Prepared for:

RIKZ-Rijkswaterstaat

Uncertainty Analysis of the Hydraulic Boundary Conditions of the Wadden Sea

Results of the uncertainty analysis

Report

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Abstract:

This report describes the results from an uncertainty analysis of the Hydra-K and SWAN models, giving an estimate of the level of accuracy of the Hydraulic Boundary Conditions (HBC) in the Wadden Sea. Specifically, the goal was to quantify the contribution of the SWAN model and Hydra-K model input parameters to the overall uncertainty in the HBC and to determine the quantitative contributions of model inputs and model parameterizations are to the uncertainty in the SWAN results. These results can then be used to assist in the improvement of the methodology.

The uncertainty analysis of the HBC was done by using a Monte Carlo sampling technique. Separate Monte Carlo simulations were used for different parts of the calculation associated with the different sources of error. The first part involved the SWAN calculation. The uncertainties associated with the SWAN parameters and input were found to be approximately 17% both for the near shore wave height and the wave period at shallow water locations. From comparison with observations (hindcasts), it was concluded that there is an additional uncertainty in the SWAN outcomes as a result of uncertainties in the SWAN model formulations. This uncertainty is responsible for a considerable systematic error.

The second part involved the Hydra-K computation of HBC. The uncertainty in three Hydra-K inputs, namely wind speed, water level and results from the SWAN model, contribute to the uncertainty of the Hydra-K output (the HBC). The overall uncertainty in the HBC, expressed as a critical crest level, was found to be between 90 and 100 cm. Although this uncertainty is considerable, it should not lead to different assessment results, because the assessment is based on the expectation value, or best estimate. The results of the uncertainty analysis can, however, be used as guidelines for further improvement of the methodology.

References: none

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Contents

1 Introduction

1.1 Reliable wave boundary conditions for the Wadden Sea

In compliance with the Flood Defences Act ("Wet op de Waterkering, 1995"), the primary coastal structures must be monitored every five years (2001, 2006, 2011, etc.) for the required level of protection. This assessment is based on the Hydraulic Boundary Conditions (HBC) and the Safety Assessment Regulation (VTV: Voorschrift op Toetsen op Veiligheid). These HBC are derived every five years and approved by the Minister of Transport, Public Works and Water Management.

Following these regulations, the HBC for the closed coastline of Holland and the Zeeland Delta were been recalculated in 2006, using the probabilistic model *Hydra-K* and the wave transformation model *SWAN* (Booij *et al.*, 1999, SWAN homepage http://www.swan.tudelft.nl). For the Wadden Sea, however, no recalculation was done, because there is insufficient confidence in the performance of SWAN in the Wadden Sea. At the same time, the quality of the current HBC for the Wadden Sea has been questioned, because they were obtained from an inconsistent set of measurements and design values (WL, 2002).

The "Strength and Load of Coastal Structures (SBW: Sterkte en Belasting Waterkeringen) project" has the task of improving the quality of the models and methods used to derive the HBC to enable the managers and experts to have sufficient confidence to use these tools for the five-yearly tests. In order to do so, the Hydra-K and SWAN models need to be validated, calibrated and if necessary, modified to achieve maximum performance in the Dutch Wadden Sea, using all available data from that area and from elsewhere. This is achieved by performing hindcasts of storm events in the Wadden Sea (WL, 2006; Haskoning, 2006, Alkyon, 2007a, b) and by sensitivity and uncertainty analyses (WL, 2007a, b).

This report describes the results from an uncertainty analysis of the Hydra-K and SWAN models, giving an estimate of the uncertainties of the HBC in the Wadden Sea. These uncertainties will not affect the results of the safety assessment, since the Flood Defences Act states that the assessment should be done based on the *average* HBC, or the best estimate. The results of the uncertainty analysis can, however, be used as guidelines for further improvement of the methodology.

1.2 Objectives of the study

The objective of this study is to assess the level of accuracy of the HBC in the Wadden Sea Area. Furthermore, we wish to quantify the contributions of the SWAN model and other components to the overall uncertainty in HBC.

The goals of this research can be summarized as follows:
- To assess the total uncertainty of the HBC of the Wadden Sea using the presently used methods.
- To quantify the contributions of the various sources of uncertainties to the total uncertainty.
- To estimate the possible reduction in uncertainty by reducing or eliminating individual sources of uncertainty.
- To make suggestions for future efforts to improve the accuracy of the HBC.

1.3 Outline

The outline of the report is as follows:

- In the remaining part of this chapter, a summary is given of previous studies, the results of which were used in this study.
- Chapter 2 discusses the general method of the HBC calculation and the uncertainty analysis and the results of the reference calculations, i.e. without any perturbation.
- Chapter 3 gives an overview of the HBC calculations, the role of SWAN and the general approach to the uncertainty analyses that are the subject of the following Chapters.
- Chapter 4 deals with the uncertainty analysis of the SWAN model.
- In Chapter 5 describes the results of the uncertainty analysis of Hydra-K.
- Finally, Chapter 6 discusses the overall conclusions and recommendations for further research. We demonstrate how a small number of important sources of uncertainty determine the total uncertainty in HBC.

1.4 Summary of previous studies

This report is the third in a series of reports with regard to the uncertainty analysis of the Hydraulic Boundary Conditions (HBC) calculations. This research has been started in 2006 with a predominantly qualitative inventory of expert opinions (WL, 2007a). In June 2007 (WL, 2007b), an identification of all the relevant sources of uncertainty in the HBC calculation has been done, as well as a specification of how the quantitative uncertainty analysis should be done. The results of these studies are summarized below.

Results from WL, 2007a

From the inventory of expert opinions (WL, 2007a) the most important sources of uncertainty in the HBC for the Wadden Sea have been identified as follows:

1. The *statistical* uncertainties concerning the extrapolation of meteorological and offshore hydraulic conditions to extremely large return periods (in the order of 10^3 up to 10^4 years).

2. Given the offshore conditions, it is the *model* uncertainty of the SWAN model and its input parameters that lead to an uncertainty in the near-shore HBC. The major contributions are:
   - The suitability of SWAN for extreme conditions, in particular because of the uncertainties concerning the model formulations. That is to say, the uncertainty in parameterization of physical processes, such as triads, quadruplets surf-beat and white-capping, in particular those affecting the near-shore wave *period*.
   - The uncertainties in the specification of the wind field used by SWAN and the modelling of the interaction between wind and waves, especially for strong winds.
   - The uncertainty in the bed topography of the Wadden Sea, in particular near the sea defences, affecting the near-shore wave *height*.
   - The lack of knowledge of current patterns in the Wadden Sea and the effect of currents on the near-shore HBC.

A quantitative sensitivity analysis was done for three locations along the Dutch North Sea coast. The following conclusions were drawn (WL, 2007a):

1. The effect of the uncertainty in the offshore water level, wave characteristics and wind on the uncertainty of the design crest levels is substantial. Quantified as a design crest level, the uncertainty due to these uncertain parameters is in the order of meters.
2. Of the parameters taken into account, the design crest level is most affected by the uncertainty in the wave periods, both near-shore and offshore.
3. The effect of uncertainty in each of the varied parameters (i.e. water level, wind speed and wave conditions) is highly dependent on the location along the coast.

The total uncertainty in the HBC at a single location is determined by several local conditions, such as the influence of offshore waves and the influence of currents on the near-shore wave conditions. This implies that the uncertainties vary per location. Roughly speaking, it seems that the HBC's in the western part of the Wadden Sea are less sensitive to uncertainties than those in the eastern part. In the eastern part, the sea defences are highly affected by uncertainty in the penetration of incoming long waves.

Results from WL, 2007b

In the first half of 2007, preliminary activities were carried out for an uncertainty analysis of the HBC for the Wadden Sea area. The most important sources of uncertainty were identified. Furthermore, it was concluded that a stepwise Monte Carlo approach is most appropriate to investigate the uncertainties in the HBC. Two separate types of Monte Carlo simulations were suggested for the two major sources of uncertainty in this calculation: the marginal exceedance probability functions of wind speed and water level on the one hand and the SWAN calculations on the other hand.

In a final step the two sources of uncertainty are combined to calculate the total uncertainty in the HBC. This uncertainty can be expressed as an uncertainty in the critical crest level, a single scalar quantity. In order to distinguish between the contributions of the two sources of uncertainty, separate runs are performed, switching 'on' and 'off' the several sources of uncertainty. This makes it possible estimate the maximum achievable accuracy if one or several sources of uncertainty would be eliminated.

1.5 Project plan

A number of activities have already been mentioned in the proposal[1] and the project plan of the SBW project. These are listed below and refer to the sections in this report where the results are discussed.

[1]Uitvoering Plan van Aanpak SBW RVW Waddenzee 2007, versie maart 2007.

1.5.1 Part 2A: Uncertainty analysis SWAN

According to the proposal, the SWAN uncertainty analysis should consist of the following activities:

- Execution of the SWAN uncertainty analysis,
- Classification of the sources of uncertainty based on the propagation and contributions to the total uncertainty,
- Interpretation and discussion of the results.

The results from these activities are discussed in Chapter 3.

1.5.2 Part 2B: Uncertainty analysis of the HBC

At the time of writing of the proposal the uncertainty analysis of the complete HBC chain could not be specified in detail. Instead, this specification was done in phase 1 of the 2007 project (WL, 2007b). The proposal offers to give at least:

- Results of the quantitative uncertainty analysis of the complete HBC chain. These are given in Chapter 4.
- Conclusions and recommendations for more detailed uncertainty analyses in a follow-up study in 2008. This is discussed in Chapter 5.

2 Method

This chapter gives a global description of the HBC calculation, which consists of a chain of smaller sub-calculations. In section 2.2, the general approach to the uncertainty analysis is discussed in more detail. In sections 2.3 and 2.4, the area of interest and the reference calculation are discussed.

2.1 General description of the model chain

The HBC for the Dutch coast are computed using a model called *Hydra-K*[2]. Hydra-K uses a probabilistic method to compute the HBC at locations along the coast. The probabilistic method is based on a Monte-Carlo technique, with the assumption that the correlations between different factors under extreme conditions correspond to those of less extreme measured correlations (the so-called method ‘De Haan’, Haan 1977). Hydra-K computes the HBC for different failure mechanisms, such as wave run-up, or damage of the dike revetment. The HBC can differ between failure mechanisms, because these mechanisms are sensitive to different parameters.

Figure 1 shows the model chain used to compute the HBC along the Dutch coast. Every step in the calculation introduces some type of uncertainty. All uncertainties combined lead to a total uncertainty in the HBC, which is represented by the critical crest level in this study.

In principle, all uncertainties propagate to an uncertainty in the end result. However, some contributions are negligible compared to others (indicated in green in Figure 1). Other sources are investigated in detail in other projects (indicated in yellow in Figure 1). For all the remaining relevant uncertainties (indicated in red in Figure 1) the propagation to the end result is analyzed in this report.

2. We note that other Hydra-models exist to compute the HBC for other water systems in The Netherlands: Hydra-B (western part of the river system of Rhine and Meuse), Hydra-M (lakes) and Hydra-VIJ (delta of rivers Vecht and IJssel). All Hydra-models are based on probabilistic computation methods (HR2006).

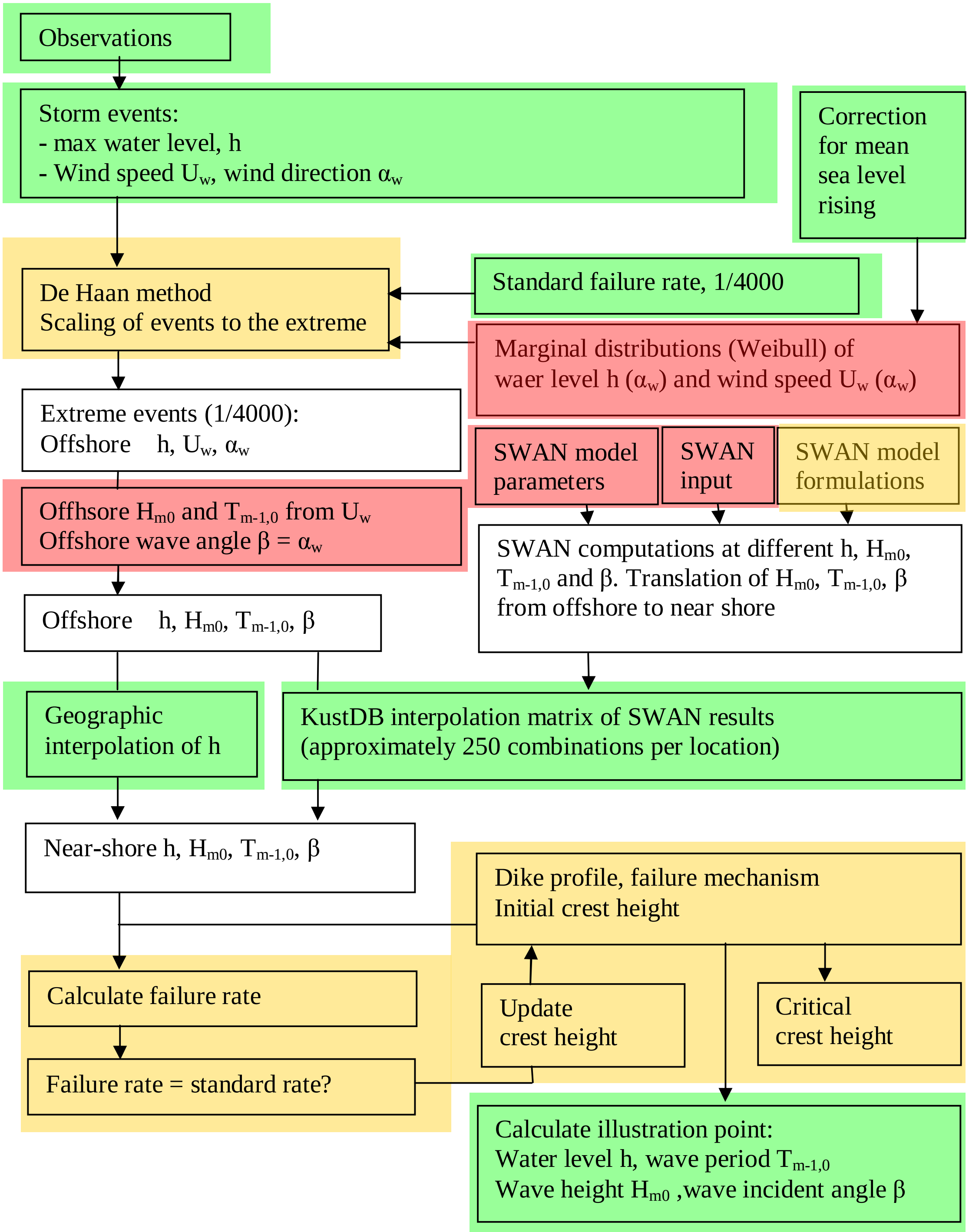

Figure 1: Schematic overview of the HBC calculation.

Green: These sources of uncertainty are negligible as will be shown in the next sections.
Red: These sources are dominant and will be quantified in detail in the following sections.
Yellow: These sources are investigated in other projects, in 2008:

- The 'De Haan' method is investigated by WL | Delft Hydraulics outside the SBW framework.
- The failure calculations are investigated by GeoDelft within the SBW framework ('onzekerheidsanalyse faalmechanismen'). The first analyses will begin in 2008.
- The uncertainty in the SWAN model formulations is derived from a rough estimation of the total uncertainty in SWAN results, see section 3.3.

An important part of the HBC calculation is the translation of offshore wave conditions to near-shore wave parameters. For this purpose Hydra-K uses the wave simulation model SWAN (or more precisely, a database with SWAN computational results). Uncertainties associated with the SWAN model are thus propagated in the HBC. In this study, we consider two sources of uncertainty in the SWAN model. The first source is the uncertainty in input parameters of the SWAN calculation, such as offshore wave height and wave period, bathymetry and currents. The second source is the set of internal model parameters that govern the physical equations. A third source, the model formulations uncertainty is estimated roughly in this study (see section 3.3) and taken into consideration in the overall uncertainty analysis (chapter 4).

2.2 General setup of the uncertainty analysis

The uncertainty analysis of the HBC is done by using a Monte Carlo sampling technique. Monte Carlo methods are a standard approach to uncertainty analysis of systems with many variables, which cannot easily be solved analytically. A Monte Carlo algorithm uses (pseudo) random numbers to generate many realizations of the same calculation. Each of the uncertain model parameters is sampled randomly from prescribed probability distributions. For each of these samples a simulation is performed, resulting in an ensemble of outputs. By statistically evaluating these random outputs we obtain information of the uncertainty of the output.

