Deltares

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Correlation between model uncertainties wave height and wave period

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A.J. Smale

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Summary
As part of the new safety assessment approach for the Dutch flood defences, the uncertainties in the hydraulic loads are taken into account. Amongst these uncertainties are the uncertainties with respect to the translation of stochastic variables (e.g. wind speed and water level) to wave conditions at the toe of the flood defences: so-called model uncertainties. The implementation of the model-uncertainties for wave conditions assumed (for various reasons amongst which restrictions in time and planning for implementation) no correlation between the model-uncertainty of the wave height and wave period. The data used to derive the model-uncertainties for the coastal water systems (Deltares, 2013a) showed however that this assumption is not valid. This study aims at providing the correlation between the already derived model uncertainties for wave height and wave period.

The derivation of the correlation between the model uncertainties for wave height and wave period is (in its basis) quite simple. We reproduce the found model-uncertainties to ensure we are using the same dataset. Finally, we use standard techniques to derive the Pearson correlation coefficient. This is done per application area, similar to the derivation of the model-uncertainties themselves. Using the Crude Monte Carlo tool as described in Deltares (2017), we subsequently apply the correlation model and compare the results with the present probabilistic model. This analysis addresses the required crest height.

The computed correlations between $\varepsilon_{H_{m0}}$ and ε_{T_p} were 0.34 and 0.57 [-] except for Lake Marken (remainder), which was negligible (0.01 [-]). The found correlations seem reasonable, as wave physics would prevent either fully or not correlated model-uncertainties. The impact of adding correlation on the HBN was relatively limited (especially compared to the impact of the bias correction): in the order of 0.1 to 0.2 metres for coast/lakes and even less for narrow river stretches. As expected, the inclusion of correlation leads to less high (more realistic) wave steepness in the design points of the probabilistic calculation. It is advised to the thoroughly evaluate impact of this correlation together with other potential improvements of the existing load model (several of which are discussed herein) before making any changes.

References
11202560-001, project plan Hydraulic Loads

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Contents

1 Introduction

As part of the new safety assessment approach for the Dutch flood defences, the uncertainties in the hydraulic loads are taken into account. Amongst these uncertainties are the uncertainties with respect to the translation of stochastic variables (e.g. wind speed and water level) to wave conditions at the toe of the flood defences.

This translation of the stochastic variables to wave conditions is either done by means of the empirical wave growth formula Bretschneider or with the spectral wave model SWAN. In both cases the translation is not “exact”, because models are fitted to measurements. In some cases the model will underestimate the wave conditions, whilst in other conditions the model will overestimate the wave conditions. This uncertainty is called model-uncertainty and is applied as follows:

$$\begin{aligned} h_{loc} &= h_{loc,exl}\left(S_{\text{vars}}\right)+\varepsilon_h \\ H_{m0,loc} &= \left(1-\varepsilon_{H_{m0}}\right)H_{m0,loc,exl}\left(S_{\text{vars}}\right) \\ T_{\text{p},loc} &= \left(1-\varepsilon_{T_p}\right)T_{\text{p},loc,exl}\left(S_{\text{vars}}\right) \\ T_{\text{m}-1,0,loc} &= \left(1-\varepsilon_{T_{m-1,0}}\right)T_{\text{m}-1,0,loc,exl}\left(S_{\text{vars}}\right) \end{aligned} \qquad (1.1)$$

In which $h_{loc,excl}$, $H_{m0,loc,excl}$ and $T_{p,loc,excl}$ are the water level, wave height and wave period without model uncertainties. These variables are a function of the stochastic variables (S_{vars}) of the considered water system (e.g. wind speed, river discharge, lake level, etc.). The variables ε_h, $\varepsilon_{H_{m0}}$ and ε_{T_p} represent the normal distributed model uncertainties for local water level, wave height and wave period. Note that the application of the model uncertainties, defined in (1.1), is subject to discussion (it does not line up with the definition of the derived model uncertainties). It seems as if the derivation includes the approximation $1/(1+x) \approx 1-x$, which can have an impact on the hydraulic loads in the same order as the impact of including correlation. Further research into this aspect is needed as it can have an impact on the hydraulic loads, but such analysis is outside the scope of this project.

As part of the WBI2017 project, the model-uncertainties (the μ and σ) have been derived for each model and application area, see Deltares (2015a). The model-uncertainties are derived for both wave height and wave period, and defined as a normal distribution $\varepsilon = N(\mu,\sigma)$ fitted to samples of the relative error $\hat{\varepsilon}$:

$$\hat{\varepsilon} = \frac{\text{model}-\text{obs}}{\text{obs}} \qquad (1.2)$$

The resulting model-uncertainties (μ and σ in $\varepsilon = N(\mu,\sigma)$) are summarised in the table below:

Hoofdsysteem	H_{m0}		$T_{m-1,0}$		T_p	
	μ	σ	μ	σ	μ	σ
I. Coastal region, IJsselmeer	-0,01	0,19	-0,04	0,11	-	-
II. Broad part of the river region	-0,06	0,15	-0,11	0,04	-0,01	0,07
III. Narrow part of the river region. Eemvallei	-0,04	0,27	-	-	+0,03	0,13
IV. Markermeer - IJburg	-0.05	0.11	+0.04	0.08	-0.04	0.05
V. Markermeer – other (excl. IJburg, Eemvallei)	-0.02	0.20	-	-	+0.16	0.11

Table 1.1 Model-uncertainties wave height and wave period as presented Deltares (2015a)

The implementation of the model-uncertainties for wave conditions assumed (for various reasons amongst which restrictions in time and planning for implementation) no correlation between the model-uncertainty of the wave height and wave period. The data used to derive the model-uncertainties for the coastal water systems (Deltares, 2013a) showed however that this assumption is not valid: the analysis of the model uncertainties showed a correlation between $\varepsilon_{H_{m0}}$ and ε_{T_p}.

