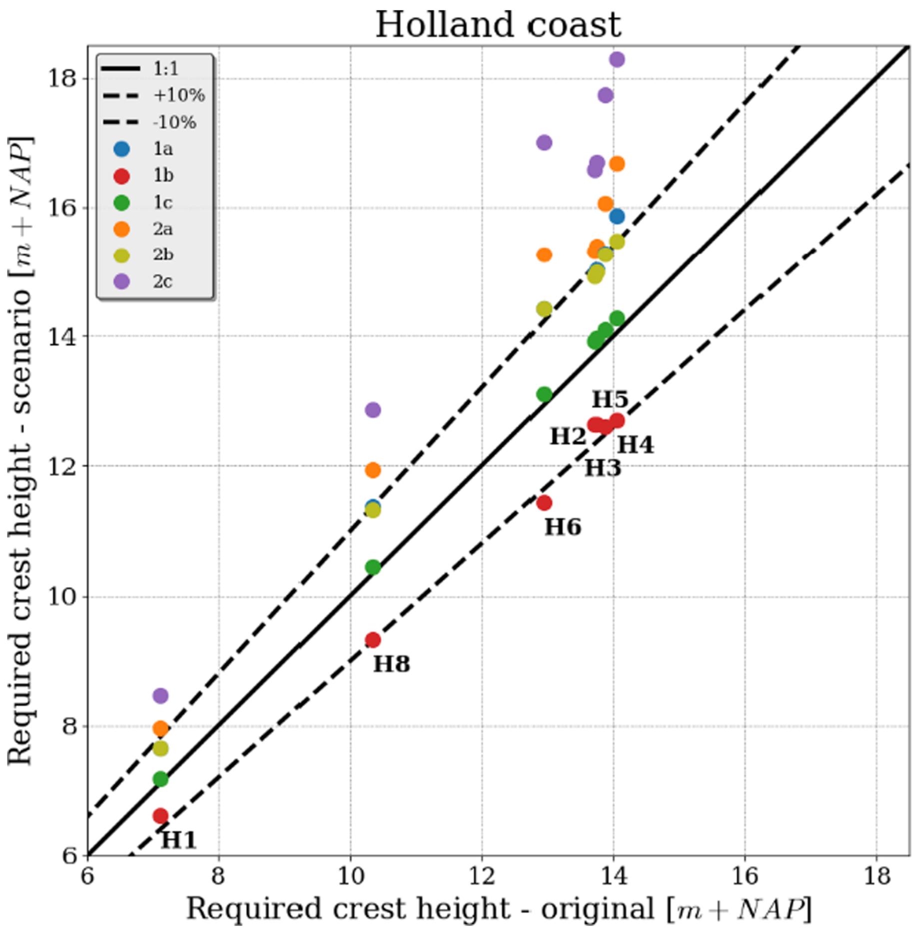

FIGURE 7 Comparison of required crest height for reference scenario versus defined scenarios at all locations along the Holland coast

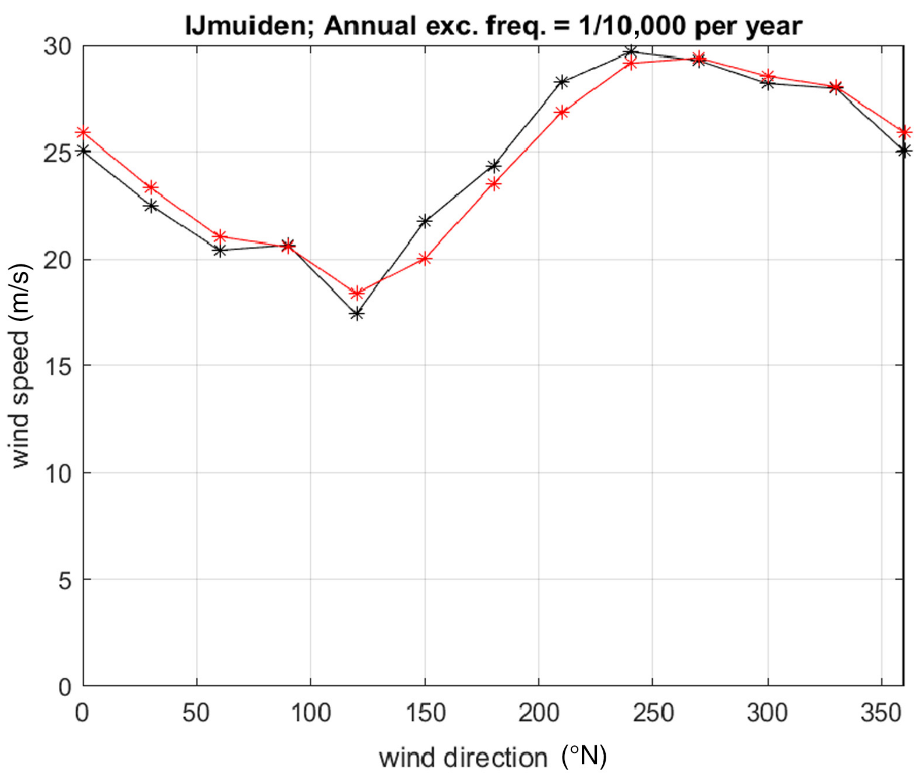

FIGURE 8 Potential wind speed 10,000-year return value estimates in metres per second at IJmuiden: Original (black) and shifted (red)