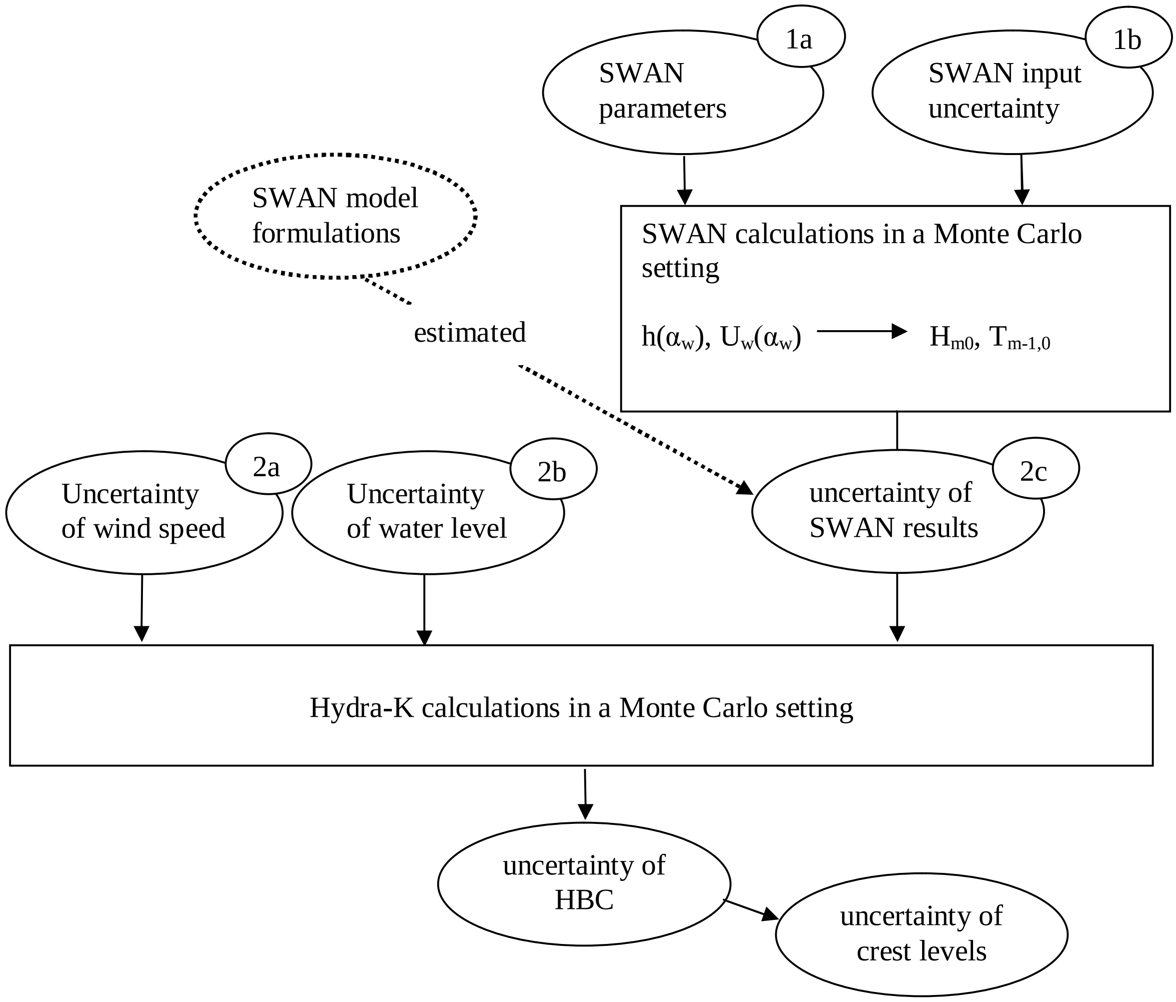

Figure 2 General setup of the HBC uncertainty analysis.

In the case of the HBC calculation, two separate Monte Carlo simulations were used for two different parts of the uncertainty analysis that are associated with the main sources of error (see Figure 2). The first part is associated with the uncertainties in the SWAN calculations (steps 1a and b). The second part is the propagation of uncertainty in the marginal distributions of wind speed (2a), water level (2b) and the SWAN uncertainty (2c) to the uncertainty of the HBC. The total uncertainty of the SWAN results (2c) also includes the uncertainty of the model formulations. This is discussed in section 3.3.

For each Monte Carlo simulation, each source of uncertainty was switched 'on' and 'off'. In this way, the contribution of each source to the total uncertainty was able to be determined. Information about these contributions can be used to estimate the possible reduction in the total uncertainty by eliminating one or several sources of uncertainty, which is one of the goals of the present study.

2.3 Area of interest

The uncertainty analysis described in this report is not an extensive study of all possible uncertainties in the complete Wadden Sea area. Instead, the goal is to give a rough estimate of the level of accuracy and the most important sources of error. In order to do so, we choose a small test area that best represents the Wadden Sea. The Frisian inlet is such an area, because it covers shallow areas and deep tidal channels, as well as an ebb tidal delta. An additional advantage of the Frisian inlet is that the area is relatively small, which limits the required computing time for the SWAN model.

Figure 3 The Frisian inlet, with the four locations for which the uncertainty analysis has been carried out.

The Frisian inlet covers a number of important aspects of wave propagation in the Wadden Sea. However, the magnitude of physical processes in the Wadden Sea varies from west to east and the

Frisian inlet cannot be taken as fully representative for all processes in the entire area. For example, the penetration of long waves hardly occurs in the Ameland inlet just to the west of the Frisian Inlet (Alkyon, 2007a,b). The Frisian inlet is wider, so more long waves may be penetrating. The Eems-Dollard area has different characteristics altogether and should be investigated in a separate study (proposed for 2008).

Observation points

We have investigated the HBC uncertainty at four locations in the Frisian inlet area, indicated in Figure 3 and Table 1. Location nr 1 is largely shielded from the North Sea by the island of Ameland. Location nr 2 is directly behind an inlet and is not shielded. This location could potentially receive swell waves. Locations nr 3 and 4 are shielded by the island of Schiermonnikoog, but are very close to a tidal channel, with strong currents and possible wave transformation through the channel. These locations thus capture a number of typical phenomena in the Dutch Wadden Sea.

Ideally, the HBC are calculated at locations 50 [m] from the coastline. In practice, the minimum distance is often determined by the SWAN grid. The distance of the selected observation points to the coastline is approximately 300 [m], as close to the coastline as possible in the SWAN grid. Four additional observation points 400 [m] north of those in Table 1 were initially included in the calculations to test the sensitivity of the results to the distance to the coastline. However, no significant differences were observed between the results at these output locations and results described in this study. The results from these four additional locations were therefore not included in this report.

Table 1 Characteristics of the observation points used in this study.

Observation point	x-coordinate [m]	y-coordinate [m]	Depth [m+NAP]
Location 1	193900	601400	4.6
Location 2	200900	602800	4.8
Location 3	207600	603550	12.9
Location 4	209400	603200	10.4

2.4 Reference calculations

The uncertainty analyses in the next two chapters are based on perturbations to a reference calculation. To accurately assess the uncertainties of the HBC, this reference calculation should reflect our best estimate of the normative conditions, i.e. an extreme storm situation. In the next section, we describe the settings and results of the reference SWAN simulation. In Section 2.4.2, we describe the settings and results of the reference Hydra-K calculation.

2.4.1 SWAN

This study uses two rectangular grids to schematize the Frisian inlet (Figure 4). A coarse grid with mesh sizes of 300 [m] in both directions and a rotation of 10º provide boundary conditions for a finer grid. The fine grid has a mesh size of 100 [m] in x direction and 50 [m] in y direction. 50

meters is considered to be the maximum grid spacing necessary to accurately reproduce the influence of processes like depth-induced wave breaking near the Frisian coastline.

Computational grid

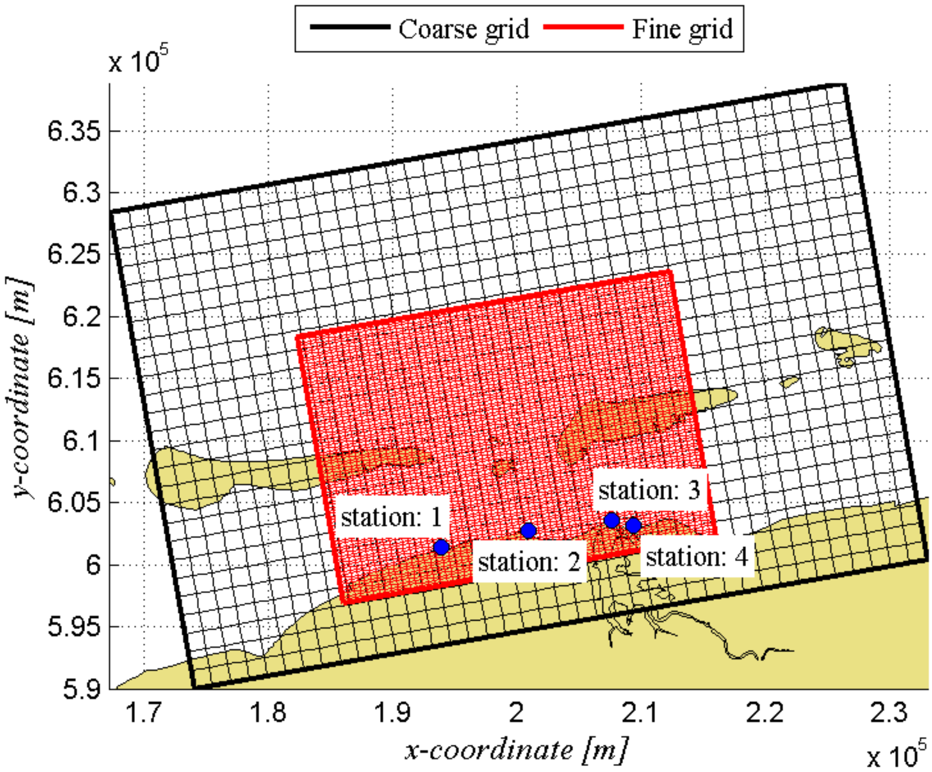

Figure 4 Observation points and computational grids used in this study (each 5th line is plotted)

Model coefficients

Model coefficients as defined in the first phase of this project will be used in the reference simulation. A summary can be found in Appendix A.

Bathymetry

Bathymetric information for the Dutch Wadden Sea is collected on a regular basis by Rijkswaterstaat. This is also known as the “vaklodingen” data. In addition to this, bathymetric data for a small coastal strip along the “kwelder” of the Frisian coast based on laser altimetry measurements are available. These and other data were previously used to construct a bathymetry for a grid that covers the entire Wadden Sea (“*GridCL*”, WL 2007c). Bathymetrical information is obtained by interpolating the depth values for this grid onto the computational grids used in this study.

Wind speed

Hydra-K uses the Rijkoort-Weibull (Rijkoort, 1983) model for estimation of extreme wind speeds. This wind speed enters as a constant in the SWAN calculations. In this study the extreme wind speed is estimated at 37 m/s with a return period of 4000 years (see Figure 13, based on Texel). This wind velocity has been used as reference in all uncertainty analysis.

Wind direction

Normative storm conditions are supposed to yield the most unfavorable wave conditions close to the shoreline of the Frisian mainland that can be expected with a return period of 4000 years. It is therefore of interest to find the wind direction giving the most severe wave condition near the coast. To that end, the local bathymetry is considered. Given the bathymetry of the Frisian inlet it is expected that most of the waves offshore will be dissipated by the ebb-tidal delta on most locations. Locally-generated waves are expected to form the main component of the load on the defence system of the Frisian mainland. Most of the foreshore is formed by flats that will restrict the development of waves. An exception to this is the channel that reaches from the inlet to the dike of the Lauwersmeer. Wind directed parallel to the main axis of this channel is expected to yield the most severe wave conditions near the coast. Therefore, a north-westerly wind (345º) is used as reference.

Offshore conditions

This study considers uncertainties of predicted HBC under storm conditions. This justifies the assumption that the offshore wave climate is dominated by locally generated wind waves and not by swell. Following this assumption offshore wave conditions are mainly determined by the wind velocity and direction. Hydra-K includes a routine that expresses a statistical correlation between offshore wave conditions and wind direction and velocity. The offshore wave conditions used in this study are deduced from this relation. Using a wind speed of 37 [m/s] and a wind direction of 345º (as chosen in the previous section), an offshore wave height (H_{m0}) of 11.702 [m] together with a peak period (T_p) of 17.86 [sec] is found. Because the offshore wave climate is assumed to be dominated by locally generated wind waves, the offshore waves are expected to have an orientation similar to wind that generates them (345º). The relation included in Hydra-K only provides information about the offshore wave conditions. Wave characteristics at the Western and Eastern boundaries between the barrier islands and mainland are obtained using the course grid.

Water level

Transformation of offshore wave conditions to near-shore wave characteristics depends on the water level. A spatially varying water level can be specified in the SWAN input file. Since our reference situation should resemble the normative (HBC) conditions, we have used a reference water level of NAP+4.90 m (“toetspeil”) at the coast.

In addition to this, the water level field can be tilted, as a result of local wind setup. Examples of this tilt can be observed in a series of scaled storm events by Alkyon (2007c). The water level field following from one of their simulations (See Figure 5) as well as hindcasted water levels during past storm events (WL 2007c, d), show similar characteristics. Wind setup creates high water levels near the mainland coast. The water level is tilted mainly in a direction perpendicular to the coast.

In this study the spatially varying water level field has been constructed using a fixed water level at the coast and a tilt, perpendicular to the coastline. This is illustrated in Figure 6. The water level at the north side of the islands is taken horizontally.

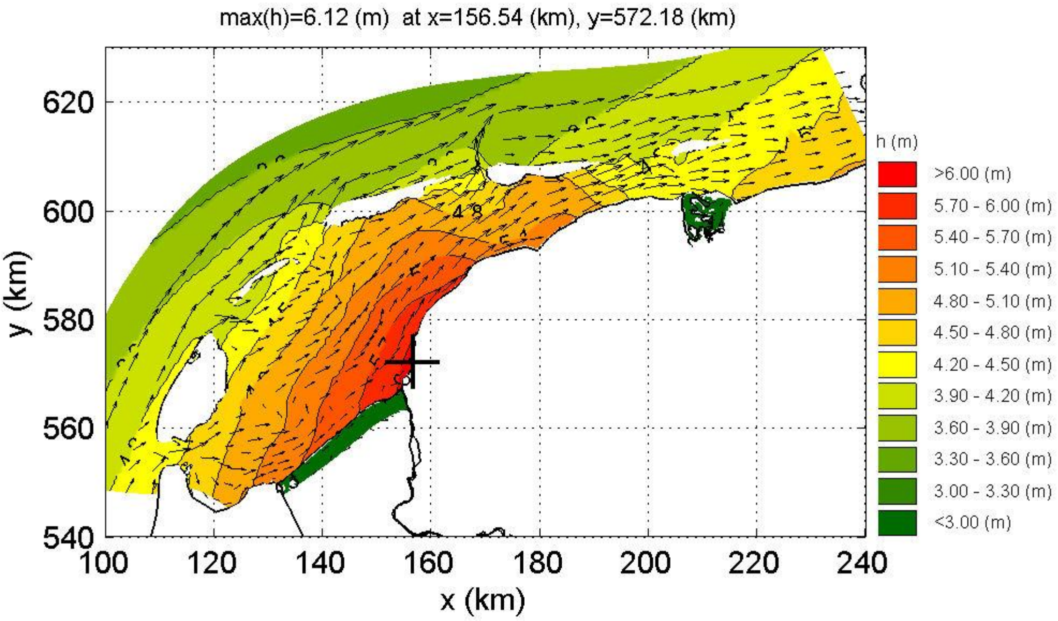

Figure 5 Variation of water level with scaled winds, obtained from Alkyon (2007c). The black cross indicates the location of the highest water level.

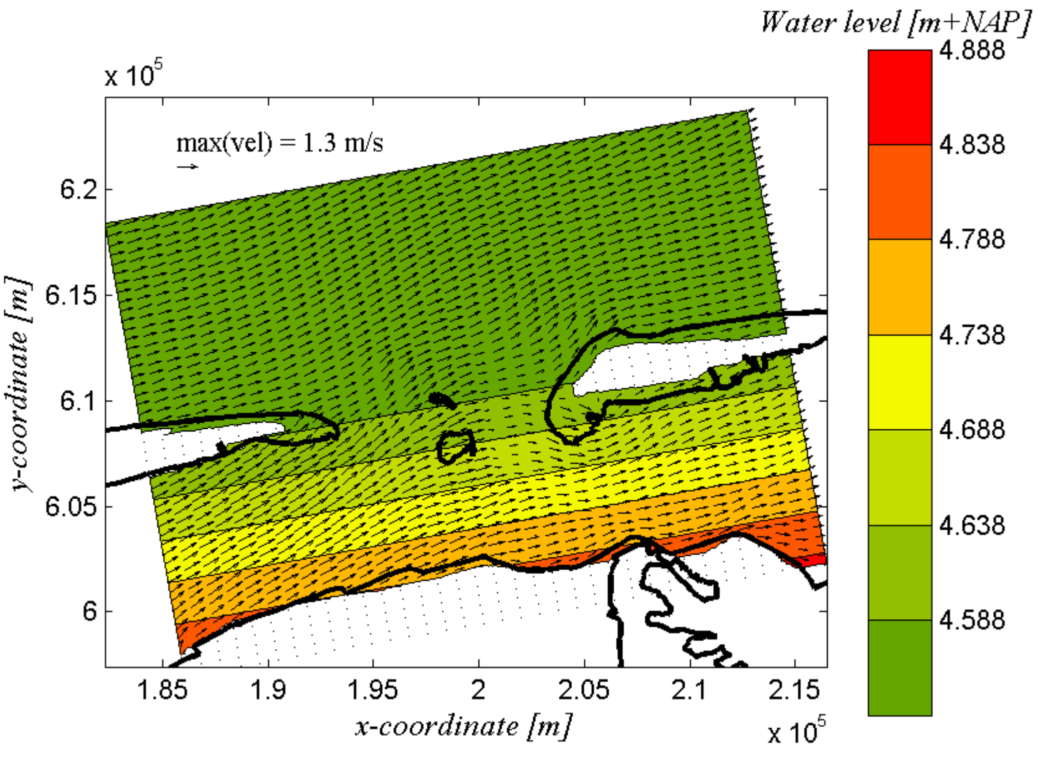

Figure 6 Current field and variation of water level used as reference

Currents

Previous studies (Alkyon 2007c, WL 2007c, d) have illustrated the importance of currents in modeling the transformation of offshore waves to near-shore wave characteristics in the Wadden Sea. Results of hindcasted storms and scaled storm simulations (Figure 5) show a current pattern that is significantly different from a normal ebb- or flood-current pattern. Due to wind set-up the water level inside the Wadden Sea is increased. A wind-driven current is flowing eastward. The magnitude and direction of this current depends on the direction and magnitude of the wind. The only example of such a current field under extreme conditions available at this moment is that of a scaled storm simulation (Alkyon, 2007c). Maximum currents following from the latter study are significantly higher than currents obtained from non-scaled storm conditions. For this reason the current field following from the simulation with scaled winds (Alkyon 2007c) will be used in this study. It should be noted that the storm used to create this scaled wind field mainly contained westerly winds. As explained above, the reference simulation considers winds from NW. This is expected to yield differences in direction and magnitude of the currents. To deal with this difference, the magnitude of the current field is varied around 80% of the reference calculation. A randomized current scaling factor with a large standard deviation will account for the large uncertainty regarding the magnitudes and directions in the current field (see also section 3.2.1).