Recent studies, e.g. Deltares (2017) have shown that neglecting the correlation between the model uncertainty wave height and wave period leads to (i) unexpected and unrealistic wave steepness's and (ii) an underestimation of the wave load for the derivation of crest height and/or revetments.

This memo describes the derivation of the correlation coefficients between model-uncertainty of wave height and wave period. Subsequently, the impact of incorporating this correlation in the hydraulic load models of WBI is investigated.

2 Approach

The derivation of the correlation between the model uncertainties for wave height and wave period is (in its core) quite simple. First we retrieve the original data use these to derive the model-uncertainties. Subsequently we reproduce the found model-uncertainties to ensure we are using the same dataset. Finally, we use standard techniques to derive the Pearson correlation coefficient. This will be done per application area, similar to the derivation of the model-uncertainties themselves.

A Pearson correlation coefficient which is not equal to zero implies some linear relation between the two variables under consideration, which we expect to be the case based on results from Deltares (2017). By modelling stochastic dependence with a correlation coefficient, we assume the relation between the two variables to be linear. Using the Crude Monte Carlo tool as described in Deltares (2017), we subsequently apply the correlation model and compare the results with the present probabilistic model. This analysis addresses the required crest height.

This year it has become clear that the derivation of the model-uncertainties and the implementation of the model-uncertainties in the probabilistic model of Riskeer (Hydra-Ring) have used different definition with respect to the sign of the bias of the model-uncertainties wave height and wave period. Effectively, $\left(1-\varepsilon_{H_{m0}}\right)$ from equation (1.1) was implemented as $\left(1+\varepsilon_{H_{m0}}\right)$ and similarly for the model-uncertainty of the wave period. In order to be complete, the analysis presented here shows (i) the impact of correcting the (interpretation of the) sign of the bias and (ii) incorporating the correlation (after correcting for the sign of the bias).

3 Derivation of correlation

3.1 Coast, Lake Ijssel

Data source
For the derivation of the correlation between the model-uncertainty of wave height and wave period the original data described in Deltares (2013a) is used. The original data also includes dummy data points (with values -9.99). These data points were erroneously included in the derivation of the correlation coefficient mentioned in Deltares (2013a), leading to a Pearson correlation coefficient of 0.7. For the present study we obviously exclude these values.

Reproduction model-uncertainties
The first step is to reproduce the model-uncertainties for wave height and wave period as presented in Deltares (2013a, 2015a). Using the data as described above, the model uncertainties as presented in Table 3.1 were derived. Comparing these with the model-uncertainties as presented in Deltares (2013a) shows only a minor (round off) difference between the two studies for the standard deviation of the wave period. This is considered acceptable.

	Deltares (2013a)		Present study	
	μ	σ	μ	σ
Wave height (H_{m0})	-0.01	0.19	-0.01	0.19
Wave period ($T_{m-1,0}$)	-0.04	0.11	-0.04	0.10

Table 3.1 Reproduction model-uncertainties for coast and Lake IJssel

Direct correlation
Using standard analysis tools, the Pearson correlation coefficient between $\varepsilon_{H_{m0}}$ and ε_{T_p} is derived and found to be 0.37 [-]. As mentioned before, this deviates from the value stated in Deltares (2013a), because dummy values were erroneously taken into account in Deltares (2013a).

3.2 Wide river stretches

Data source
For the derivation of the correlation between model-uncertainties for wave height and wave period we use the data as used in Deltares (2014), which is an extension of the dataset used in Deltares (2013b).

Reproduction model-uncertainties
As for the coast and Lake IJssel, the first step is the reproduction of the model-uncertainties as reported in Deltares (2014). Using the data as described above, the model uncertainties as presented in Table 3.2 were derived. Comparing these with the model-uncertainties as presented in Deltares (2013a) or Table 1.1 shows a large difference for the mean of the model-uncertainty wave height: this is caused by the fact that in Deltares (2014) the mean was corrected with +8% to account for the ‘opklotsfout” (in English: error due to wave run-up against the instrument). This correction only changes the bias of the model uncertainty, but one may expect that the “opklotsfout” also influences the standard deviation (the “opklotsfout” may be proportional to the wave conditions). It is recommended to verify whether the

"opklotsfout" should also affect the standard deviation, as would be the case if the "opklotsfout" were proportional to the wave height.

For the remainder of the values only a minor (round off) difference between the two studies for the standard deviation of the wave period was found. This is considered acceptable.

	Deltares (2014)		Present study	
	μ	σ	μ	σ
Wave height (H_{m0})	-0.14*	0.15	-0.14	0.15
Wave period ($T_{m-1,0}$)	-0.11	0.04	-0.11	0.05

Table 3.2 Reproduction model-uncertainties for wide rivers

* *This is prior to the in RWS (2015) applied correction for "opklotsfout"*

Direct correlation

Using standard analysis tools, the Pearson correlation coefficient between $\varepsilon_{H_{m0}}$ and ε_{T_p} is derived and found to be 0.39 [-].