quantify the effect of possible trends and uncertainties in storm climate on levee design. Uncertainties in storm climate are overcome by defining different scenarios that provide a sensitivity analysis of levee designs. A valuable extension of this approach would be to extend the number of scenarios, each with a weight or likelihood of occurrence to provide insight into the variance of the results. The presented approach can also be applied to other protective measures, for example, dunes.

Worldwide the effect of storm climate on storm surge and waves has been studied, for example, Muis et al. (2020), Morim et al. (2019), Bricheno and Wolf (2018). However, the translation from storm surge to flood defence is not often made. The current paper shows that increasing trends and uncertainties in storm climate is significant for a robust levee design, the cost of which are estimated hundreds of millions of euros. Therefore, storm climate trends and uncertainties should be evaluated when looking at coastal adaptation and the costs and impacts of climate change. That is not necessarily done with a probabilistic approach as presented here, but could also be taken into account with a deterministic approach, by defining scenarios that represent the trends and uncertainties of the storm climate, as sketched here. The global climate change induced changes in wind speed statistics can therefore be also accounted for in areas outside the Netherlands.

6 | CONCLUSIONS AND RECOMMENDATIONS

6.1 | Conclusions

Based on experts' opinions storm climate trends and uncertainties were identified, defined into scenarios and translated to adaptations of the wind statistics. The adapted wind statistics were used in the probabilistic tools to determine hydraulic loads on dikes in the Netherlands. The hydraulic loads, in terms of water level and required crest height, were calculated in the lakes and coastal regions in the Netherlands for the various defined scenarios. The following conclusions can be drawn from this impact analysis:

Including the trends and uncertainties in storm climate mostly results in higher hydraulic loads. Based on the results for Scenario 1b and 1c, we conclude that Hydraulic loads only decrease when a point estimate change of −5% is combined with a standard deviation change of less than 10%.

The water levels and required crest heights hardly change when replacing the currently applied wind statistics by the "adapted statistics" Scenario 1c (point estimates −5% and statistical uncertainty 10%). However, in case either the standard deviation is increased to 10% (Scenario 1a) or the point estimate is decreased by 5% (Scenario 1b), a 10% change in water level and required crest height is observed.

For the future scenario with increased point estimates (+5%) and increased standard deviation (to 12%), the water levels increase significantly (0.4–0.6 m at the lakes for wind-dominant locations), compared to the values obtained with the currently applied wind statistics. The required crest height increases by 1–2 m at wind-dominated lake locations and 1.5–4 m at the coastal regions, costing roughly 75–200 million euro for 10 km dike reinforcement. A change in wind direction of 10° in Lake IJssel and Lake Marken hardly seems to affect the water levels and required crest heights, at most 0.2 m. A similar change in the coastal regions is qualitatively estimated to result in 0.25 m increase of the storm surge level. Compared to the change in storm surge level due to future Scenario 2c (approximately 20% × 5 m = 1 m), this is a secondary effect, as for the lakes.

6.2 | Recommendations

From the expert meeting it was concluded that revision of the current wind statistics is desirable. The main issue was that the exponential distributions in the reference statistics may lead to overestimation of point estimates and to an underestimation of the standard deviation of the point estimates. However, this study has shown that the effect of a decrease of the point estimates by 5%, combined with an increase of the standard deviation to 10% show a minor effect on the hydraulic loads. The considered variations in the wind statistics parameters are rough estimates. Changing only one of the parameters and keeping the other unchanged results in a 10% change in water level or required crest height. Though relevant, we do not yet recommend a revision of the current statistics.

For the future scenario, a 5% net increase of the current point estimates (10% gross increase, and 5% decrease linked to the conservative point estimates of exponential distributions as mentioned above) and a higher value for the standard deviation (12%) were used. This to account for potential increases in storminess, for example due to a higher probability of tropical cyclone remnants reaching the Netherlands and regarding uncertainties in climate projections, wind farm developments and others. As already mentioned, these estimates are very rough and can only be used for the present sensitivity analysis to get a first impression of the effect on the hydraulic loads. We therefore first of all recommend to improve future storm climate projections, for example by investigating the probability of tropical cyclone remnants reaching the Netherlands in more detail. If an increase of 5% of the point estimates is not realistic and only 10% standard deviation should be considered (i.e., Scenario 1a), the increases in water level and required crest height would be 50% to 70% less than those of a 5% increase of the point estimates.