SWAN Reference simulation results

In many respects the reference run with extreme conditions shows similar results to calculations of regular storm events (WL 2007c, d). As offshore waves reach the inlet, most of the energy is dissipated due to breaking of the waves on the ebb-tidal delta. This is illustrated by Figure 7. The red lines denote a relative wave height (wave height over depth ratio) close to 0.73. Shoreward of the inlet gorge and barrier islands the relative wave height is low. The wave height increases towards the mainland due to wind input, but is restricted by the water depth. The relative wave height near the coast amounts to approximately 0.4 [-]. This decrease can also be observed when analyzing the development of wave periods (Figure 8). The main channel is the only exception to this. Figure 8 shows a small intrusion of the larger wave periods into the Wadden Sea just east of the main channel and west of the smaller channel. Similar results are presented in WL (2007c) and WL(2007d).

Wave characteristics at the four observation points following from the reference simulation are denoted in Table 2.

Table 2 Wave characteristics at the observation points following from the reference simulation

Observation point	H_{m0} [m]	T_{m02} [s]	T_p [s]	$T_{m-1,0}$ [s]	*Dir* [degrees]
Location 1	1.89	3.0	4.7	4.5	353
Location 2	1.94	2.8	4.8	4.4	352
Location 3	2.96	3.5	5.4	4.6	341
Location 4	2.85	3.4	5.4	4.5	335

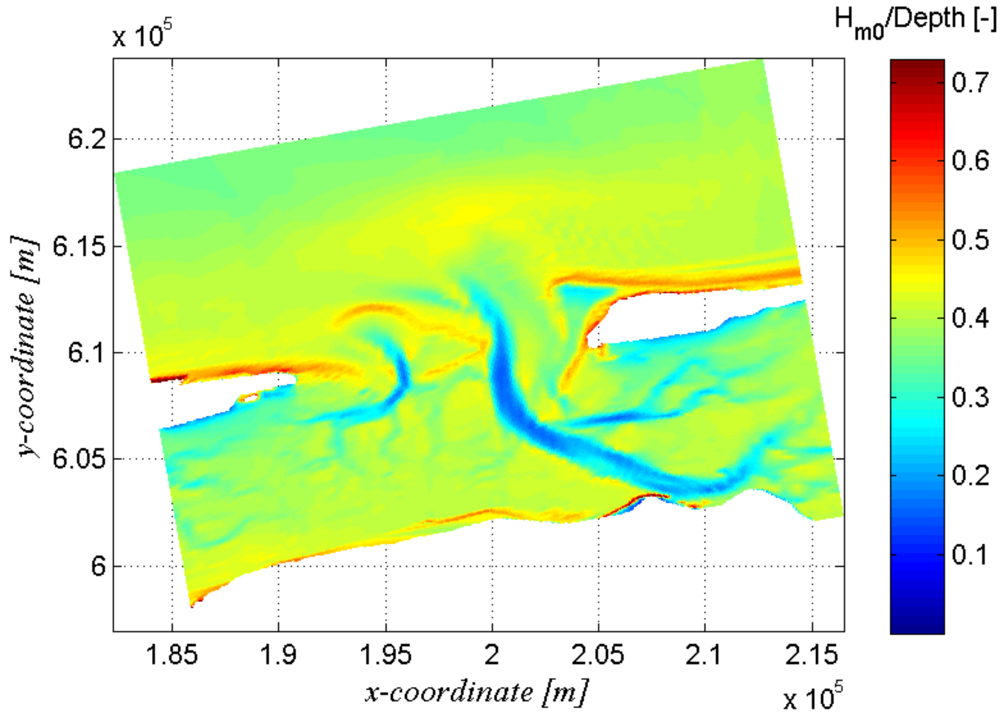

Figure 7 Relative wave height ($H_{m0}/Depth$) resulting from the reference calculation

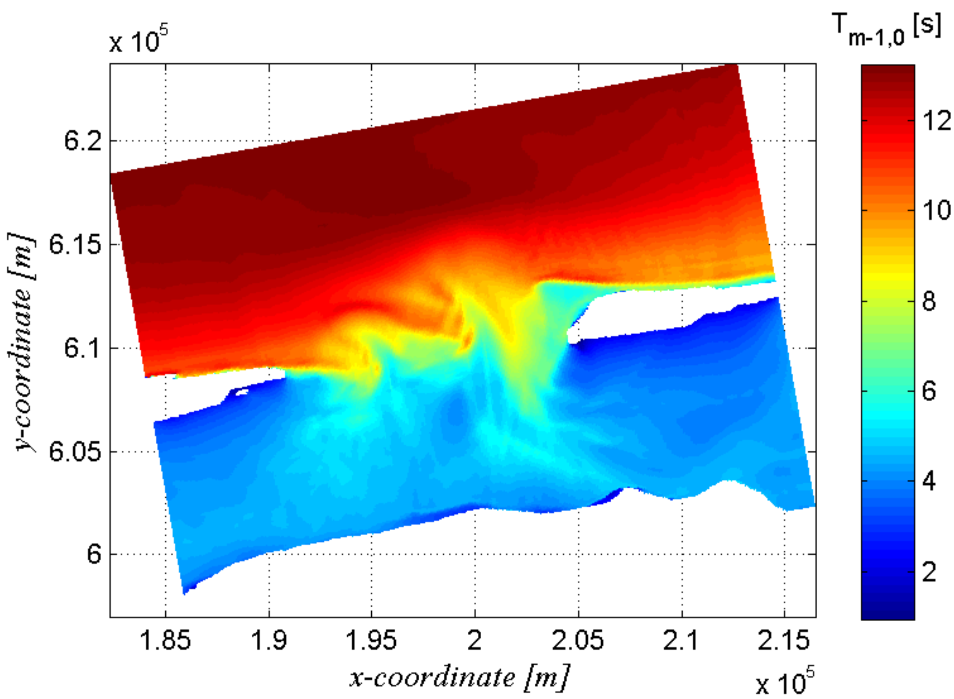

Figure 8 $T_{m-1,0}$ resulting from the reference calculation

2.4.2 Hydra-K

The uncertainty analysis was done using a modified version of Hydra-K, previously used for sensitivity analysis and impact analysis of upper bounds on wave parameters (WL, 2007a). This version gives comparable results to the 'official' version of Hydra-K, which was used for the HBC calculations in 2006. Minor differences between the two versions are considered negligible for the purpose of this study.

For the Wadden Sea, however, no HBC have been calculated in 2006 and there is no database of SWAN results ('KustDB') for this area. For reasons of efficiency, a relatively small KustDB SWAN database was created for this study including only the four locations in the Frisian inlet and only a limited number of wind directions. We used the following combinations for the SWAN database:

Variable	Nr values	Values
Water level h	3	2, 4, 6 m+NAP
Wind speed U_w	6	15, 20, 25, 30, 35, 40 m/s
Wind direction	5	0-30, 30-60, 60-300, 300-330, 330-360º

For each combination of variables a SWAN calculation was done. The results (near-shore wave height, period and wave incident angle) were stored in the database. For the range mentioned above the database thus required 3*6*5=90 SWAN runs for each location. Since we have four locations, the total number of entries in the database was 360.

Hydra-K reference run results

The Hydra-K reference calculation of the HBC (illustration points) at the four locations mentioned before produced the results indicated in Table 3. The return period is 4000 years. Note that the water levels for these illustration points are not fixed to the normative water levels ("toetspeil"). This is different to common practice in HBC. However, if we would use a fixed water level in the uncertainty analysis, then all the uncertainty in the HBC would be translated to variations of wave conditions, leading to unrealistic results. Therefore, we prefer to let the water level in the illustration point be variable and not fixed.

Table 3: Results of the HBC reference calculation.

	X	Y	h [m]	H_{m0} [m]	$T_{m-1,0}$ [s]	Crest level [m]
1	193900	601400	4.84	1.75	4.23	6.47
2	200900	602800	4.91	1.84	4.31	6.63
3	207600	603550	4.92	2.55	4.23	7.28
4	209400	603200	4.90	2.49	4.18	7.19

We find that the water level is approximately equal to the normative water level ("toetspeil") for most of the Wadden Sea (4.9 [m]) as expected. The wave height is about 1.8 [m] for locations 1 and 2, which are shielded from incoming waves by the Wadden Sea islands and limited by shallow water effects. At locations 3 and 4 the wave height is larger: approximately 2.5 [m]. The spectral wave period is comparable for all locations.

These HBC results are approximately 10% lower than the results of the SWAN reference calculation (see previous section). Ideally, the two would have been closer to each other. However, we do not expect major differences in the outcome of the uncertainty analysis.

The critical crest level is the height of an imaginary dike that would just withstand the HBC. This is explained in more detail in Chapter 3. Table 3 shows that the crest levels at locations 1 and 2 are lower than those at locations 3 and 4, due to the larger wave height at the latter locations.

3 SWAN uncertainty analysis

This chapter discusses the SWAN uncertainty analysis. The contributions of two main sources (described below) of uncertainty to the overall uncertainty are assessed by Monte Carlo simulations, in which we make perturbations to a reference calculation. The configuration and results of the reference calculation have been described in Chapter 2.

Two main sources of uncertainty in the results of a SWAN calculation are the input uncertainty and the model parameter uncertainty. The next section, Section 3.1, discusses the uncertainty in the settings of SWAN model parameters (1a in Figure 1), or the coefficients in the physical formulations. Although the parameter settings are based on extensive calibration and validation studies, there is considerable remaining uncertainty. The second source of uncertainty in the SWAN calculations is the input of the SWAN calculations (1b in Figure 1), such as offshore boundary conditions, bathymetry, current, water level and wind. This is discussed in section 3.2.

In order to quantify the effect of uncertainty in the model parameters and inputs on the SWAN results, we use a Monte Carlo approach. Perturbations of the model and input parameters are applied according to their estimated uncertainty. The resulting variation of the SWAN outcome, i.e. the near-shore wave height and spectral period, will give an estimate of their uncertainty, as a result of the uncertainty in input and model parameters.

In this SWAN uncertainty analysis, we ignore the uncertainty associated with the SWAN model formulations of the physical processes. Although the SWAN model is state-of-the-art, there is evidence that for instance the depth-limited wave growth is underpredicted by the SWAN model (WL, 2007c). This is due to insufficient knowledge of the wave evolution processes. Improved formulations will increase the modelled wave height for a given water depth, and will thus affect the loads on dikes. In the analyses described in sections 3.1 and 3.2, only the uncertainty of the model *parameters* (for a given formulation) and the model *inputs* are considered. The propagation of these two contributions leads to an uncertainty in the answer that SWAN produces. However, the *total* uncertainty of the SWAN outcome may be larger due to the error in the model *formulations*, which is not taken into account in the Monte Carlo analysis. This contribution is assessed in section 3.3.

The uncertainty probability distributions of the uncertain parameters (model and input) are not known in full detail. They can only be estimated. As a consequence, the uncertainty in the SWAN results can only be quantified roughly. However, we believe that the approach described above will provide a good estimate of the uncertainties of the wave characteristics, represented by their Root Mean Square Error (RMSE).

3.1 Uncertainty analysis model parameters

3.1.1 UA-Tools

The uncertainty analysis is carried out using UA-Tools. UA-Tools is part of the DATools data assimilation environment that is under developed at WL | Delft Hydraulics at this moment (El

Serafy *et al.*, 2007). UA-Tools enables the user to perform Monte Carlo simulations with various models. One of these models is SWAN.

All uncertain input parameters need to be specified in UA-Tools. At the time this analysis was carried out, UA-Tools allowed the user to specify this uncertainty using two distribution-types (uniform- and normal distribution). For input parameters with an uncertainty defined using a uniform distribution the program needs an upper and lower limit. For normal distributed variables a central value, a standard deviation and optionally also upper and lower limits can be defined.

Furthermore, the number of SWAN calculations needed for the Monte Carlo simulation has to be specified. First, UA-Tools runs the SWAN model using all central values (see description of the reference calculation, Chapter 2) for uncertain parameters. Next, UA-Tools creates an instance of the SWAN model with values for uncertain input parameters defined using the specified distributions. After an instance is created, the SWAN calculation is performed. UA-Tools isolates results at predefined output locations. The UA-Tools result file also includes the values of disturbed input parameters that lead to these outcomes. After isolation of the result, the model instance is deleted and a new SWAN calculation is initiated. UA-Tools stops creating new instances when the predefined number of SWAN calculations is reached. As a first guess 50 SWAN calculations are assumed to be sufficient for the determination of the RMSE of output parameters to within 10% accuracy[3]. We will check the convergence behavior in sections 3.1.3 and 3.2.2. The results show that the convergence of the RMSE of output parameters is indeed sufficient after 50 samples.

3.1.2 Specification of uncertainty of model parameters

A specification for the distribution of uncertain model parameters regarding simulations of the Frisian inlet under extreme conditions is presented in the first phase of this project (WL 2007b, section 3.2.2). Uncertainties of some parameters have been redefined in this study. Changes of the uncertainty specifications are discussed below.

Uncertainties of model parameters are specified using ranges. A normal or uniform distribution is suggested for most parameters. The given range could then be interpreted as the 95% confidence interval. Some parameters, however, are bound to stay within a certain domain. This requirement is not met by using a normal distribution. Other parameters are specified having an asymmetric mean value, i.e. a mean that is not in the middle of the accompanying range. It is suggested to use a beta-distribution (Sakasegawa, 1983; Zechner and Stadlober (1993)) in these cases.

At the moment this study was carried out UA-tools only allowed the user to assign uniform- or normal distributions to the input variables. However, a data validation option in UA-Tools allows making sure that a random variable does not exceed certain upper or lower limits. Non-symmetric distributions are approximated by taking a symmetric (normal) distribution with similar mean value and range width. This induces a small shift of the range placing the mean value in the center. Using these methods uncertainties are adjusted for parameters that could not be modeled as specified in the first phase of this project. These changes are not expected to significantly influence the results of the uncertainty analysis.

3. For a normally distributed random variable, the RMSE converges as $0.71/\sqrt{N}$, where N is the number of MC samples.

The uncertainty of the model parameters as applied in this study is discussed below. We discriminate between the model parameters present in deep water terms and model parameters in shallow water terms.

Deep water terms

The deep water processes include the source terms of wind input, white-capping dissipation and non-linear four-wave interactions (quadruplet interaction) which, together with the propagation terms, form the primary spectral evolution balance in deep water. The processes of wind input and white-capping are modelled using the expressions of Komen *et al.* (1984) and for quadruplet interactions the Discrete Interaction Approximation (DIA) of Hasselmann *et al.* (1985) is applied. Both the expressions for wind input and white-capping dissipation are linear in the variance density. The source term for quadruplet wave-wave interactions, on the other hand, is a nonlinear cubic function of the variance density, and tends to impress a frontal shape (in frequency space) onto the spectrum and it is responsible for the downshifting of the peak frequency during wave growth. Quadruplet wave-wave interactions therefore have a dominant role in imposing a self-similarity onto the wave spectra during all stages of development. Uncertainty in transfer of energy from wind to waves is assumed to be small compared to other source terms (WL, 2007b), such as white-capping. Uncertainty of the outcomes due to uncertainty of the parameter in the term that expresses wave growth as a result of wind input is assumed to be small compared to other model parameters (Personal communication Van der Westhuysen) and therefore not taken into account in this study. However, in the wave modelling community there is some discussion about the saturation of the drag coefficient in wind speeds higher than 30 m/s.

Table 4 gives an overview of the parameters as suggested in the first phase of this project (WL, 2007b) compared with the uncertainties applied in this phase. Uncertainty of all parameters in the deep water source terms will be assessed using a normal distribution. The mean and range coincide with the means and ranges specified in WL (2007b) except for $C_{ds,wc}$, which has a slightly different range due to the symmetric shape of a normal distribution.