3.3 Narrow river stretches

Data source

The derivation of the correlation coefficient will be based on the data as presented in Appendix A of RWS (2015). This data set is however incomplete: the measured wave periods for the last 7 records are lacking. For the present study we neglect these 7 records. Furthermore, the model-uncertainties derived from the source data are modified/adjusted to incorporate additional aspects, see RWS (2015), so comparison should be made to intermediate model-uncertainties which are purely based on a comparison of model versus measurement (Table 4.1 and table 5.2 of RWS (2015).

Reproduction model-uncertainties

As for the coast and Lake IJssel, the first step is the reproduction of the model-uncertainties as reported in RWS (2015). Using the data as described above, the model uncertainties as presented in Table 3.3 were derived. Note that we only reproduce the bias and standard deviation as reported in table 4.1 and table 5.2 from RWS (2015), which are not the final model-uncertainties as presented in Deltares (2015a). We limit ourselves to this reproduction because this study focusses on the derivation of the correlation and not the reproduction of the model-uncertainties themselves. We observe differences between the present study and table 4.1 and 5.2 from RWS (2015). The differences with respect to model-uncertainty of the wave height can be attributed to the fact that the present study neglects the last 7 records (since we need both wave height and period for the correlation analysis), whilst RWS (2015) has included these records for the derivation of the model-uncertainty for wave height. The differences for model-uncertainty wave period (+0.03 versus +0.06 for the bias) could not be explained.

	Deltares (2014)		Present study	
	μ	σ	μ	σ
Wave height (H_{m0})	-0.09*	0.14**	+0.01	0.12
Wave period (T_p)	+0.03	0.11***	+0.06	0.11

Table 3.3 Reproduction model-uncertainties for narrow rivers

* *This is prior to the in RWS (2015) applied correction for "opklotsfout"*

** *The validation part only; in RWS (2015) various corrections/additions are applied afterward*

*** *The validation part only (for Tp¬; in RWS (2015) various corrections/additions are applied afterward*

Direct correlation
Using standard analysis tools, the Pearson correlation coefficient between $\varepsilon_{H_{m0}}$ and ε_{T_p} is derived and found to be 0.53 [-].

3.4 Lake Marken (IJburg)

Data source
For the area Lake Marken (IJburg) , the data used in Deltares (2015b) is used as source. Note that this concerns the dataset of 26 samples (which are considered representative for IJburg) used for the derivation of model-uncertainties for IJburg, not the translation towards the remainder of Lake Marken.

Reproduction model-uncertainties
Table 3.4 shows the reproduction of the model-uncertainties wave height and wave period for Lake Marken (IJburg). The model-uncertainties reported in Deltares (2015b) are reproduced up to two decimals accurate. Note that Deltares (2015a) presented a value of 0.11 for the standard deviation for the model uncertainty of the wave height, contrary to the value of 0.10 mentioned in Deltares (2015b).

	Deltares (2015b), table 2.2		Present study	
	μ	σ	μ	σ
Wave height (H_{m0})	-0.05	0.10	-0.05	0.10
Wave period (T_p)	-0.04	0.05	-0.04	0.05

Table 3.4 Reproduction model-uncertainties for Lake Marken (IJburg)

Direct correlation
Using standard analysis techniques, a Pearson correlation coefficient between $\varepsilon_{H_{m0}}$ and ε_{T_p} of 0.34 [-] was found.

3.5 Lake Marken (remainder)

Data source
The wave model used for the remainder of Lake Marken is the second generation spectral wave model HISWA. This model has become obsolete, but its results are still used in the derivation of the hydraulic boundary conditions. The model-uncertainties for HISWA are derived in Deltares (2015b) by means of (i) comparing HISWA with measurements and (ii) using uncertainty propagation from measurements to SWAN and subsequently from SWAN to HISWA. For this study we use the data used in tranche (ii).

Reproduction model-uncertainties
The reproduction of the results of Deltares (2015b) for the remainder of Lake Marken has not been attempted, because the approach followed in Deltares (2015b) does not allow for the derivation of the correlation between $\varepsilon_{H_{m0}}$ and ε_{T_p}. Instead we followed a different approach and compared the results of this different approach with the results from Deltares (2015b), tranche (ii). A direct comparison of HISWA with measurements, as done in tranche (i) from Deltares (2015b), can not be used for the derivation of a correlation coefficients, as there are no simultaneous samples of the errors in wave height and wave period.

Starting point for the analysis is the comparison between SWAN and measurements as used for IJburg. In order to use this data for the remainder of Lake Marken, we need to translate the SWAN results to HISWA (without running HISWA itself). We achieve this by constructing a (linear) relation between SWAN and HISWA results, including a normally distributed error term. This relation is based on the data presented in figures B.2.5 and B.2.6 of Deltares (2015b), which show a comparison of SWAN and HISWA for identical situations.

$$\begin{aligned} H_{m0,HISWA} &= a_{H_{m0}} + b \cdot H_{m0,\mathrm{SWAN}} + \varepsilon_{H_{mo},HISWA} \\ T_{p,HISWA} &= a_{T_p} + b \cdot T_{p,\mathrm{SWAN}} + \varepsilon_{T_p,HISWA} \end{aligned} \tag{3.1}$$

The values for coefficients a and b are obtained via linear regression. Subsequently the error term of this linear regression model (ε) is derived by deriving the deviation of the individual samples from the linear regression relation. Subsequently, for each of the data points the difference between the linear regression and the actual data point is used to obtain $\hat{\varepsilon}$. Since simultaneous wave height and wave period measurements are available, the correlation between $\hat{\varepsilon}_{H_{m0}}$ and $\hat{\varepsilon}_{T_p}$ is also determined. Finally a normal distribution is fitted to this error (including the correlation between $\varepsilon_{H_{m0},HISWA}$ and $\varepsilon_{T_p,HISWA}$). The relations presented in equation (3.1) are used to translate the 26 data points (SWAN versus measurement) to N*26 data points for the comparison HISWA versus measurements using N random (but correlated) samples for $\varepsilon_{H_{m0},HISWA}$ and $\varepsilon_{T_p,HISWA}$). This procedure is graphically presented in Figure 3.1. The resulting data points are used to derive the model-uncertainties as shown in Table 3.5.