Further recommendations following from the expert meeting are:

- Historical observations show a slightly decreasing trend in the wind speeds above the Netherlands due to an increase in surface roughness. This trend (and perhaps also other trends) should be considered when deriving wind statistics. Note that a decreasing trend has not been observed above the North Sea.
- To investigate potential wind-reducing effects of planned large-scale wind farm developments in the North Sea.
- Changes in the seasonality of storms should be further investigated. In principle remnants of tropical cyclones occur early or before the start of the storm season. However, given the large uncertainties there are no concrete adjustments to storm climate that can be recommended yet.

ENDNOTE

[1] The Royal Netherlands Meteorological Institute (KNMI) is the Dutch national weather service.

DATA AVAILABILITY STATEMENT

Data available on request from the authors

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REFERENCES

Bricheno, L. M., & Wolf, J. (2018). Future wave conditions of Europe, in response to high-end climate change scenarios. *Journal of Geophysical Research: Oceans*, *123*, 8762–8791. https://doi.org/10.1029/2018JC013866

Caires, S. (2009). Extreme wind statistics for the hydraulic boundary conditions for the Dutch primary water defences. SBW-Belastingen: Phase 2 of subproject “wind modelling”. *Deltares Report*, 1200264-005.

Caires, S., & Sterl, A. (2005). 100-year return value estimates for wind speed and significant wave height from the ERA-40 data. *Journal of Climate*, *18*(7), 1032–1048.

Chbab, H. (2015). *Waterstandsverlopen Kust. Wettelijk Toetsinstrumentarium WTI-2017. Deltares rapport 1220082-002-HYE-0003, December 2015 (in Dutch)*. Deltares.

De Vries, H., Van Meijgaard, E., Van Ulft, B., Groeneweg, J., Slagter, D., & Bottema, M. (2018). Als orkaan Ophelia Nederland had bereikt. *Meteorologica*, *3*, 4–8 (in Dutch).

Fagherazzi, S., & Wiberg, P. L. (2009). Importance of wind conditions, fetch, and water levels on wave-generated shear stresses in shallow intertidal basins. *Journal of Geophysical Research*, *114*(F3). https://doi.org/10.1029/2008JF001139

Feser, F., Barcikowska, M., Krueger, O., Schenk, F., Weisse, R., & Xia, L. (2015). Storminess over the North Atlantic and northwestern Europe—A review. *Quarterly Journal of the Royal Meteorological Society*, *141*, 350–382. https://doi.org/10.1002/qj.2364

Geerse, C. (2016) *Werkwijze uitintegreren onzekerheden basisstochasten voor Hydra-NL—Afvoeren, meerpeilen, zeewaterstanden en windsnelheden. HKV-rapport PR3216.10* (in Dutch). HKV Lijn in Water.

Haarsma, R. J., Hazeleger, W., Severijns, C., De Vries, H., Sterl, A., Bintanja, R., Van Oldenborgh, G. J., & Van den Brink, H. W. (2013). More hurricanes to hit western Europe due to global warming. *Geophysical Research Letters*, *40*(9), 1783-1788. https://doi.org/10.1002/grl.50360

HKV. (2019). *Hydra-NL gebruikershandleiding versie 2.7.1. HKV report PR4022.10, September 2019 (M. Duits)* (in Dutch).

Mölter, T., Schindler, D., Albrecht, A. T., & Kohnle, U. (2016). Review on the projections of future storminess over the North Atlantic European region. *Atmosphere*, *7*, 60.

Morim, J., Hemer, M., Wang, X. L., Cartwright, N., Trenham, C., Semedo, A., Young, I., Bricheno, L., Camus, P., Casas-Prat, M., Erikson, L., Mentaschi, L., Mori, N., Shimura, T., Timmermans, B., Aarnes, O., Breivik, Ø., Behrens, A., Dobrynin, M., … Andutta, F. (2019). 2019: Robustness and uncertainties in global multivariate wind-wave climate projections. *Nature Climate Change*, *9*, 711–718. https://doi.org/10.1038/s41558-019-0542-5

Muis, S., Apecechea, M. I., Dullaart, J., de Lima Rego, J., Madsen, K. S., Su, J., Yan, K., & Verlaan, M. (2020). A high-resolution global dataset of extreme sea levels, tides, and storm surges, including future projections. *Frontiers in Marine Science*, *7*, 1–15. https://doi.org/10.3389/fmars.2020.00263

Slomp, R., Knoeff, H., Bizzarri, A., Bottema, M., & De Vries, W. (2016). Probabilistic flood defence assessment tools. *Proceedings of FloodRisk2016, E3S Web of Conferences*, *7*, 03015.

Wever, N and G. Groen, (2009). *Improving potential wind for extreme wind statistics. KNMI Scientific Report WR2009-02, March 2009*. KNMI.

Wolf, J., Woolf, D., & Bricheno, L. (2020). Impacts of climate change on storms and waves relevant to the coastal and marine environment around the UK. *MCCIP Science Review*, *2020*, 132–157. https://doi.org/10.14465/2020.arc07.saw

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