Shallow water terms

The balance of source terms in water of finite depth is more complex and not as well studied as the balance in deep water mentioned above. The dissipation processes induced by bottom friction and depth-induced breaking are modelled using turbulence and hydraulic jump (bore) analogies respectively.

Little is known about the mechanism of these dissipation processes, and the expressions are therefore empirical. Nonetheless, the source term for depth-induced breaking of Battjes and Janssen (1978) has proven robust in a wide range of applications. This modified expression as implemented in SWAN has only two parameters[4], namely α_{BJ} and γ_{BJ}. For bottom friction dissipation, the expression of Hasselmann *et al.* (1973) is used. This expression has a single parameter in the form of a proportionality coefficient $C_{ds,bot}$.

4. It is noted that the original expression of Battjes and Janssen (1978) also has a steepness related parameter, but this one is omitted in the SWAN implementation, because it is assumed that the whitecapping term accounts for steepness related effects on the wave dissipation.

In the first phase of this project no uncertainty is specified for α_{BJ}, whereas γ_{BJ} is assumed to be beta distributed having a mean value of 0.73 and a range between 0.44 and 0.92 (WL, 2007). α_{BJ} has been varied in different studies as well. Dingemans (1997) states that these two parameters are correlated:

$$\alpha\gamma^{-5} = \text{constant.} \tag{3.1}$$

This equality suggests that variations of γ_{BJ} in this uncertainty analysis should be compensated by variations of α_{BJ}. Uncertainty of α_{BJ} is estimated to range from 0.5 to 1.5 (personal communication Groeneweg). Relation 3.1 can be included by defining uncertainty of one of the parameters that characterizes depth-induced wave breaking (α_{BJ}) and calculate the matching other (γ_{BJ}). This approach would lead to non-realistic ranges of uncertainty of γ_{BJ}. In fact, the value of the constant in relation 3.1 is not known for simulations of the Wadden Sea under extreme conditions. This is expressed by defining the uncertainties of both parameters separately using uniform distributions within the ranges 0.49-0.97 (γ_{BJ}) and 0.5-1.5 (α_{BJ}).

Dissipation due to bottom friction is characterized by $C_{ds,bot}$. Different values are specified for wave fields dominated by swell and wave fields dominated by locally generated wind waves (WL, 2007). The purpose of this study is to assess the uncertainty of predicted transformation of off shore wave characteristics to wave characteristics in the Wadden Sea under extreme storm conditions. In case of a storm locally generated wind waves are expected to be dominant in the Wadden Sea. It is therefore chosen to use values that are valid for wind sea dominated wave fields. A mean value of 0.067 is used combined with an uncertainty ranging between 0.042 and 0.092.

At the moment, the uncertainty of the non-linear triad interaction is lacking a thorough physical background. Estimates of the uncertainty in the parameter α_{AE} can not be soundly underpinned with empirical data. Using an on/off switch for the contribution of triad interaction is therefore suggested in phase one (WL, 2007b). This method has two drawbacks. Firstly, it is difficult to define a reference. By enabling or disabling triad interactions the reference calculation can either include or exclude the three-wave interaction whereas the mean of the uncertainty assessed using this method accounts for 50% inclusion of triad interactions. Secondly, switching off triad interactions overestimates the uncertainty concerning triad interactions. Although there is no thorough physical background for estimation of its uncertainty, it is certain that this phenomenon plays a role in the propagation of wave characteristics in shallow water. Completely disabling triad interactions therefore does not represent the current knowledge on the uncertainty of three-wave interactions. Non-linear triad interaction is characterized by two coefficients determining the proportion of the contribution (α_{AE}, default = 0.05, see also Van der Westhuysen, 2007) and the maximum frequency that is considered ($f_{max,EB}$, which is calibrated to a value of $2.5T_{m01}$ by Van der Westhuysen, 2007). Rather than switching on (α_{AE} = 0.05) or off (α_{AE} = 0) triad interactions in the calculations we choose to impose a normal distribution representing the uncertainty of α_{AE} with a mean of 0.05 and standard deviation 0.0125 (resulting in a confidence interval of 0.025 – 0.075). Variations of the cut-off frequency would have an effect on calculated HBC. Since the LTA formulation is not valid for high frequencies, the cut-off frequency should not be strongly varied. Therefore, this parameter is kept fixed in this study. Uncertainty of this parameter is considered to represent part of the uncertainty of the model structure (Figure 1), which is not assessed in the current study.

Summary

Distributions used in this study to express uncertainty of the model parameters are summarized in Table 4. All variables are normally distributed except for the ones indicated in the table (using a * symbol). These parameters are similar to calibration parameters indicated in WL (2006) except for the saturation level B_r in the whitecapping formulation of Van Der Westhuysen (2007). This is due to a different formulation used for the modeling of whitecapping.

Table 4 Uncertainty specifications of model parameters in deep- and shallow water source terms

Process	Para-meter	default	standard deviation	range (this study)	range (WL, 2007)
Deep water terms					
Dissipation of wave energy due to whitecapping	$C_{ds,wc}$	5.0*10^{-5}	0.325*10^{-5}	4.35– 5.65*10^{-5}	4.2 – 5.5*10^{-5}
	B_r	1.75*10^{-3}	0.125*10^{-3}	1.5 – 2.0*10^{-3}	1.5 – 2.0*10^{-3}
Non-linear transfer of wave energy due to quadruplet (four-wave) interaction	C_{nl4}	3.0*10^{7}	0.25*10^{7}	2.5 – 3.5*10^{7}	2.5 – 3.5*10^{7}
	λ	0.25	0.025	0.2 – 0.3	0.2 – 0.3
Shallow water terms					
Dissipation due to bottom friction*	$C_{ds,bot}$	0.067	-	0.042 – 0.092	0.05 – 0.1
Dissipation due to depth induced breaking*	α_{BJ}	1.0	-	0.5 – 1.5	-
	γ_{BJ}	0.73	-	0.49 – 0.97	0.44 – 0.92
Non-linear triad (three-wave) interaction	α_{AE}	0.05	0.0125	0.025 – 0.075	on/off switch
	$f_{max,EB}$	2.5	-	-	-

Uniform distribution *

3.1.3 Results of the uncertainty analysis of model parameters

Uncertainty of the SWAN output parameters H_{m0} and $T_{m-1,0}$ is obtained by calculating the Root Mean Square Error (RMSE) of the 50 calculation results of all parameters. The RMSE represents the uncertainty of the output parameter as a result of the uncertainty in the model parameters. For all model parameters the mean value calculated over 50 SWAN runs does not differ significantly from the reference value for that parameter (values are listed in Appendix B).

The convergence of the RMSE of H_{m0} as a function of the number of Monte Carlo samples for all observation points is illustrated in Figure 9. From this it is concluded that there is no need to perform more than 50 calculations in order to improve the accuracy of the resulting RMSE’s.

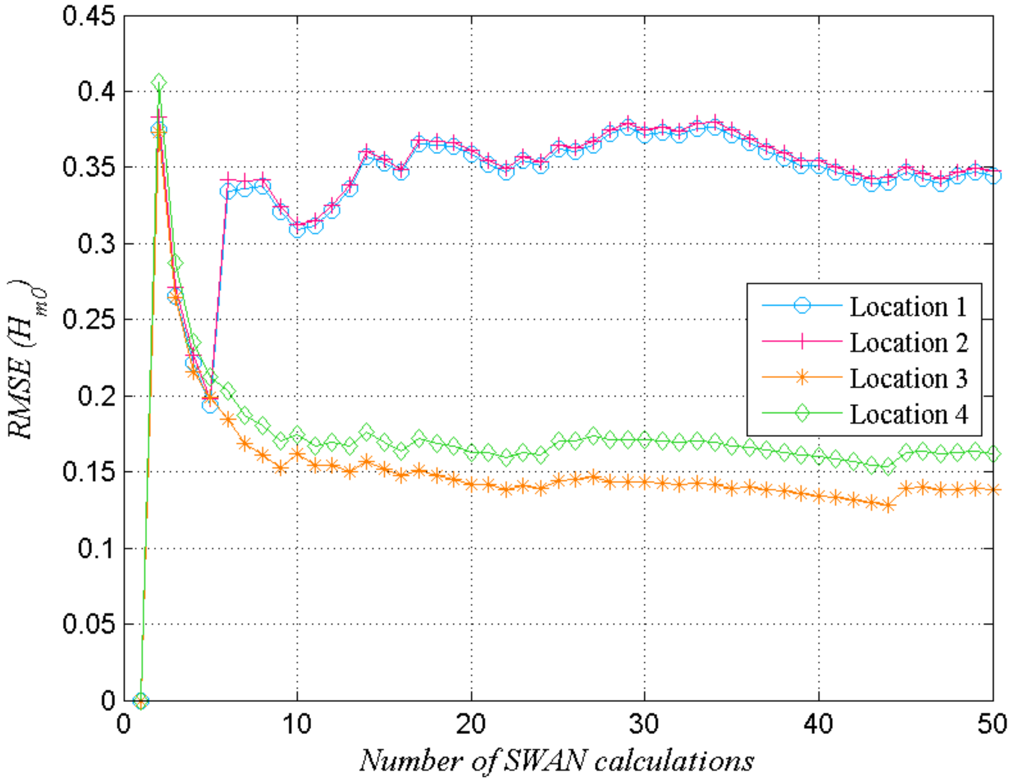

Figure 9 RMSE of H_{m0} as a function of the number of Monte Carlo samples with variation of model parameters.

Table 5 RMSE (actual and as a percentage of the mean) of the results of a series of Monte Carlo SWAN simulations to assess the uncertainty of HBC due to uncertainties of model parameters.

	RMSE (H_{m0})		*RMSE ($T_{m-1,0}$)*		*RMSE (T_p)*		*RMSE (T_{m02})*		*RMSE (Dir)*	
	[m]	%	[s]	%	[s]	%	[s]	%	[°]	%
Location 1	0.34	17.3	0.77	16.1	0.87	17.2	0.38	12.2	2.16	0.6
Location 2	0.35	17.1	0.77	16.8	0.88	17.3	0.37	12.8	1.81	0.5
Location 3	0.14	4.7	0.16	3.5	0.18	3.2	0.10	2.7	0.42	0.1
Location 4	0.16	5.7	0.19	4.1	0.22	4.2	0.12	3.6	0.96	0.3

Table 5 contains Root Mean Square Errors (RMSE) of the individual parameters for each location. For all parameters the RMSE at locations 1 and 2 appear to be larger than the RMSE at the locations 3 and 4. Location 1 is sheltered behind Ameland and location 2 lies unsheltered behind the inlet. Both output locations have in common that they are positioned at a flat part of the basin. Location 3 and 4 are placed next to a relatively deep (channel) part of the basin. These results indicate that uncertainty of model outcomes due to uncertainty of the model parameters is larger at shallow parts compared to relatively deep parts.

The contribution of the uncertainty of a single model parameter to the overall uncertainty of output quantities can be obtained by calculating the correlation coefficient between the used values of this model parameter and output quantities (Appendix B). The uncertainty of all output quantities except for wave direction at the first two (shallow) locations appears to be highly dominated by uncertainty of the parameter concerning shallow-water breaking (γ_{BJ}). Correlation between output and other model parameters is insignificant compared to the correlation between this model parameter and output quantities. The same conclusion can be drawn for the two observation points at deeper water although it should be noted that for uncertainty of the significant wave height in these locations also uncertainty regarding B_r plays a minor role. From this it is concluded that the overall uncertainty of predicted wave conditions at the coast under extreme conditions due to uncertainty of model parameters is mainly caused by the uncertainty of the γ_{BJ} parameter.

3.2 Uncertainty analysis SWAN input

3.2.1 Specification of the uncertainty of SWAN input

The following input parameters of SWAN and their uncertainties are discussed in this section:

- Bathymetry
- Current
- Water level
- Wind velocity
- Wind direction
- Offshore wave conditions

The results of the Monte Carlo uncertainty analysis are discussed thereafter.

Bathymetry

Uncertainty in the bathymetry can be divided into a contribution due to horizontal movement of bottom features and vertical movement of the bottom. Horizontal movement of channels and flats mostly occurs in or near the inlet. In phase 1 of this project it is suggested to shift the complete bathymetry to account for uncertainty of the horizontal movement of the bottom near the inlets. However, this will lead to an unrealistic horizontal shift near the coastline. Furthermore, a practical problem arises when the bathymetry is shifted north, because observation points near the coast will then be placed on land.

The influence of changes of the bottom geometry on the wave conditions is assessed with the exact same model configuration as the reference run (WL, 2007e). Calculations with bottom measurements of various years lead to the following conclusion. The influence of bottom changes that can occur within 5 years on calculated wave characteristics at observation points near the Frisian coastline is very small. From this result it is decided to exclude the influence of uncertainty of the bottom geometry from the present study.

Currents

The importance of currents when modeling transformation of wave characteristics through the Wadden Sea has been addressed in section 2.4.1. Also, the large uncertainty concerning current fields under extreme conditions is discussed in that section. The only indication of currents during extreme storm conditions depend on wind characteristics is obtained by a hydrodynamic simulation using a storm wind scaled to match an extreme condition (Alkyon, 2007c), viz. the water level at Nes. In that study it was found that extreme storm winds dominate over tidal effects and that large scale flows are generated in the Wadden Sea. This may point to a strong relation between storm winds and currents. However, no systematic analysis has yet been performed to the relation between wind direction, wind speed and these wind-driven currents. Therefore, large uncertainties exist in the magnitude and (overall) direction of the currents.

Uncertainty of a current at any position can be divided into an uncertainty of the direction and an uncertainty of the magnitude of this velocity. The influence of different wind directions and velocities on current directions and magnitudes under extreme conditions in the Frisian inlet is not well known. Because of lack of information about the variation of the current pattern (no other wind directions have been up-scaled) it is decided not to take into account the uncertainty of the current directions in this study. To account for the large uncertainty of the flow field as a whole, the magnitude of the current field is multiplied by a scaling factor that ranges between 0.3 and 1.3. This factor is represented by a normally distributed random variable with mean 0.8 and standard deviation 0.25.

The variation of the current velocities is a very rough estimate of the uncertainty of the current field. Previous studies (Alkyon 2007c, WL 2007c, WL 2007d) have show the importance of taking into account currents for accurate calculation of wave periods inside a basin. It is therefore recommended to further investigate the current fields under extreme conditions.

Water level

Uncertainty of the water level prediction at the coast of the mainland is assessed in the Hydra-K uncertainty analysis (Chapter 3) and will not be included in this uncertainty analysis. A water level of 4.90 m+NAP (HR2001) is supposed to reflect the water level that can be expected near the coast during storm conditions with a probability of exceedance of $2.5*10^{-4}$ per year (1/4000 year return period) at the Frisian coastline.

Section 2.4.1 discusses the uncertainty of the water level tilt under extreme conditions. In the reference calculation the water level is tilted between the mainland and islands. The hindcasted water level fields during past storm events (WL 2007d and Alkyon 2007c) typically show tilt angles of around $2.5*10^{-5}$ for the Frisian inlet. Note that, for very small tilt angles, the tangent of this angle is equal to the angle itself. At this moment most of the calculation of inlets in the Wadden Sea are performed with a horizontal water level (tilt angle = 0). Analysis of observed tilt angles during regular tidal cycles shows a maximum of $5*10^{-5}$ (WL, 2007b). In the uncertainty analysis the tilt angle is therefore represented by a normally distributed stochastic variable with mean $2.5*10^{-5}$ and standard deviation $1.25*10^{-5}$. This results in an uncertainty range between zero and $5*10^{-5}$. North of the islands the water level is assumed to always have a constant value.

Wind velocity

Uncertainty of the wind velocity is assessed with Hydra-K (Chapter 3). In this study a constant wind speed of 37 m/s (see section 2.4.1) is used.

Wind direction

Hydra-K divides the wind direction in 30º sectors. To account for this uncertainty, the wind direction is uniformly distributed ranging 15º in both directions relative to the reference wind direction (345º, see also section 2.4.1). For this uncertainty analysis the wind direction therefore will thus be varied between 330º and 360º.

Offshore wave characteristics

Wind velocity and direction can be directly translated to offshore wave characteristics using the formulation already included in Hydra-K (see also section 2.4.1). Each simulation therefore has its own offshore wave characteristics matching the wind conditions that are determined beforehand. There is, however, an additional uncertainty associated with this transformation from wind characteristics to offshore wave characteristics. This imposes an extra perturbation to the translated wave characteristics. The perturbation can be expressed using normally distributed parameters for the significant wave height (H_{m0}), peak period (T_p) and direction having means that match the translated wave characteristics in each run. The perturbed value for the wind direction is taken as the mean of the offshore wave direction. Standard deviations of respectively 20%, 20% and 15° will be used (as determined in the first phase of this project (WL 2007b)).

Summary

Distributions used in this study to express uncertainty of SWAN input are summarized in Table 4. All variables are normally distributed except for those noted with an asterisk in the table.