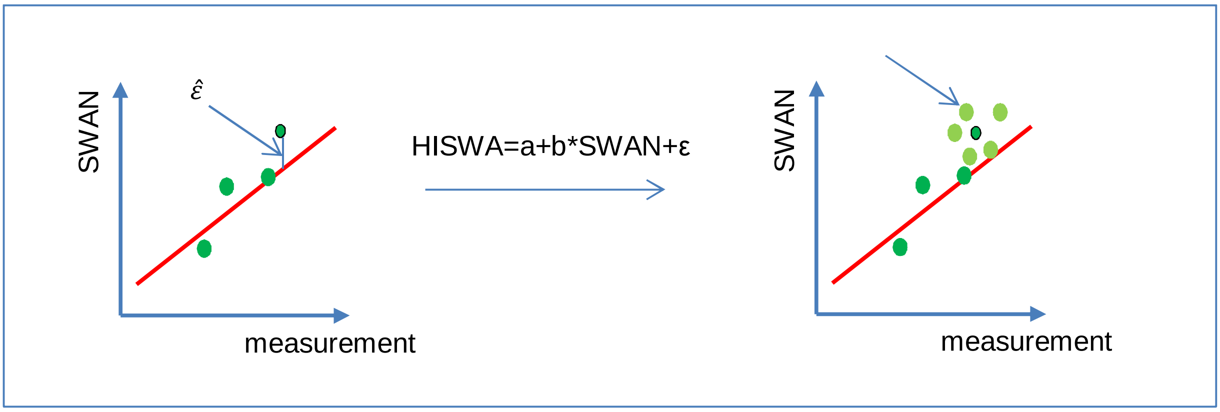


Figure 3.1 Translation of SWAN to HISWA model results

The difference between model-uncertainty between Deltares (2015b) and the present study for wave height is considerable. The difference is the result of the followed approach: in Deltares (2015b) first the relative errors of SWAN vs measurement and HISWA versus SWAN are derived, which are subsequently combined via a Monte Carlo analysis. The present study does something similar but includes a linear regression model with error term for the relation between SWAN and HISWA results. In the present approach we assume no correlation between the individual steps (SWAN-HISWA and measurement-SWAN), which can overestimate the standard deviation and underestimate the correlation. As we are interested in obtaining the correlation between $\varepsilon_{H_{m0}}$ and ε_{T_p} (recalculation of the model-uncertainties is outside the scope of this project), we recommend to use the correlation associated with the uncertainties for the present study. It is recommended to further analyse the differences between the two approaches and try to obtain more data to substantiate the findings. The present data is insufficient to refine the present analysis: more data is needed.

	Deltares (2015b), table 2.4		Present study	
	μ	σ	μ	σ
Wave height (H_{m0})	-0.16	0.16	-0.27	0.27
Wave period (T_p)	+0.11	0.08	+0.12	0.06

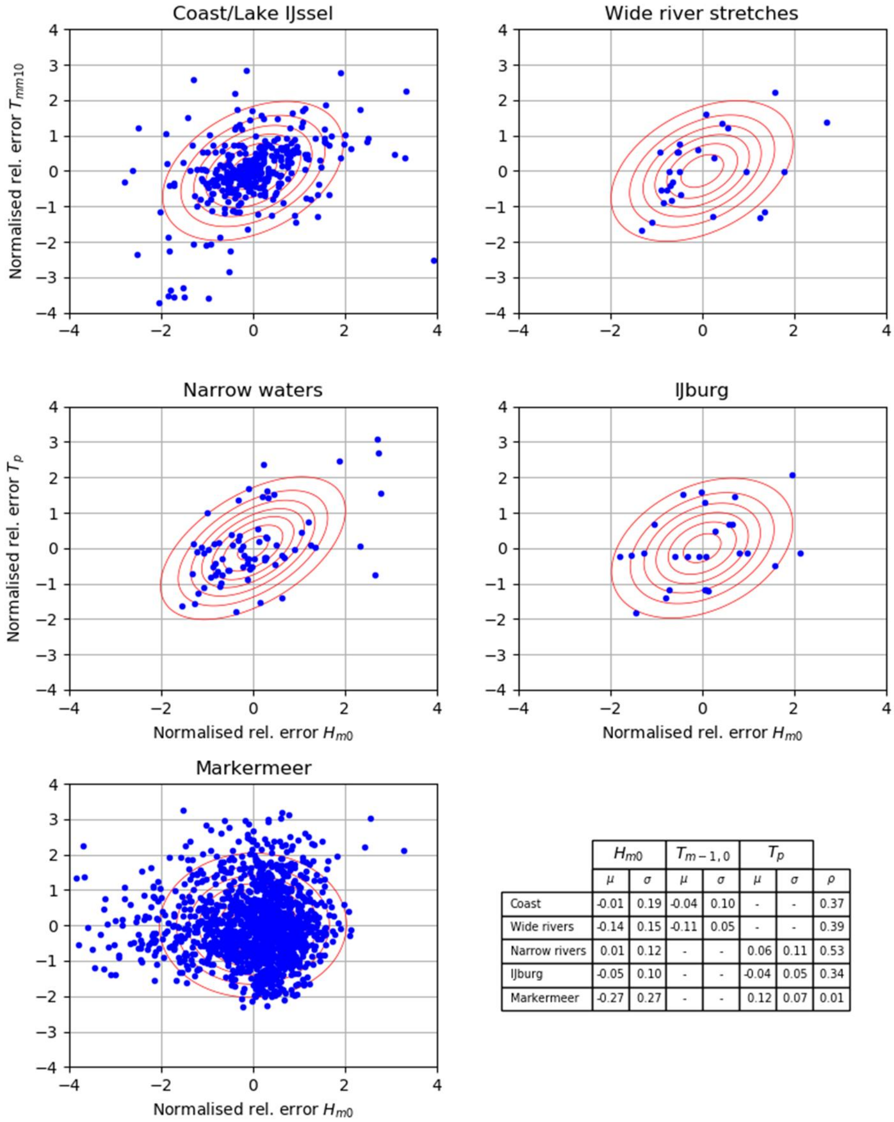
Table 3.5 Reproduction model-uncertainties for Lake Marken (remainder)