Table 6 Specification of the SWAN input uncertainty

	Parameter	default	standard deviation	range (this study)	range (WL 2007b)
Offshore wave boundary					
Wave height	H_{m0} [m]	11.7	20 %	40%	40%
Peak period	T_p [s]	17.9	20 %	40%	40%
Wave direction	*dir* [°]	345	15°	30°	30°
Other parameters					
Water level tilt	*tilt angle* [-]	$2.5*10^{-5}$	$1.25*10^{-5}$	$0 – 5*10^{-5}$	1*10-5 – 5*10-5
Current magnitude	*fac* [-]	0.8	0.25	0.3 – 1.3	0.3 - 1.3
Wind direction *)	*wdir* [°]	345	-	330 – 360	330 – 360

*) Uniform distribution

3.2.2 Results of the uncertainty analysis of SWAN input

Figure 10 shows the convergence of the RMSE of H_{m0} as a function of the number of Monte Carlo samples. Similar to the uncertainty analysis of model parameters, the RMSE of the H_{m0} is converged to an estimated 10% accuracy after 50 samples. There is no need to further extend the number of SWAN calculations.

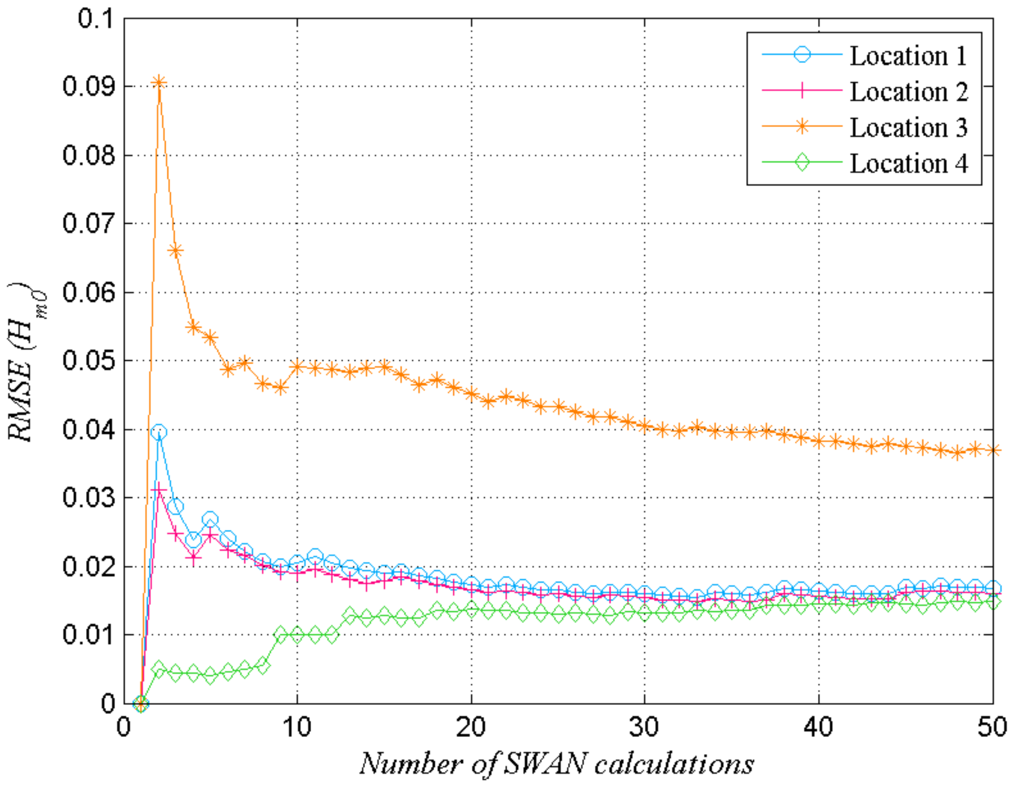

Figure 10 The RMSE of H_{m0} as a function of the number of Monte Carlo samples with variation of SWAN input.

Table 7 RMSE (absolute and percentage of the mean) resulting from the Monte Carlo simulation to assess the uncertainty of HBC due to uncertainties of SWAN input

	RMSE (H_{m0})		*RMSE* ($T_{m-1,0}$)		*RMSE* (T_p)		*RMSE* (T_{m02})		*RMSE (Dir)*	
	[m]	%	[s]	%	[s]	%	[s]	%	[°]	%
Location 1	0.017	0.9	0.18	4.1	0.049	1.0	0.16	5.5	10.6	3.0
Location 2	0.016	0.8	0.15	3.5	0.042	0.9	0.14	4.9	9.2	2.6
Location 3	0.037	1.3	0.09	1.9	0.015	0.3	0.14	3.9	9.1	2.7
Location 4	0.015	0.5	0.08	1.9	0.012	0.2	0.10	3.0	10.7	3.2

The RMSE following from this Monte Carlo simulation (Table 7) are relatively small, except for the standard deviation of the wave direction. No large differences in results between the various observation points can be observed.

Except for the wind direction, current magnitude and tilt angle all uncertainties assessed in this Monte Carlo simulation concern parameters that determine offshore boundary conditions. The reference calculation shows that most of the offshore waves are dissipated at the ebb-tidal delta. Locally generated waves dominate the wave climate behind the barrier islands. A small influence of the uncertainties of parameters that determine offshore conditions is therefore expected.

This is also confirmed by the correlation of SWAN input and output parameters individually (see also Appendix B). No correlation is found between the variation of the offshore wave height and period and the wave characteristics near the shoreline. There is a small correlation between the offshore wave direction and certain output quantities, which can be explained by the causal relation between the wind direction and offshore wave direction. The offshore wave direction in SWAN is largely determined by the perturbed wind direction. Small deviations may occur due to refraction effects north of the Wadden islands. Any output parameter that is correlated with the wind direction will therefore also show a correlation with the offshore wave direction. However, this does not necessarily mean that these output parameters also have a causal relationship with the offshore wave direction.

Furthermore, variations of the wind direction are almost fully correlated with the wave direction in all output locations. The small variations of the wave height appear to be dominated by the tilting of the water level. Although the tilt angle parameter is intended to take into account variations of the water levels at other points in the basin relative to the output locations (influence of variations of the water depth itself is assessed using Hydra-K, Chapter 3) it also influences the water depth at the output locations. This is caused by the fact that the water level at the southern boundary of the model is kept constant and water levels further offshore are determined by the amount of tilt. Because the output locations are not exactly located at the Southern boundary, also their water depths are varied a small amount due to the variation of the tilt angle. This could influence the result of this uncertainty analysis, because variations of the local water depth are assessed to have a relatively large influence compared to SWAN input assessed in this uncertainty analysis (see also section 4.3). The influence of uncertainties of the current magnitude as defined in this study on wave characteristics near the shoreline is marginal.

3.3 Estimate of the uncertainty of SWAN model formulations

In the uncertainty analysis described so far, the uncertainty, associated with the model formulations was disregarded. These model formulations are mathematical expressions for physical processes such as wind wave growth, triad interactions and wave breaking in shallow waters. The mathematical representation of these processes is not without error, and is therefore associated with an uncertainty.

It is difficult to isolate this model uncertainty from input and parameter uncertainties. Although alternative formulations exist for some processes, most of these alternative formulations are poorly calibrated and cannot be seen as a representative for the uncertainty in the standard model formulation.

Nevertheless, we have made a very rough estimate of the uncertainty in the SWAN model formulations from hindcast studies and comparison to observations. Table 8 shows the results of a hindcast study of waves in the Amelander zeegat for three storms in January-March of 2007 (Haskoning, 2007). The values in this table are based on differences between model results and observations from waverider buoys at shallow water locations, comparable to the nearshore locations 1 and 2 in this study. The deep water locations are comparable to locations 3 and 4 in this study.

location		Bias	Stdev
shallow water	H_{m0}	-26 %	13 %
	$T_{m-1,0}$	-7 %	5 %
deep water	H_{m0}	-12%	10%
	$T_{m-1,0}$	-10%	6%

Table 8 Total uncertainty in SWAN outcomes, estimated from differences between a hindcast study and observations, from (Haskoning, 2007).

The Stdev in Table 8 corresponds reasonably well with the RMSE found from the Monte Carlo uncertainty analysis in sections 3.1 and 3.2. Compared to the RMSE values in Table 5, the Stdev of the H_{m0} in Table 8 are smaller. The Stdev of the wave heights are larger than the RMSE in Table 5.

The negative bias indicates that the SWAN model systematically underestimates the wave height and wave period, in particular in shallow regions. Compared to the uncertainties in model parameters and model input, the bias is at least of the same order and non-negligible. This will be taken into account in the Hydra-K analysis of Chapter 4.

3.4 Conclusions SWAN uncertainty analysis

In general, the uncertainties of predicted wave heights at the observation points are in the order of 17% (35 [cm], RMSE) or less due to uncertainties of the model parameters and 1.3% (3.5 [cm], RMSE) or less due to uncertainties of SWAN input (Table 9). For the various wave periods this amounts 17% (0.88 [sec], RMSE) and 5.5% (0.16 [sec], RMSE), respectively. Uncertainty of the wave direction is mainly determined by uncertainty of the SWAN input parameter "*wind direction*" (maximum: 10.7º, RMSE) and less by uncertainty of the model parameters (2.2º at maximum).

Comparing the results of the SWAN model parameters and model input uncertainty analysis it can be concluded that uncertainties the model parameters are generally larger. In shallow regions of the Wadden Sea, the effect of the uncertainty of model parameters is found to be the largest. In deeper waters, the influence of these uncertainties is significantly less, but still large compared to the influence of uncertainties of SWAN input.

	RMSE(H_{m0} [%])		*RMSE*($T_{m-1,0}$ [%])		*RMSE*(T_p [%])		*RMSE*(T_{m02} [%])		*RMSE*(*Dir* [%])	
	model	input	model	input	model	input	model	input	model	input
Location 1	17.3	0.9	16.1	4.1	17.2	1.0	12.2	5.5	0.6	3.0
Location 2	17.1	0.8	16.8	3.5	17.3	0.9	12.8	4.9	0.5	2.6
Location 3	4.7	1.3	3.5	1.9	3.2	0.3	2.7	3.9	0.1	2.7
Location 4	5.7	0.5	4.1	1.9	4.2	0.2	3.6	3.0	0.3	3.2

Table 9 Summary of RMSE (as a percentage of the mean) resulting from the Monte Carlo analysis to assess uncertainty of the HBC due to uncertainty of model parameters (model) and SWAN input (input)

Based on the correlation between the stochastic variables and the SWAN outcomes it can be concluded that two parameters dominate the uncertainty of SWAN results. The uncertainty of the near-shore wave height and wave period can be almost fully attributed to the uncertainty of the γ_{BJ} parameter, which greatly affects the maximum significant wave height relative to the water depth. The uncertainty of the direction of the calculated waves near-shore is mostly determined by variations of the wind direction.

Influence of the uncertainty of SWAN input is relatively small. This seems to contradict previous findings (WL 2007c, d and Alkyon 2007c), which found that input quantities such as water level, wind speed and currents play an important role. However, the SWAN uncertainty analysis in this study does not include variations of the water level or wind speed and only takes into account limited variations of the current (only its magnitude, and not the case of turning currents on or off). The influence of the first two parameters on the calculated HBC is assessed separately using

Hydra-K (chapter 4). Results of that assessment show the importance of those parameters relative to the influence of the uncertainty of model parameters and uncertainty of other input parameters.

The small influence of uncertainties of SWAN input that is assessed in this chapter can be explained by the results of the reference calculation. Most of the SWAN input assessed in this chapter concerns offshore wave characteristics (except for the current magnitude, wind direction and tilt angle). In section 3.2.2 it is concluded that offshore waves break on the barrier islands and ebb-tidal delta causing the waves near the Frisian coastline to be locally generated. Changes of the offshore wave conditions are therefore not affecting the near-shore wave conditions. Model parameters influence the generation-, dissipation- and transformation processes of waves between the barrier islands and the mainland. The fact that the influence of uncertainties of SWAN input is small compared to uncertainties of model parameters shows that uncertainties of current magnitude, tilt angle, wind direction and offshore wave characteristics do not play a large role compared to uncertainties of model parameters. Previous studies showed the importance of accurately modeled currents to resulting wave characteristics at places where high currents take place, viz. mainly in the central part of the tidal inlets. Although the effect of the uncertainty of currents proved to be small in this study, it is recommended to further investigate the current field under extreme conditions to provide a more reliable description of its uncertainty.

The results of the uncertainty analysis show that the uncertainty in the offshore conditions hardly affect the uncertainty of the HBC, because the offshore waves dissipate on the barrier islands and ebb-tidal delta. Other inlets in the Dutch Wadden Sea are assumed to show comparable wave development patterns as a result of their similar geometries. This assumption is confirmed by findings in WL (2007c, d) and Alkyon (2007b). It therefore seems reasonable to assume that the SWAN uncertainties found in this study represent the uncertainties for most of the Dutch Wadden Sea. An exception to this is the Eems-Dollard estuary, because of its dissimilar geometry.

The Monte Carlo uncertainty analysis in this study concerns the uncertainty in the model inputs and model parameters for a given set of physical formulations. The model formulations have not been varied, although alternative formulations can have a large effect on the results. A rough estimate of the total uncertainty associated with SWAN (including the model formulations) based on hindcast studies suggests that the bias in the SWAN outcome, as a result of the error in model formulations, is at least of the same order as those in the model parameters and input.

4 Uncertainty analysis Hydra-K

In this chapter the Hydra-K uncertainty analysis (steps 2a-c in Figure 2) is described. The uncertainty analysis has been carried out using a Monte Carlo (MC) approach, the details of which are discussed in section 4.1. In the MC approach, each Hydra-K calculation produces a different Hydraulic Boundary Condition (HBC) as a result of an applied random noise on the input parameters. The set of Hydra-K calculations produces an ensemble of HBC's. The spread, or the Root Mean Square Error (RMSE), of this ensemble represents the uncertainty in the HBC calculation.

The major contributions to the overall uncertainty are: the extreme statistics (probability of exceedance) of wind speed and water level, and the uncertainty in the SWAN results. Section 4.2 discusses the uncertainty in the wind speed statistics (2a in Figure 2). The uncertainty in the extreme water levels (2b in Figure 2) is discussed in section 4.3. In section 4.4 we investigate the propagation of uncertainty in SWAN results, quantified in chapter 3, into the HBC.

In section 4.5 the three contributions to the overall uncertainty are combined in a final MC-simulation, in which wind speed, water level and SWAN results are all perturbed. The variation of the HBC as a result of these perturbations will give an estimate of the total uncertainty. For all the analyses in this chapter, the uncertainty in HBC is also expressed as a variation of the critical crest level of an imaginary dike. This is explained in more detail in the next section. The uncertainty analyses were done for the four locations along the Wadden Sea coastline, shown in Figure 3.

4.1 Method

The Monte Carlo sampling method was implemented in Matlab. The algorithm is illustrated by the pseudo code below:

```
global Noise;

for i = 1:NrSamples

    % define noise (for shallow water locations 1 and 2)
    Noise.U = 0.2 * RandomNormal();
    Noise.H = 0.4 * RandomNormal();
    Noise.HM0 = 0.17 * RandomNormal();
    Noise.Tm_10 = Noise.HM0 + 0.04 * RandomNormal();

    % add bias to account for SWAN model uncertainty
    Noise.HM0 = Noise.HM0 - 0.29;
    Noise.Tm_10 = Noise.Tm_10 - 0.07;

    % call Hydra-K
    Hydra_K_Batch();

    % collect results from this Hydra-K run
    Collect_Results();

end % end loop over all samples
```

Before Hydra-K is called, the perturbations to the water level (`H`), wind speed (`U`) and SWAN results (`HM0` and `Tm_10`) are defined by random draws from standard normal distributions (provided by `RandomNormal()`). Multiplication of the standard normal distribution by a constant 0.4 yields a normal distribution with standard deviation of 0.4. The noise distributions are discussed in more detail in the following sections. After Hydra-K has been run with the perturbations, the results are collected and written to file.

Within Hydra-K the noise is applied at the proper point by:

```
OffshoreData(:,1) = OffshoreData(:,1) + Noise.H;
OffshoreData(:,2) = OffshoreData(:,2) * (1 + Noise.U);

NearshoreData(:,3) = NearshoreData(:,3) * (1 + Noise.Tm_10);
NearshoreData(:,4) = NearshoreData(:,4) * (1 + Noise.HM0);
```

Columns 1 and 2 in the array `OffshoreData` represent the water level and wind speed for each storm. Likewise, the columns 3 and 4 in the array `NearshoreData` are the near-shore spectral wave period and wave height respectively. Note that the perturbation to the water level is done by an absolute value, whereas the other perturbations are relative.

The computing time per MC sample was about 3 minutes. The number of samples per MC simulation was at least 200 (in a few cases more to check the convergence). A 200-sample MC run thus takes approximately 600 minutes, or 10 hours.

Expressing the uncertainty in terms of crest level

The HBC are usually represented by a so-called illustration point: one combination of water level and wave conditions from the collection of all possible hydraulic loads that combined have the specified probability of exceedance. An illustration point for a sea defence consists of four variables:

- water level at the toe of the sea defence
- near-shore wave height (H_{m0})
- near-shore spectral wave period ($T_{m-1,0}$)
- wave incident angle (not considered in this study)

The uncertainty in the HBC calculation is reflected in an uncertainty in each of these four variables. However, the various sources of uncertainty in the HBC calculations contribute differently to the four variables. For example, the uncertainties in the SWAN model only affect the wave parameters, not the water level. This complicates the prioritization of efforts to minimize the overall uncertainty.