Direct correlation

Using standard analysis techniques, a Pearson correlation coefficient between $\varepsilon_{H_{m0}}$ and ε_{T_p} of 0.01 [-] was found. This correlation is so small that the impact will be negligible: impact of this correlation is not investigated further (small correlation means that the present assumption of no correlation is a good approximation).

3.6 Summary

For all water systems (except for the wave period of the narrow river stretches) it was possible to retrieve and reproduce the model-uncertainties for wave height and wave period (all prior to manual changes of the model-uncertainties). After this reproduction, the correlation (Pearson correlation coefficient) between the two model-uncertainties was derived. The resulting correlations are summarised in Figure 3.2. In addition, Figure 3.2 also shows normalised (using the fitted bias and standard deviation) model-uncertainties in combination with isolines for the multi-variate standard normal distribution, using the derived correlation coefficients. The points presented in Figure 3.2 do not justify a choice for a different correlation model. Hence, we use the derived correlation for the remainder of this study.



	H_{m0}		$T_{m-1,0}$		T_p		
	μ	σ	μ	σ	μ	σ	ρ
Coast	-0.01	0.19	-0.04	0.10	-	-	0.37
Wide rivers	-0.14	0.15	-0.11	0.05	-	-	0.39
Narrow rivers	0.01	0.12	-	-	0.06	0.11	0.53
IJburg	-0.05	0.10	-	-	-0.04	0.05	0.34
Markermeer	-0.27	0.27	-	-	0.12	0.07	0.01

Figure 3.2 Plots of the observed model-uncertainties wave height versus wave period (normalised to a standard normal distribution) and isolines of the multi-variate standard normal distribution associated with the found correlation.

4 Impact of correlation

4.1 Approach

The impact of correlation between the model-uncertainty wave height and wave period has been investigated using the Crude Monte Carlo tool described in Deltares (2017). In essence, we use additional Riskeer (Hydra-Ring) output (samples of the hydraulic load variables) to perform a Monte Carlo analysis. The samples for the model-uncertainty wave period are adjusted to account for the correlation with the model-uncertainty wave height.

This year it has become clear that the derivation of the model-uncertainties and the implementation of the model-uncertainties in the probabilistic model of Riskeer (Hydra-Ring) have used different definition with respect to the sign of the bias. In order to be complete, the analysis presented here shows (i) the impact of correcting the sign of the bias and (ii) incorporating the correlation (after correcting for the sign of the bias).

There are two important aspects to be mentioned for interpretation of the results:

1. The analysis uses a deterministic calculation of the required Hydraulic Load Height (in Dutch ‘Hydraulisch Belasting Niveau’ and abbreviated in this study as HBN). This means that the critical overtopping discharge and associated coefficients are treated as a deterministic variable, only in the load calculation. As a result, the results presented in this chapter cannot be compared directly with Riskeer results, as Riskeer uses 5 stochastic variables for the HBN calculation.
2. The analysis assumes that the model-uncertainties have a time-scale equal to the smallest time scale in the probabilistic model (which is 12 hours), whilst its original definition is ‘constant in time”. The present implementation of the tool does not yet have the option to consider stochastic variables that are constant in time, the largest time scale possible is equal to the largest time scale of the main stochastic variable (e.g. river discharge). For a number of calculations (along the narrow rivers and Lake IJssel) presented in this chapter we have investigated the impact of using the largest time scale instead of the smallest time scale for the model-uncertainties. This had no significant impact on the results, which is according to the findings in Deltares (2017). The results presented here are thus with a time-scale of 12 hours for model-uncertainties. We expect that conclusions of this study are independent of this choice of time-scale, but recommend to verify this as soon as it is possible to incorporate the correlation between model-uncertainties into Riskeer.

4.2 Coast, Lake IJssel

Figure 4.1 shows the resulting HBN for a location along the Wadden Sea (location 900052, nearby Oosterbierum). The black line in the left hand plot shows the exceedance curve of the original Monte Carlo analysis (no changes to model-uncertainties). The blue line shows the exceedance curve after correction of the bias definition (which in this case means a 2% increase of the bias of the model-uncertainty wave height and an 8% increase of the bias of the model-uncertainty wave period). Effectively this leads to an increased HBN of 0.3 to 0.4 metres for exceedance probabilities of 10^{-3} to 10^{-4} per year.

Figure 4.1 (left hand plot) also shows the exceedance curve of the HBN after subsequently adding the correlation between the model-un certainty wave height and wave period. The right hand plot shows that the impact of the correlation is in the order of 0.1 to 0.2 metres on top of the impact of the correction of the bias definition. The increase HBN due to the addition of the correlation is relatively small, which is caused by the fact that the correlation coefficient is small as well (ρ = 0.37).

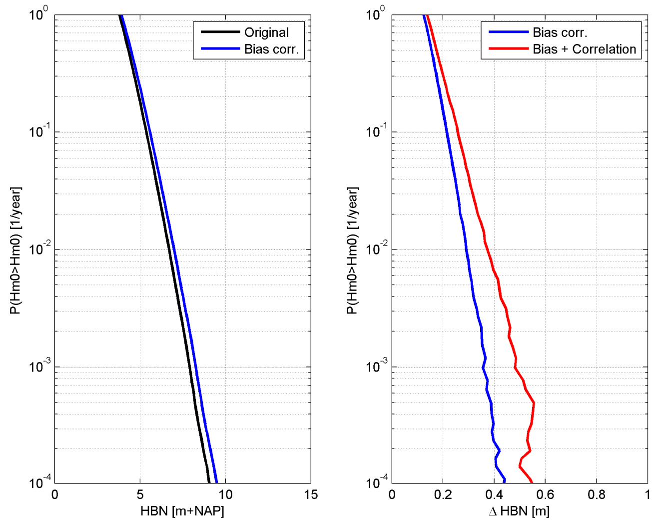


Figure 4.1 Location 900025. Left: exceedance curve of Hydraulic Load Height (HBN). Right difference in computed Hydraulic Load Height (blue= corrected bias minus original, red= corrected bias+ correlation minus original)

One of the reasons for incorporating the correlation between $\varepsilon_{H_{m0}}$ and ε_{T_p} is to obtain more realistic wave steepness values in the probabilistic calculations. Figure 4.2 shows the exceedance curve of wave steepness based on 100 samples around the 10^{-4} HBN-level. As expected, the probability of obtaining large wave steepness in the probabilistic calculation has decreased.

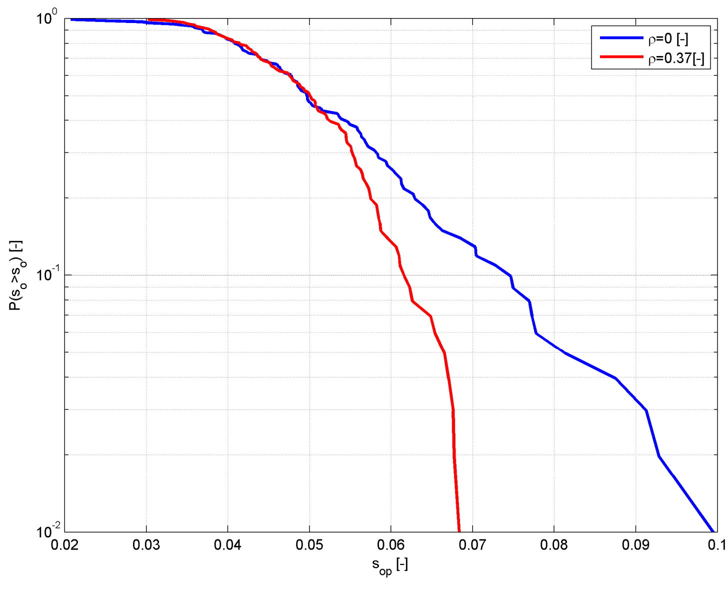


Figure 4.2 Location 900025. Exceedance curve of wave steepness in design point for the 10^{-4} HBN-level. Blue: without correlation, red: with ρ = 0.37.

A similar analysis is performed for a location in Lake IJssel (location 700056, near Urk). Figure 4.3 shows the resulting exceedance curves for HBN and a difference plot. The impact of both the change in bias as well as the addition of correlation is similar to the impact observed for the Wadden Sea. This is due to the fact that (i) the wave conditions are similar and (ii) the model-uncertainties for wave conditions (including correlation) are similar for this location.

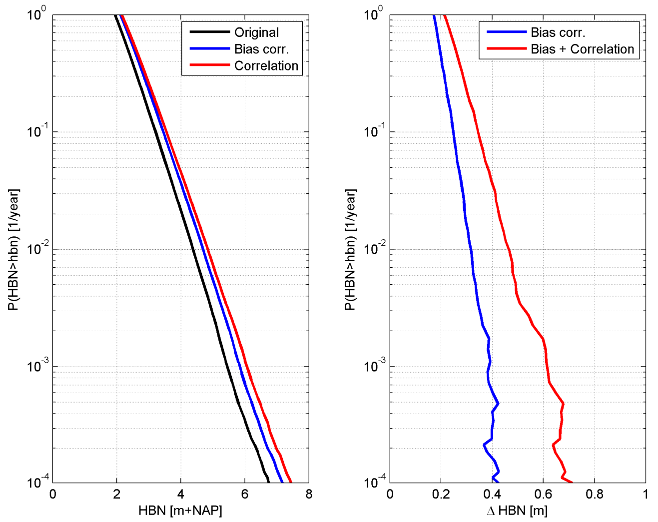


Figure 4.3 Location 700056. Left: exceedance curve of Hydraulic Load Height (HBN). Right difference in computed Hydraulic Load Height (blue= corrected bias minus original, red= corrected bias+ correlation minus original)

As for the coast, the impact of the correlation on the wave steepness has also been investigated. Figure 4.4 shows the exceedance curve of the wave steepness following from 100 samples around the 10^{-4} design point for HBN. The figure shows a reduction of the wave steepness by introducing the correlation. The impact of the correlation between $\varepsilon_{H_{m0}}$ and ε_{T_p} is less compared to the coast because model-uncertainties contribute less to the design point.