Another way to represent the HBC is to compute the minimally required height, or the critical crest level (CCL) of an imaginary dike (design dike) that would just withstand the HBC at the location of interest. For this we assume that the failure mechanism ‘wave overtopping’ is dominant and consider a dike with a variable height. The critical crest level is then a single scalar quantity that is associated with a given set of HBC. Consequently, the uncertainty in the HBC is also expressed as a single scalar. This is very convenient because the contributions to the total uncertainty in the crest height can now be determined unambiguously. It is also clear what reduction in the total uncertainty can be expected by minimizing one of the sources of uncertainty (Den Heijer *et al.*, 2006).

The imaginary dike used in this study has a bottom slope of 25% (1 on 4), then a horizontal part of 13 m and finally a top slope of 33% (1 on 3). The dike is covered with smooth asphalt. The failure mechanism is wave overtopping with a critical overtopping discharge of 1 l/s/m. The crest level calculation is done deterministically and without considering any uncertainties. In practice, the computed failure probability and the critical crest level are associated with considerable uncertainties. The analysis of this uncertainty will, however, be the subject of a separate activity, which is currently under preparation[5]. For this study we thus assume that the failure probability calculation is perfect. We only use the failure model to express the uncertainty in HBC as an uncertainty in a single quantity, i.e. the critical crest level.

The empirical model that is used to calculate the amount of wave overtopping as a function of the water level and wave parameters is an integrated part of Hydra-K. There is also a stand-alone version of this model, called PC-Overslag (see Figure 11). Version 6.1.9 MKH has been used.

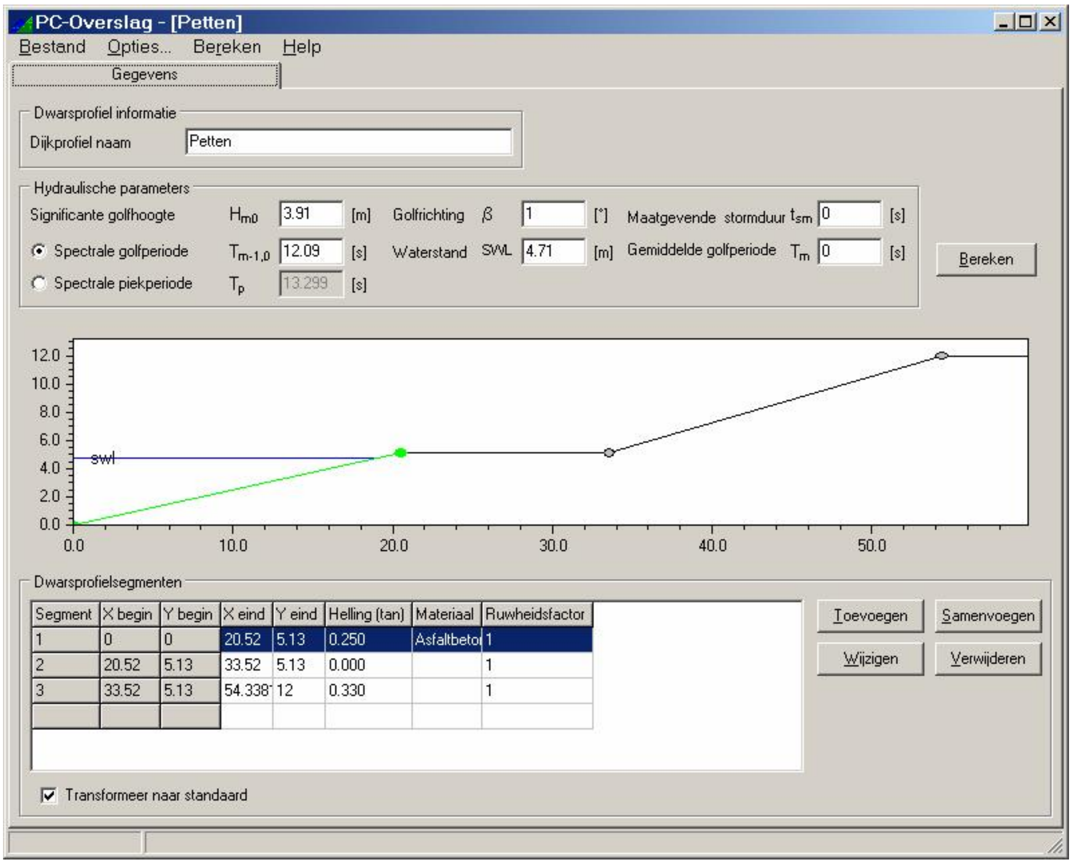

Figure 11 PC-overslag stand-alone version, with the profile of the imaginary dike.

[5] ‘Onzekerheidsanalyse Faalmechanismen’, supplementary activity by GeoDelft within the SBW Waddenzee project.

4.2 Uncertainty in wind speed

The probability of exceedance (POE) function of the wind speed has been identified as one of the main sources of uncertainty in the HBC calculation (see WL 2007b, Section 2.2). This uncertainty propagates into the wind speed of the 'de Haan' up-scaled storms. The 'de Haan' up-scaling procedure is visualised in Figure 12. The return period of an observed wind speed is determined from the POE function. Subsequently, the return period is multiplied by a 'de Haan' scaling factor, to obtain the return period of an extreme event. In the final step, the wind speed of the upscaled event is found from the inverse POE function. The uncertainty in the exceedance frequencies occurs predominantly in this last step.

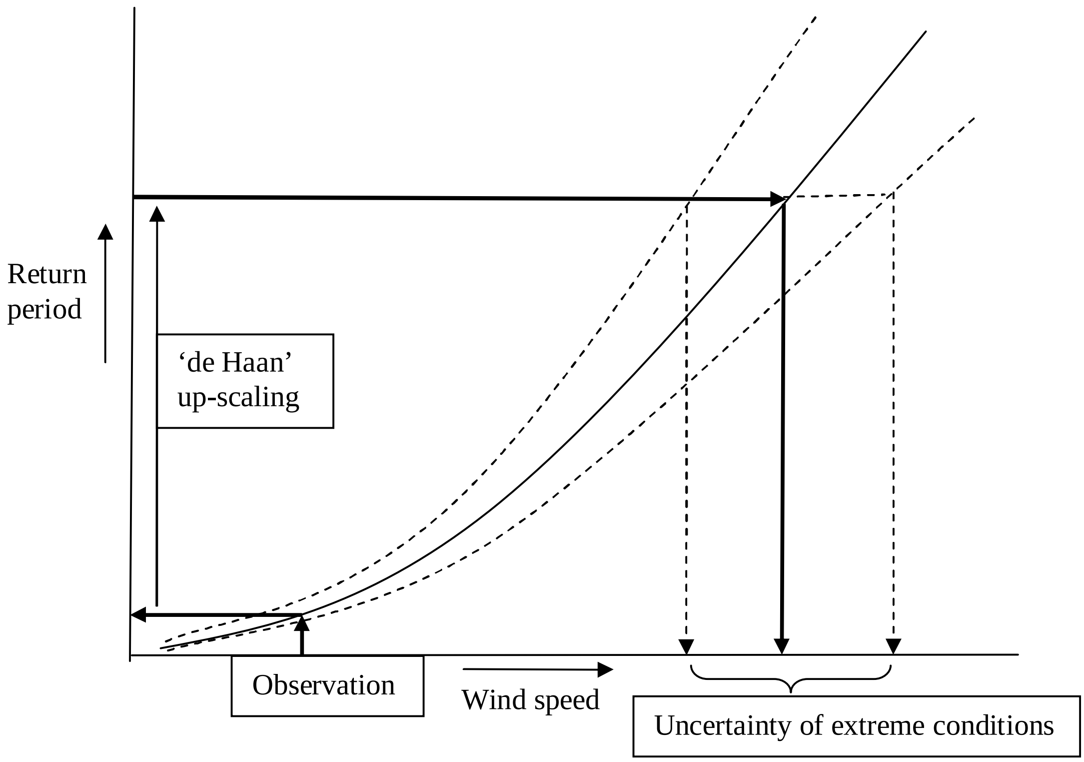

Figure 12 The probability of exceedance (POE) function of the wind speed is used for up-scaling of observations to extreme events. The dashed lines represent the uncertainty.

As a result of a possible over- or underestimation of the wind speed, the local wave growth on the Wadden Sea will be larger or smaller than in the reference calculation. As a consequence, the HBC at near shore locations will be different. We investigate the variation in the HBC as a result of variations of the POE function of the wind speed.

The uncertainty associated with the POE function is represented by applying a 'noise factor' to the wind speeds of the up-scaled storm events. The uncertainty in the extreme wind speed range has been estimated at 20% for return periods of 4000 years (see WL 2007b, Section 2.2). The wind speed noise factor is therefore defined as $1+\varepsilon$, with ε drawn from a normal distribution with zero mean and a standard deviation of 0.2. The wind speeds of all the up-scaled storms are multiplied by this factor (2a in Figure 1).

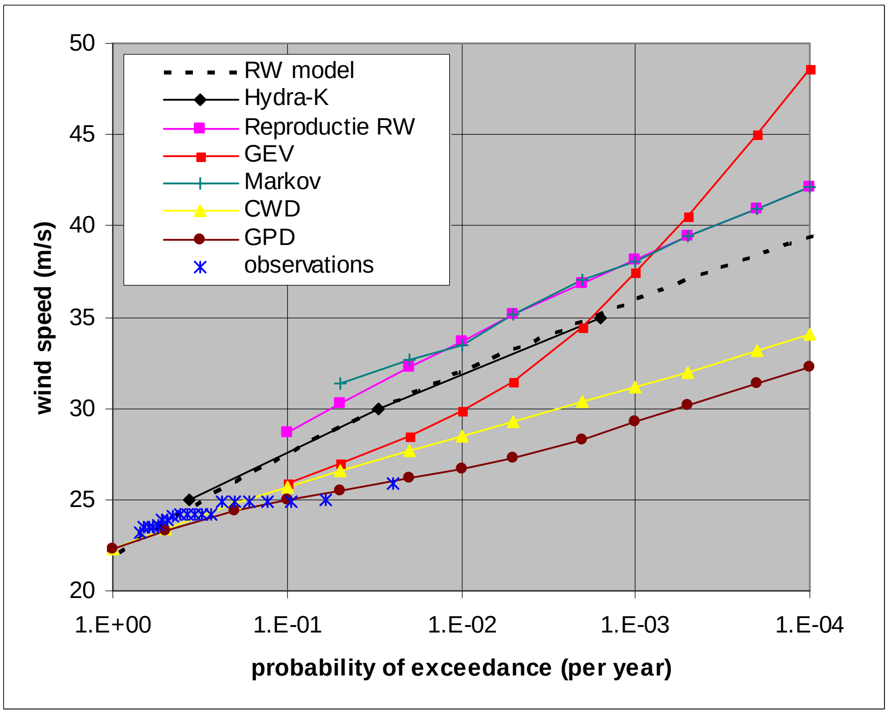

Figure 13 Different probability of exceedance models and observations of the wind speed at Texel (from WL 2007b).

Results

Table 10 shows the results of the Monte Carlo simulation with perturbations of wind speed. The results indicate that the uncertainty in wind speed leads to a considerable uncertainty of 54-55 cm in the significant wave height at near-shore locations 3 and 4. Considering the normative wave height of 2.5 m, this amounts to 20% relative uncertainty. For locations 1 and 2 the uncertainty in wave height is 16-17 cm (9%). The water level and wave period are less affected by the variation in wind speed.

Table 10: Results of the Hydra-K uncertainty analysis with perturbation of wind speed.

Location	RMSE(h) [cm]	RMSE(H_{m0}) [cm]	RMSE($T_{m-1,0}$) [s]	RMSE(CCL) [cm]
1	3	16	0.2	10
2	3	17	0.3	6
3	2	55	0.3	63
4	2	54	0.3	63

The uncertainty in the critical crest level of an imaginary dike at locations 1 and 2 is small: 10 cm is an acceptable level of accuracy in terms of the safety assessment of coastal defences. At locations 3 and 4, however, the uncertainty is a considerable 63 cm. The mean of the set of sampled crest levels was in accordance with the reference calculation (differences 1-4 cm).

The different findings for locations 1 and 2, compared to locations 3 and 4 can be explained by inspecting the local bathymetry. Locations 3 and 4 are close to a tidal channel, with possible wave growth and translation through the channel. The local wave growth is governed by wind speed and, as a consequence, the uncertainty in wave height at these locations is strongly affected by the uncertainty in wind speed. In contrast, at locations 1 and 2 the wave growth is limited by shallow water effects. The wave height at these locations is mainly determined by the local depth, not by the wind speed. Consequently, a variation in wind speed does not affect the wave height.

4.3 Uncertainty in water level

Similar to wind speed, the probability of exceedance (POE) function for water level (see Figure 14) has been identified as another major source of uncertainty in the HBC calculation (WL 2007b). This uncertainty propagates into the water level of the 'de Haan' up-scaled storms, analogous to the wind speed.

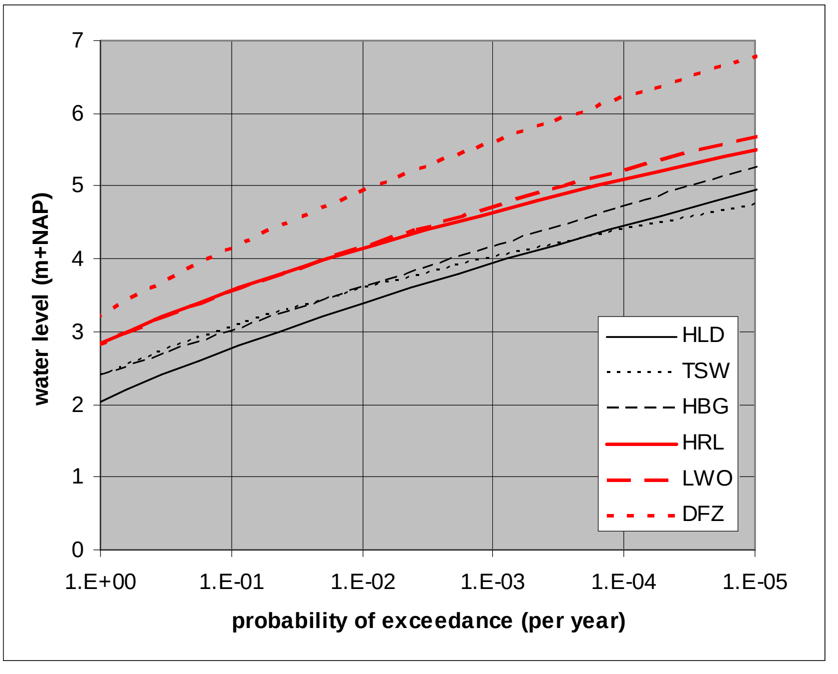

Figure 14 Probabilities of exceedance (POE) of water levels in the Wadden Sea (from WL 2007b). Locations are: HLD= Den Helder, TSW=Tereschelling, HBG=Huibertgat, HRL=Harlingen, LWO=Lauwersoog, DFZ=Delfzijl.

An error in the water level leads directly to an error in the near-shore water level of the HBC. Moreover, a variation of the water level has an effect on the wave heights, especially for the Wadden Sea. Since waves in most part of the Wadden Sea are depth limited, an increase in water level will also lead to a larger wave height. Therefore, the uncertainty in the water level is expected to have a large contribution to the uncertainty of the HBC at near-shore locations.

The uncertainty associated with the POE function of the water level is represented by applying a perturbation to the water level of every up-scaled storm event. Since water levels are expressed in terms of a more or less arbitrary mean sea level reference (m+NAP), it is incorrect to express the uncertainty as a percentage of this reference. Therefore, the uncertainty in water level is defined by an absolute value.

The uncertainty in the water level at Lauwersoog with a return period of 4000 years has been estimated at 40 cm, based on a comparison between several statistical extrapolation functions and physical modelling studies (RIKZ, 1993)[6]. The perturbations to the water level were defined as a random shift with zero mean and standard deviation 40 cm. Since the uncertainty is associated with the POE function and not with the individual storm event, the same shift was applied to all the offshore water levels of upscaled storm events (step 2b in Figure 2).

Results

The results of the HBC uncertainty analysis with perturbation of water levels are listed in Table 11. Obviously, the water level in the HBC is directly affected by the uncertainty in the POE function of the water levels in Hydra-K. The RMSE in the water levels of 40 cm at all four locations is a direct consequence of the 40 cm standard deviation of the applied noise. In addition to this, the variation of water level causes a variation of wave heights at locations 1 and 2, where the wave height is limited by the water depth. The RMSE of the critical crest level (CCL) is approximately 50 cm at all four locations.

Table 11: Results of the Hydra-K uncertainty analysis with perturbation of water level.

Location	RMSE(h) [cm]	RMSE(H_{m0}) [cm]	RMSE($T_{m-1,0}$) [s]	RMSE(CCL) [cm]
1	42	14	0.2	51
2	41	15	0.2	56
3	42	4	0.1	49
4	42	4	0.1	49

The mean of the sampled set of crest levels was larger than the reference calculation for each location. The sample distribution is positively skewed, with higher probability of deviations to larger crest levels. This is due to the non-linear increase of crest level with increasing water level and wave height (see Figure 16).