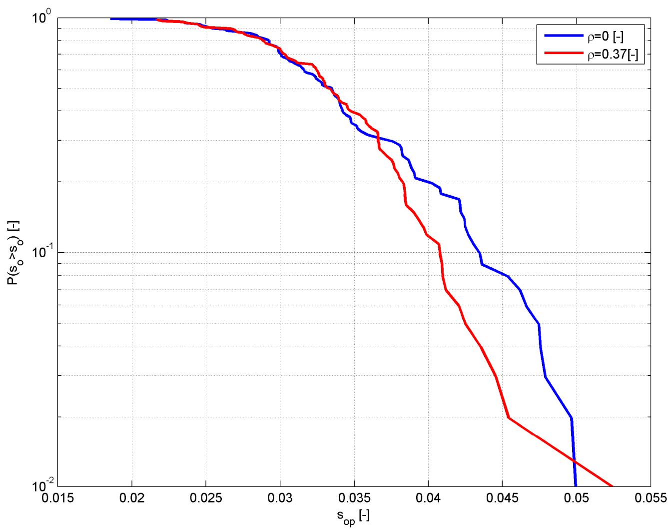


Figure 4.4 Location 700056. Exceedance curve of wave steepness in design point for the 10^{-4} HBN-level. Blue: without correlation, red: with ρ = 0.37.

4.3 Wide river stretches

The crude Monte Carlo model used to assess the impact of the correlation is not available for the wide river stretches. Conclusions regarding the impact of the correlation between the model-uncertainties wave height and wave period can therefore not be drawn.

4.4 Narrow river stretches

Similar to the coast and Lake IJssel, the impact of the correlation (and bias correction) have been analysed for the narrow river stretches. For this study we investigated location 106801 (near Wamel). Wave conditions in the narrow river stretches are mild compared to the other water systems and the impact of both the bias correction and addition of the correlation between model-uncertainty wave height and wave period is expected to be limited. Figure 4.5 confirms this: the impact of the correction of the bias on the HBN is close to zero. The impact of adding the correlation is somewhat bigger but still limited to a maximum of 0.05-0.1 metres. As this is a location oriented towards the west with large fetch lengths, we consider this location to give the highest impacts. Other locations in the upper river area are expected to give a smaller impact of adding the correlation. An exception may be the Grebbedijk along the Nederrijn, because of the added contribution of wind to the HBN (due to “Lek ontzien”).

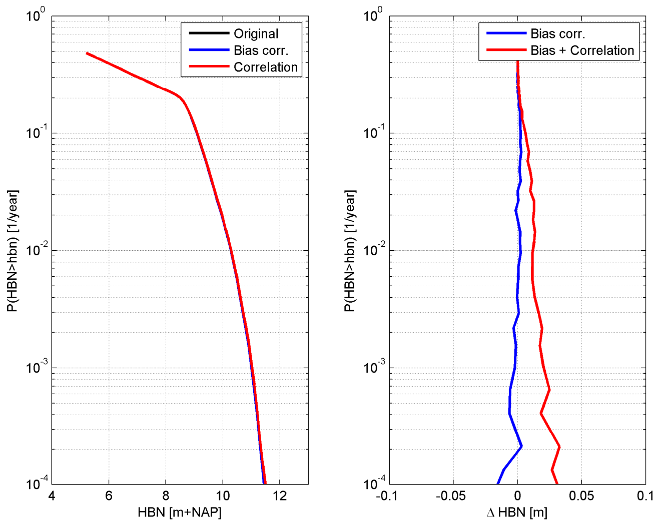


Figure 4.5 Location 106801. Left: exceedance curve of Hydraulic Load Height (HBN). Right difference in computed Hydraulic Load Height (blue= corrected bias minus original, red= corrected bias+ correlation minus original)

Analysis of the wave steepness in the 10^{-4} design point for HBN, see Figure 4.6, shows that adding correlation has a large impact on the wave steepness (although wave conditions do not contribute significantly to the HBN). The correlation of ρ = 0.53 reduces the wave steepness significantly from 0.12 to 0.9 for 10^{-2} exceedance at the design point.

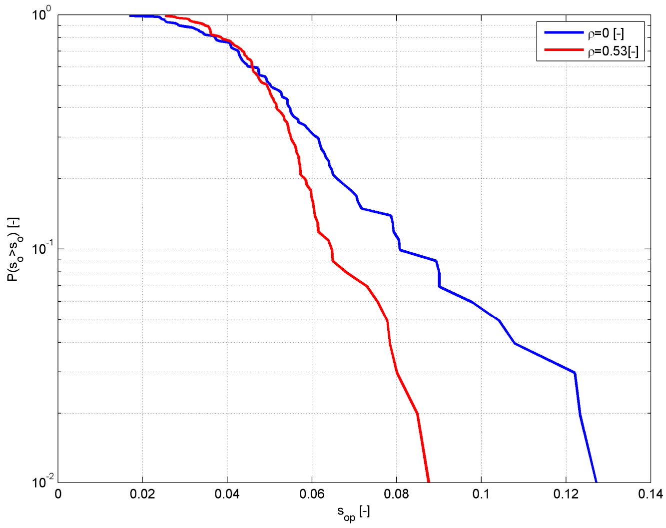


Figure 4.6 Location 106801. Exceedance curve of wave steepness in design point for the 10^{-4} HBN-level. Blue: without correlation, red: with ρ = 0.53.