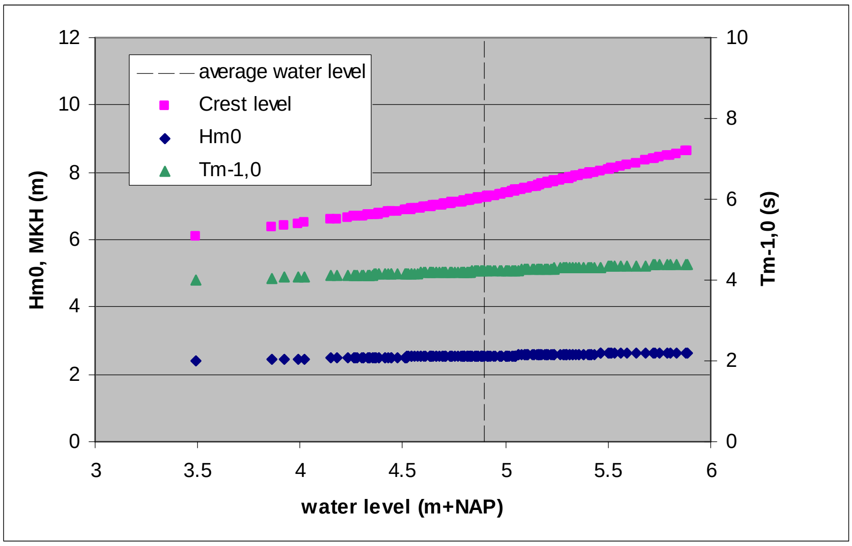

Figure 15 Correlation between samples of water level, wave conditions (H_{m0} and $T_{m-1,0}$) and critical crest level (CCL).

6. This value differs from the estimate in WL 2007b, Section 2.2. After some discussion with experts (Dillingh, den Heijer) we believe that a standard deviation of 40 cm is a more realistic value for the uncertainty in the 1/4000 year water level at Harlingen, Terschelling-West and Lauwersoog.

4.4 Propagation of SWAN uncertainty

The third source of uncertainty in Hydra-K that is considered here is associated with the SWAN calculation (step 2c in Figure 2). Hydra-K uses a database of SWAN computations to relate an offshore wind and water level to near-shore wave conditions. The uncertainty in SWAN is therefore represented by a perturbation to the data retrieved from this database. We apply a noise factor to each near-shore wave height and spectral period retrieved from the database (2c in Figure 1). The magnitude of this noise factor is based on the total estimated uncertainty of the SWAN outcomes, listed in Table 8. Since this uncertainty depends on the local bathymetry, the noise factor applied in Hydra-K was varied accordingly between shallow water locations 1 and 2 and deep water locations 3 and 4.

In this study we have disregarded the uncertainty in wave incident angle. This contribution to the total uncertainty is assumed of minor importance at the moment, at least compared to the wave height and spectral wave period. It is, however, recommended to investigate this additional uncertainty contribution in a follow-up study.

The combined uncertainty in SWAN results can be calculated from the contributions of SWAN input and model parameters (see Chapter 3), assuming that these are independent and approximately Gaussian:

$$\left(RMSE_{total}\right)^2 = \left(RMSE_{input}\right)^2 + \left(RMSE_{parameters}\right)^2 + \left(RMSE_{model}\right)^2 \quad (4.1)$$

Combination of the input and parameter uncertainty leads to an uncertainty in near-shore wave height of 17% at locations 1 and 2 and 5% at locations 3 and 4 based on the Monte Carlo analysis of Chapter 3. For the spectral wave period the combined SWAN uncertainty is 17% at locations 1 and 2, and 4% at locations 3 and 4. The uncertainty of the SWAN model formulations (the last term on the RHS of Eq. 4.1) was estimated to have an effect of the same order of magnitude (see section 3.3). From comparison with observations it was found that the uncertainty in model formulations introduces a bias of -29% in wave height and -7% in wave period at shallow water locations 1 and 2. At deep water locations 3 and 4 the bias is estimated at -12% and -10% respectively. This bias was added as an additional perturbation to H_{m0} and $T_{m-1,0}$.

The SWAN uncertainty analysis in chapter 3 showed that the uncertainties in wave height and wave period are correlated. This correlation should be included in the propagation analysis by introducing a correlation between the noise factors for the wave height and period. This was done by using a common relative noise factor for wave height and wave period and subsequently applying an additional noise factor (of 4%) to the wave period (see section 4.1). The resulting correlation between the sampled wave heights and wave periods, expressed in R^2, is then comparable to the results from the SWAN uncertainty analysis (see Figure 16 and Table 12).

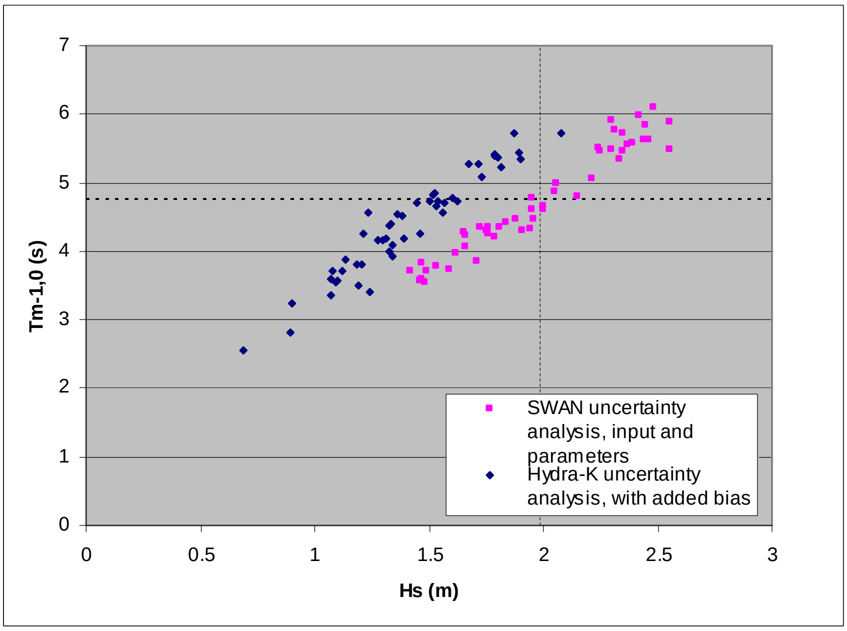

Figure 16: Correlation between the uncertainty in wave height (H_{m0}) and spectral wave period ($T_{m-1,0}$) for the SWAN uncertainty analysis and the simulated noise in the Hydra-K uncertainty analysis (data for location 1). Note that the samples in the Hydra-K analysis deviate from the mean values for H_{m0} and $T_{m-1,0}$ (dashed lines), as a result of the applied bias.

Table 12 Correlation (R^2) between wave height and spectral wave period in the SWAN uncertainty analysis and the Monte Carlo sampling in Hydra-K.

Location	R^2(SWAN)	R^2(Hydra-K)
1	0.94	0.96
2	0.95	0.96
3	0.53	0.52
4	0.64	0.66

Results

The uncertainty of the near-shore wave height and period, as a result of the total uncertainty of the SWAN model, leads to an uncertainty in the Hydra-K results. This uncertainty in the HBC is listed in Table 13.

Table 13: Hydra-K uncertainty as a result of propagation of the total estimated uncertainty of SWAN (including the bias as a result of the uncertainty in model formulations).

Location	RMSE(h) [cm]	RMSE(H_{m0}) [cm]	RMSE($T_{m-1,0}$) [s]	RMSE(CCL) [cm]
1	12	60	0.8	72
2	9	63	0.9	78
3	1	32	0.5	53
4	1	31	0.5	52

The RMSE of the crest level, as a result of the total SWAN uncertainties is more than 50 cm at all locations. This is large in terms of safety assessment of coastal defenses.

4.5 Combined uncertainty

The next step in the Hydra-K uncertainty analysis is to combine all sources of uncertainty to find the overall uncertainty in the HBC. Since the sources of uncertainty are independent and we have assumed Gaussian distributions of the corresponding random variables, we expect to find a combined uncertainty according to the standard combination rule for independent contributions to the total uncertainty:

$$\left(RMSE_{MKH,total}\right)^2 = \left(RMSE_{MKH,h}\right)^2 + \left(RMSE_{MKNH,U_w}\right)^2 + \left(RMSE_{MKH,SWAN}\right)^2 \qquad (4.2)$$

The results are listed in Table 14. We find that the standard rules for combining independent Gaussian sources of error apply to within a few cm.

Table 14: Results of the Hydra-K combined uncertainty analysis. The expected values from standard error combination rules (equation 4.2) are shown in brackets.

Location	RMSE(h) [cm]	RMSE(H_{m0}) [cm]	RMSE($T_{m-1,0}$) [s]	RMSE(CCL)[cm]
1	44	64	0.9	90 (89)
2	42	67	0.9	97 (97)
3	42	64	0.6	95 (96)
4	42	62	0.6	98 (95)

Convergence behavior

The RMSE of the crest level as a function of the number of Monte Carlo samples is shown in Figure 17. After 100 samples the results have converged to an estimated 7% accuracy. After 200 samples the values have converged to approximately 5%. However, given the rough estimates of the distributions of sources of uncertainty, we believe that the accuracy level of the uncertainty estimates in this chapter is no better than 10%.

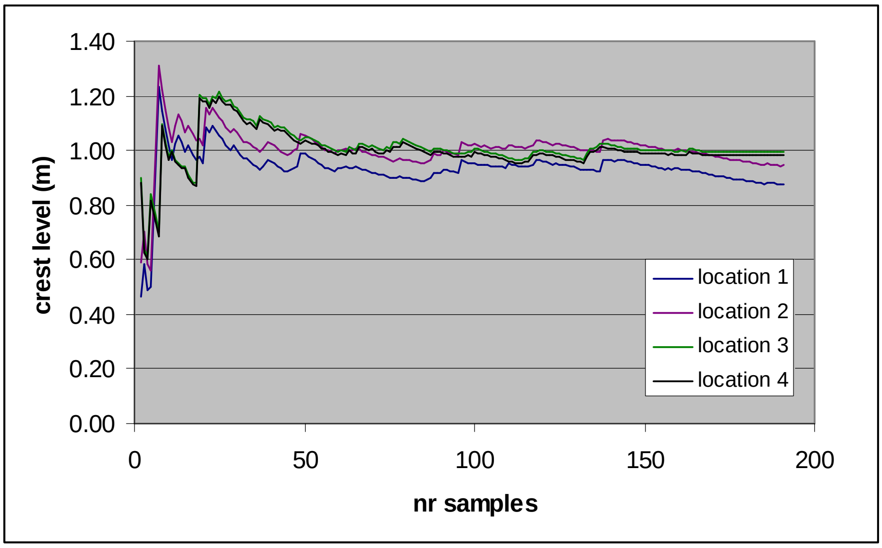

Figure 17: Convergence of the RMSE of the critical crest level (CCL) for the combined uncertainty run.

Histograms

The distributions of crest levels from the combined uncertainty run are shown in Figure 18. Also shown are Gaussian distributions, using the mean and standard deviation calculated from the sample distribution. It can be concluded that the uncertainty in crest levels is approximately Gaussian. However, all the crest level distributions seem to have a small positive skew. This is probably due to the non-linear increase in crest level for increasing water level (see Section 4.3).

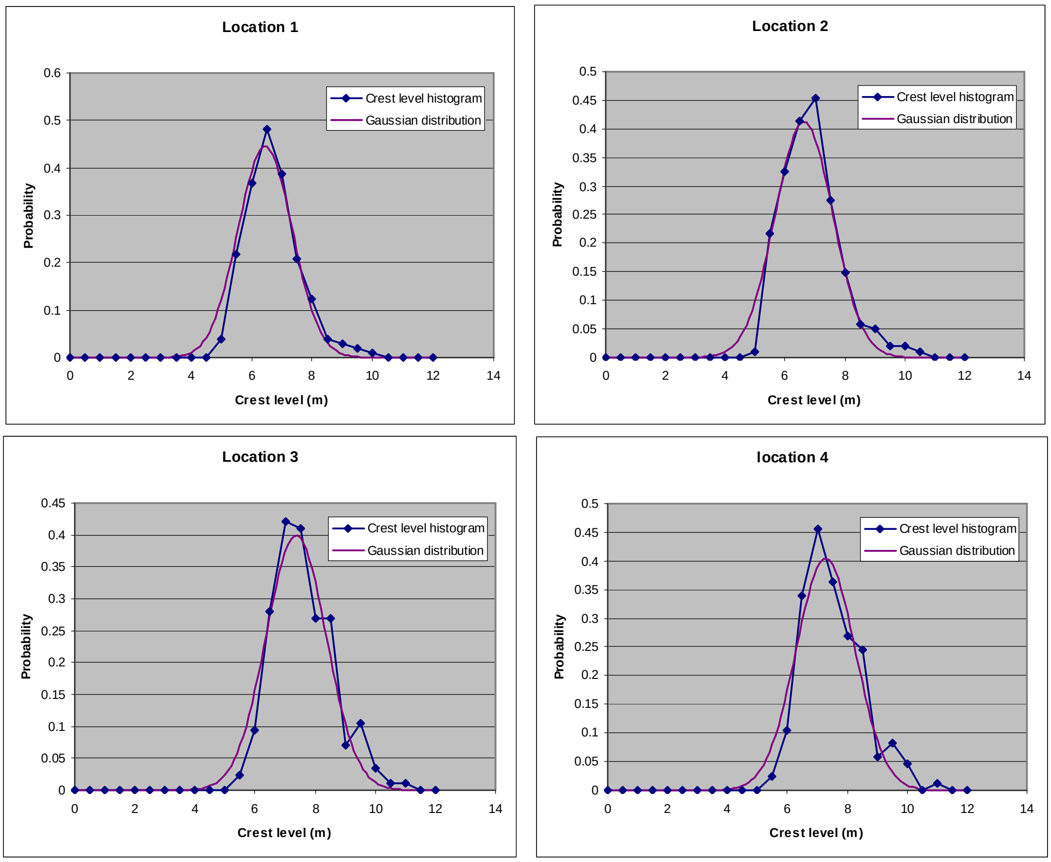

Figure 18 Probability density distributions of crest levels from the uncertainty analysis. Also shown are Gaussian distributions using the mean and standard deviation calculated from the sample set.

Contributions to the total uncertainty

The relative contributions to the combined uncertainty are visualised in Figure 19. These contributions have been calculated based on the RMSE from the separate Monte Carlo runs. Locations 1 and 2 are very similar, as are locations 3 and 4. The difference between the distributions can be explained by the local bathymetry. At locations 1 and 2, the shallow bathymetry strongly reduces the effect of the variations in wind speed. At locations 3 and 4, the nearby channel allows for additional wave build-up in case of stronger wind. Consequently, the sensitivity to variations in wind speed is larger at these locations.

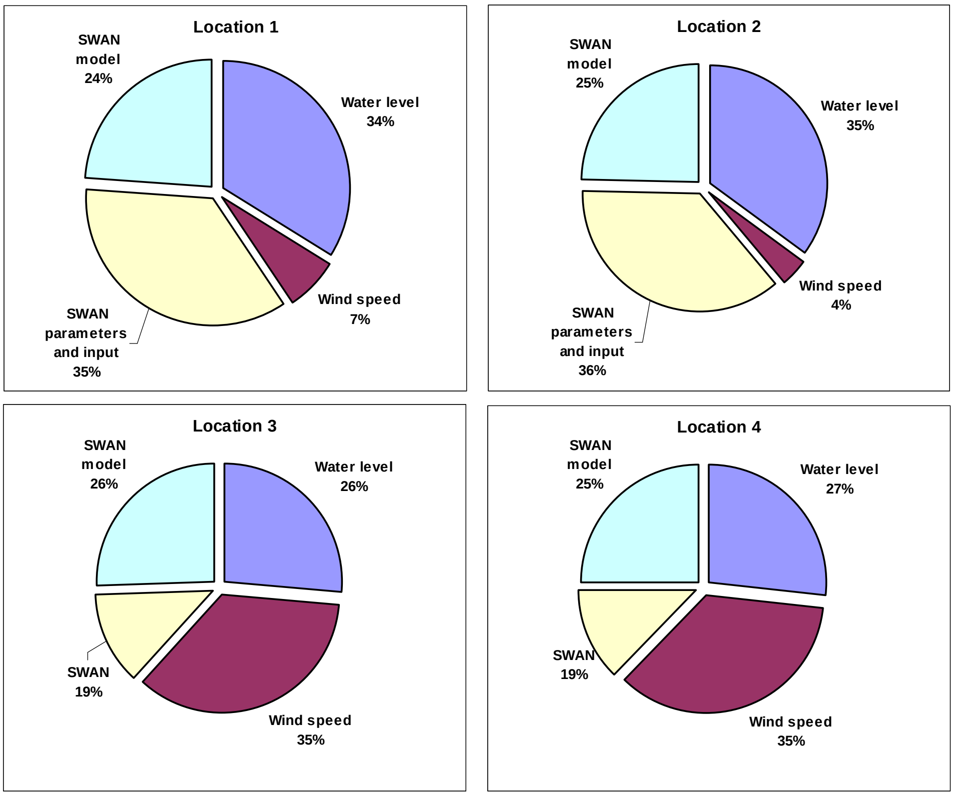

Figure 19: Relative contributions to the total uncertainty in critical crest level at the four locations under investigation. Locations 1 and 2 are next to shallow water, locations 3 and 4 are near a channel.