4.5 Lake Marken (IJburg)

The impact of correlation between $\varepsilon_{H_{m0}}$ and ε_{T_p} has been investigated for location 800020 at IJburg, see Figure 4.7. The analysis first of all shows a large impact (reduction) of the correction of the sign of the bias, which is to be expected due to the magnitude and sign of the bias for both model-uncertainties (wave height and wave period). Adding correlation with ρ = 0.34 subsequently increases the HBN slightly, but nog significant. Analysis of the wave steepness in the 10^{-4} design point for HBN shows a small reduction in the wave steepness, see Figure 4.8.

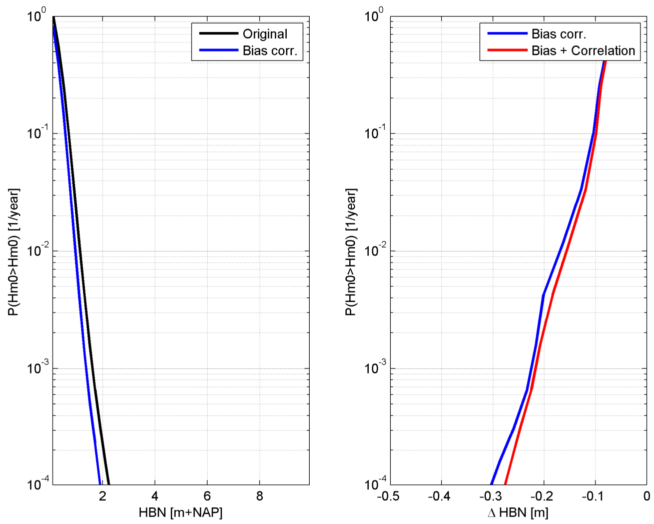


Figure 4.7 Location 800020. Left: exceedance curve of Hydraulic Load Height (HBN). Right difference in computed Hydraulic Load Height (blue= corrected bias minus original, red= corrected bias+ correlation minus original)

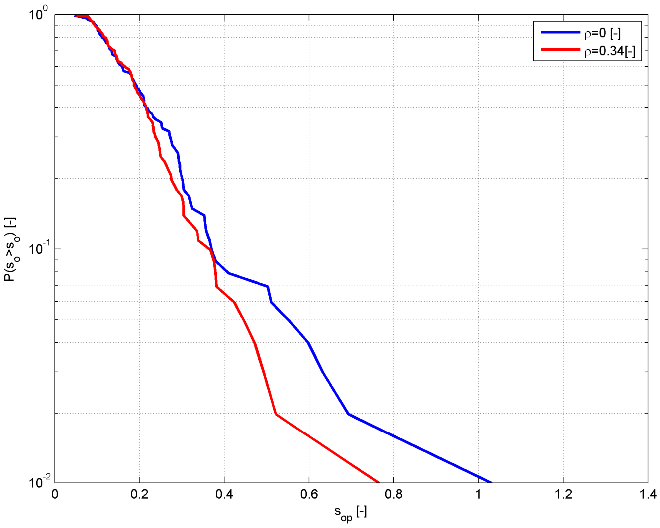


Figure 4.8 Location 800020. Exceedance curve of wave steepness in design point for the 10^{-4} HBN-level. Blue: without correlation, red: with ρ = 0.34.

5 Conclusions and recommendations

The study started with the reproduction of model-uncertainties derived in the period 2013 to 2015. This reproduction was successful for all model-uncertainties except the wave period of the narrow river stretches and Lake Marken. The data used for this reproduction was the bases for the derivation of the correlation between $\varepsilon_{H_{m0}}$ and ε_{T_p}.

An exception was necessary for the uncertainties of Lake Marken (remainder), because the data and procedure followed in Deltares (2015b) did not allow for the derivation of the correlation between $\varepsilon_{H_{m0}}$ and ε_{T_p}. Following an alternative approach led to significantly different model-uncertainties for wave height for this system. Due to the found difference in model uncertainties (as well as the limited correlation found), the remainder of Lake Marken is excluded from the impact analysis. It is recommended to further analyse the differences for Lake Marken (remainder) and try to obtain more data to substantiate the model uncertainties for HISWA.

The computed correlations between $\varepsilon_{H_{m0}}$ and ε_{T_p} were 0.34 and 0.57 [-] except for Lake Marken (remainder), which was negligible (0.01 [-]), see Figure 3.2. The found correlations seem reasonable, as wave physics would prevent either fully or not correlated model-uncertainties.

The impact of adding correlation on the HBN was relatively limited (especially compared to the impact of the bias correction): in the order of 0.1 to 0.2 metres for coast/lakes and even less for narrow river stretches. As expected, the inclusion of correlation leads to less high (more realistic) wave steepness in the design points of the probabilistic calculation. Note that these findings are based on an analysis that uses a slightly different definition of the time scale of the model uncertainties. It is recommended to verify the findings using Riskeer (which than uses the correct definition of the time scale of model uncertainties).

Given the relatively small impact of the correlation (especially compared to the bias correction) we recommend to find a suitable moment (e.g. in combination with other improvements) to incorporate the correlation into the load model.

Two additional recommendations are made: (i) further investigate/make consistent the definition of the model uncertainties en (ii) further investigate the definition and application of the “opklotsfout” because these may have an impact on the hydraulic loads that is broadly similar to the impact of adding correlation. It is recommended to asses these aspects in the context of the entire uncertainty modelling.

6 References

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