The theoretical accuracy after elimination of one of the sources of uncertainty can be found by switching ‘on’ and ‘off’ each source and calculating the remaining combined uncertainty. Table 15 lists these remaining uncertainties in crest level if any one of the three major sources of uncertainty is set to zero.

Table 15 Uncertainty in critical crest level (cm) if any of the sources of uncertainty was eliminated.

Location	All uncertainties	Uncertainty(h)=0	Uncertainty(U_w)=0	Uncertainty(SWAN)=0
1	90	72	88	52
2	97	78	96	57
3	95	82	72	80
4	98	81	71	79

We find that at shallow water locations (1 and 2) the largest reductions in total uncertainty can be achieved by elimination of the uncertainties in SWAN (including model formulations, input and parameter settings). For relatively deep water locations (3 and 4), the largest improvement in accuracy can be achieved by reducing the uncertainty in wind statistics.

4.6 Conclusion Hydra-K uncertainty analysis

The overall uncertainty in the critical crest level is between 90 and 100 cm (RMSE) for all test locations in this study. This uncertainty is smaller than computed in an earlier study (WL, 2007) for the North Sea coast, which can be explained by the shallow bathymetry of the Wadden Sea, limiting the wave growth. The major contributions to this uncertainty are the uncertainties in the water level, wind speed and the uncertainty associated with the SWAN model.

The uncertainty of SWAN is a major contribution to the total uncertainty in HBC for all four locations that have been investigated. This uncertainty is attributed to both the model formulations and parameter settings, these contributions are distributed about evenly. The water level is another important source of uncertainty, contributing about one third to the total uncertainty in HBC at shallow water locations. For locations 1 and 2, the uncertainty in the wind speed is almost negligible, because the wave conditions are dominated by the shallow bathymetry. For locations 3 and 4, which are close to a channel with considerable depth, the most important source of uncertainty is the wind speed.

The standard rules for combining independent Gaussian sources of error apply to within a few cm. However, comparison of the distributions of crest levels to Gaussian distributions shows that the crest level distributions are slightly skewed: the probability of higher crest levels is larger than that of smaller crest levels. This is due to the more than linear increase in the crest level with increasing wave height and wave period.

The uncertainty in HBC will not affect the results of the safety assessment, since the Flood Defences Act states that the assessment should be done based on the average HBC, or the best estimate. The results of the uncertainty analysis can, however, be used as guidelines for further improvement of the methodology.

The theoretical accuracy after elimination of one of the sources of uncertainty can be found by switching ‘on’ and ‘off’ each source and calculating the remaining combined uncertainty. For locations near shallow water, the largest reductions in total uncertainty are achieved by reducing the uncertainties in water level and SWAN parameters. For deeper locations the 20% uncertainty in 1/4000 years wind speed is most important.

5 General conclusions and recommendations

The objectives of this research have been listed in Section 1.2:
- To assess the total uncertainty of the HBC of the Wadden Sea using the current methods.
- To gain insight in the contributions of the major sources of error to the overall uncertainty.
- To estimate the possible reduction in uncertainty by eliminating sources of error.
- To make suggestions for future efforts to improve the accuracy of the HBC.

The first three objectives will be addressed in Sections 5.1 and 5.2. The last will be discussed in Section 5.3.

5.1 Conclusions SWAN uncertainty analysis

The total uncertainties of near shore wave height and wave period, as computed by the SWAN model are a result of uncertainties in model parameters, model input and model formulations. The first two sources have been quantified in some detail in this study. The third source of uncertainty could only be estimated roughly by comparing observations to the results of a hindcast study in the Amelander Zeegat (Alkyon, 2007).

The uncertainties of near shore wave heights at the observation points are approximately 17% (35 [cm], RMSE) or less due to uncertainties of the model parameters and 1.3 % (3.5 [cm]) or less due to uncertainties of SWAN input. The wave period uncertainty is approximately 17% (0.88 [s]) and 5.5 % (0.16 [s]) respectively. The uncertainties of predicted near shore waves by SWAN are mainly determined by uncertainties of the model parameters.

In contrast, previous studies (WL 2007c, d and Alkyon 2007c) found that input quantities such as water level, wind speed and currents do play an important role. However, the SWAN uncertainty analysis in this study did not include variations of the water level or variations of the wind speed. The influence of these parameters on the calculated HBC has been assessed separately, using Hydra-K (Chapter 3).

From the correlation between individual stochastic variables in the analysis and SWAN results it can be concluded that one parameter dominates the uncertainty of SWAN results in shallow areas. Most of the uncertainty of the wave height and wave period can be attributed to the uncertainty of the parameter γ_{BJ} . This SWAN parameter greatly affects the maximum significant wave height relative to the water depth.

The uncertainty of the direction of the calculated waves near-shore is mainly determined by variations of the wind direction. This uncertainty is mainly determined by uncertainty of SWAN input parameter "*wind direction*" (maximum: 10.7º, RMSE) and less by uncertainty of the model parameters (2.2º at maximum). The propagation of the uncertainty in wave incident angle was not taken into account further and is left for future studies.

Previous studies (WL 2007c, d and Alkyon 2007c) showed the importance of accurately modeled currents to resulting wave characteristics at places where high currents take place. Although the effect of the uncertainty of currents was found to be small in this study, it is recommended to further investigate the current field under extreme conditions to provide a more reliable description of its uncertainty.

The results of the uncertainty analysis are not affected by uncertainties in the offshore wave conditions because they dissipate on the barrier islands and ebb-tidal delta. Other inlets in the Dutch Wadden Sea are likely to show comparable wave development patterns because of their similar geometries. This is confirmed by findings in WL (2007c) and WL (2007d). It therefore seems reasonable to assume that the SWAN uncertainties found in this study represent the uncertainties for most of the Dutch Wadden Sea. An exception to this is the Eems-Dollard estuary, because of its dissimilar geometry.

5.2 Conclusions Hydra-K uncertainty analysis

The total uncertainty in the critical crest level of an imaginary (design) dike at four locations in the test area was found to be between 90 and 100 [cm] (RMSE). This uncertainty is smaller than computed in an earlier study (WL, 2007) for the North Sea coast, which can be explained by the shallow bathymetry of the Wadden Sea, limiting the wave growth.

From separate runs we have assessed the relative contributions of the various sources of uncertainty. The uncertainty of SWAN is a major contribution to the total uncertainty in HBC for all four locations that have been investigated. This uncertainty is attributed to both the model formulations and parameter settings, these contributions are distributed about evenly. The water level is another important source of uncertainty, contributing about one third to the total uncertainty in the HBC at shallow water locations. For locations 1 and 2, the uncertainty in the wind speed is almost negligible, because the wave conditions are dominated by the shallow bathymetry. For locations 3 and 4, which are close to a channel with considerable depth, the most important source of uncertainty is the wind speed.

The uncertainty in the HBC will not affect the results of the safety assessment, since the Flood Defences Act states that the assessment should be done based on the average HBC, or the best estimate. The results of the uncertainty analysis can, however, be used as guidelines for further improvement of the methodology.

The theoretical accuracy after elimination of one of the sources of uncertainty can be found by switching ‘on’ and ‘off’ each source and calculating the remaining combined uncertainty. For locations near shallow water, the largest reductions in total uncertainty are achieved by reducing the uncertainties in water level and SWAN parameters. For deeper locations the 20% uncertainty in 1/4000 years wind speed is most important.

5.3 Recommendations

We recommend a number of follow-up activities:

- An important source of uncertainty is the uncertainty of the SWAN model. The settings of the SWAN parameters, in particular those of the shallow water breaking terms, were shown to be a significant source of uncertainty in the HBC. This uncertainty can be reduced by parameter calibration based on field measurements. Within the SBW project, extensive measurements are being conducted for this purpose. Furthermore, a software environment for efficient calibration of SWAN is being developed (DAtools). This will help reducing the uncertainty in parameter settings.
- The uncertainty in SWAN model formulations was only estimated roughly in this study. It is recommended to further investigate the contribution of the model formulations to the total uncertainty. The validity of alternative model formulations can be considered by comparing wave measurements with SWAN hindcasts. In addition, the range of validity of model formulations should be considered since most model formulations have not been verified for extreme storm conditions. For instance, for wind speeds larger than 30 m/s the wind drag coefficient may become saturated, thereby limiting the amount of momentum transfer from the atmosphere to the wave field. Also, under strong wave action, the effective bottom roughness may decrease, because bottom ripples are smoothed out. Finally, for the non-linear four-wave interactions more accurate methods are available than the presently used DIA method.
- The uncertainty in the probability of exceedance function of the water levels at large return periods was also found to be a large contribution to the overall uncertainty in HBC. We recommend investigating the possibility of reducing this uncertainty. This could be done, for example, by stochastic modeling of hydrodynamics (WAQUA/Delft3D). A possible approach is described in WL (2007f).
- For locations near deeper water, e.g. tidal channels, we find that the wind speed is an important factor in the total uncertainty of the HBC. We therefore recommend investigating the possibility to improve the wind speed probability of exceedance functions. This should be done by, or in close collaboration with KNMI.
- The current field under extreme conditions and the associated uncertainty should be investigated further, in particular its dependence on wind speed and wind direction. In the uncertainty analysis in this study only the current magnitude was varied, not the current direction. In reality, the situation is more complex, because the currents evolve during a storm as will their effect on the waves. This implies that it is probably insufficient to consider only one time instance during a storm. Also, the variation of mean wave direction should be included in a future uncertainty analysis.
- Finally, the uncertainty in HBC as a result of uncertainty in the wave incident angle was ignored in this study. We recommend investigating this in a follow-up project.

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A Coefficients used in the SWAN Uncertainty Analysis of model and input parameters

Process:	Para-meter	reference	standard deviation	range (this study)	range (WL, 2007)
Deep water balance					
Dissipation of wave energy due to whitecapping	$C_{ds,wc}$	$5.0*10^{-5}$	0.325E-5	4.35E-5 – 5.65E-5	4.2E-5 – 5.5E-5
	B_r	$1.75*10^{-3}$	0.125E-3	1.5E-3 – 2.0E-3	1.5E-3 – 2.0E-3
Non-linear transfer of wave energy due to quadruplet (four-wave) interaction	C_{nl4}	$3.0*10^{7}$	0.25E7	2.5E7 – 3.5E7	2.5E7 – 3.5E7
	λ	0.25	0.025	0.2 – 0.3	0.2 – 0.3
Shallow water balance					
Dissipation due to bottom friction*	$C_{ds,bot}$	0.067	-	0.042 – 0.092	0.05 – 0.1
Dissipation due to depth induced breaking*	α_{BJ}	1.0	-	0.5 – 1.5	-
	γ_{BJ}	0.73	-	0.42 – 0.092	0.44 – 0.92
Non-linear triad (three-wave) interaction	α_{AE}	0.05	0.0125	0.025 – 0.075	on/off switch
	$f_{max,EB}$	2.5	-	-	-
Offshore wave boundary					
Wave height	H_{m0}	11.7	20 %	40%	40%
Peak period	T_p	17.9	20 %	40%	40%
Wave direction	*dir*	345	15°	30°	30°
Other input parameters					
Water level tilt	*tilt*	$2.5*10^{-5}$	$1.25*10^{-5}$	$0 – 5*10^{-5}$	$1*10^{-5} – 5*10^{-5}$
Current magnitude	*fac*	0.8	0.25	0.3 – 1.3	0.3 - 1.3
Wind direction*	*wdir*	345	-	330 – 360	330 – 360

Table 16 Specification of reference values and uncertainty parameters of SWAN input and model parameters varied in the uncertainty analysis of SWAN

Uniform distribution *

B Results of the SWAN uncertainty analysis

	H_{m0}				$T_{m-1,0}$				T_p				T_{m02}				*Dir*			
Location :	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**
$C_{ds,wc}$	0,01	0,01	0,06	0,04	0,00	0,00	0,01	0,01	0,01	0,01	0,01	0,01	0,00	0,01	0,01	0,01	0,00	0,05	0,03	0,04
B_r	0,00	0,00	**0,26**	**0,16**	0,06	0,05	0,02	0,02	0,03	0,03	0,00	0,01	0,04	0,04	0,01	0,01	0,02	**0,12**	0,00	0,02
C_{nl4}	0,02	0,02	0,00	0,00	0,02	0,02	0,00	0,00	0,02	0,02	0,00	0,00	0,02	0,02	0,00	0,00	0,00	0,01	0,04	0,01
λ	0,00	0,00	0,00	0,00	0,03	0,03	**0,17**	**0,14**	0,03	0,03	0,04	0,05	0,02	0,03	**0,14**	**0,11**	0,09	**0,27**	0,07	**0,14**
$C_{ds,bot}$	0,07	0,07	0,04	0,06	**0,10**	0,09	0,06	0,06	0,07	0,07	0,08	0,07	0,08	0,07	0,05	0,06	0,01	0,02	0,00	**0,13**
α_{BJ}	0,03	0,03	0,02	0,01	0,02	0,02	0,00	0,00	0,02	0,03	0,00	0,00	0,02	0,02	0,00	0,00	0,00	**0,14**	0,00	0,01
γ_{BJ}	**1,00**	**1,00**	**0,63**	**0,75**	**0,95**	**0,95**	**0,85**	**0,86**	**0,97**	**0,97**	**0,88**	**0,86**	**0,97**	**0,97**	**0,85**	**0,85**	0,08	**0,38**	**0,24**	**0,40**
α_{AE}	0,01	0,01	0,03	0,03	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,01	0,00	0,03

Table 17 Correlation coefficients between input and output of the Monte Carlo simulation for analysis of SWAN uncertainty due to uncertainty of model parameters

	H_{m0}				$T_{m-1,0}$				T_p				T_{m02}				*Dir*			
Location :	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**
Current magnitude	0,08	0,08	**0,11**	**0,19**	0,01	0,05	0,02	**0,11**	0,00	**0,43**	**0,11**	0,00	0,03	**0,19**	0,07	**0,20**	0,01	0,01	0,00	0,01
Water level tilt	**0,82**	**0,92**	0,03	0,07	0,08	**0,11**	0,06	0,06	**0,11**	**0,14**	**0,29**	**0,40**	0,05	0,07	0,03	0,05	0,00	0,00	0,01	0,01
Wind direction	**0,17**	0,07	**0,74**	**0,25**	**0,86**	**0,88**	**0,92**	**0,87**	**0,37**	0,01	**0,14**	**0,18**	**0,94**	**0,83**	**0,93**	**0,82**	**1,00**	**1,00**	**0,98**	**0,98**
H_{m0} (offshore)	0,00	0,02	0,01	0,03	0,00	0,00	0,00	0,00	0,03	0,05	0,02	0,00	0,00	0,00	0,00	0,00	0,00	0,01	0,00	0,00
T_p (offshore)	0,01	0,00	0,00	0,05	0,00	0,00	0,00	0,00	0,01	0,02	0,03	0,03	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Wave direction (offshore)	0,04	0,02	0,05	0,00	**0,14**	**0,16**	**0,17**	**0,18**	0,02	0,00	0,01	0,00	**0,17**	**0,18**	**0,18**	**0,18**	**0,15**	**0,14**	**0,16**	**0,17**

Table 18 Correlation coefficients between input and output of the Monte Carlo simulation for analysis of SWAN uncertainty due to uncertainty of SWAN input

	H_{m0} [m]			$T_{m-1,0}$ [s]			T_p [s]			T_{m02} [s]			*Dir* [degrees]		
	mean	*st. dev.*	*std(%)*	*mean*	*st. dev.*	*std(%)*	*mean*	*st. dev.*	*std(%)*	*mean*	*st. dev.*	*std(%)*	*mean*	*st. dev.*	*std(%)*
Location 1	1.99	0.34	17.3	4.8	0.77	16.1	5.0	0.87	17.2	3.1	0.38	12.2	354	2.2	0.6
Location 2	2.04	0.35	17.1	4.6	0.77	16.8	5.1	0.88	17.3	2.9	0.37	12.8	352	1.8	0.5
Location 3	2.93	0.14	4.7	4.6	0.16	3.5	5.4	0.17	3.2	3.5	0.10	2.7	341	0.5	0.1
Location 4	2.83	0.16	5.7	4.5	0.19	4.1	5.4	0.22	4.2	3.4	0.12	3.6	336	1.0	0.3

Table 19 Uncertainties resulting from the assessment of the influence of uncertainties of SWAN model parameters

	H_{m0} [m]			$T_{m-1,0}$ [s]			T_p [s]			T_{m02} [s]			*Dir* [degrees]		
	mean	*st. dev.*	*std(%)*	*mean*	*st. dev.*	*std(%)*	*mean*	*st. dev.*	*std(%)*	*mean*	*st. dev.*	*std(%)*	*mean*	*st. dev.*	*std(%)*
Location 1	1.89	0.017	0.9	4.4	0.18	4.1	4.8	0.049	1.0	2.9	0.16	5.5	351	10.6	3.0
Location 2	1.94	0.016	0.8	4.3	0.15	3.5	4.8	0.042	0.9	2.8	0.14	4.9	349	9.2	2.6
Location 3	2.94	0.037	1.3	4.6	0.09	1.9	5.4	0.015	0.3	3.5	0.14	3.9	340	9.1	2.7
Location 4	2.85	0.015	0.5	4.5	0.09	1.9	5.4	0.012	0.2	3.4	0.10	3.0	334	10.7	3.2

Table 20 Uncertainties resulting from the assessment of the influence of uncertainties of SWAN input

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