The effect of hydraulic roughness on design water levels in river models

J.J. Warmink
Department of Water Engineering and Management, University of Twente, The Netherlands

M.W. Straatsma
Faculty of Geo-information Science and Earth Observation, University of Twente, The Netherlands

F. Huthoff
Department of Geology, Southern Illinois University, Carbondale, USA
HKV Consultants, Lelystad, The Netherlands

ABSTRACT: Accurate estimates of design water levels are essential, because they determine the required dimensions of the flood defences. Hydrodynamic models are used for the prediction of flood water levels to support flood safety and are often applied in a deterministic way. However, the modelling of river processes involves numerous uncertainties. Literature has shown that the hydraulic roughness is one of the main sources of uncertainty in hydrodynamic computations. Knowledge of the type and magnitude of uncertainties is crucial for a meaningful interpretation of the model outcomes and their usefulness in decision making. We show that the uncertainty of a complex model factor, such as the hydraulic roughness, can be quantified explicitly. The hydraulic roughness has been unravelled in separate components, which have been quantified separately and then combined and propagated through the model. Expert opinions revealed that the uncertainty due to bed form roughness in the main channel and vegetation roughness in the floodplains were shown to be the major contributors. Quantification of these sources and propagation through the WAQUA model using Monte Carlo analyses showed that this resulted in a 95% confidence interval around the Design Water Levels (DWL) of 68 cm for the river Waal. This uncertainty range consisted of the uncertainty due to bed forms with an uncertainty of 49 cm on the DWL, and an uncertainty of 34 cm due to vegetation roughness uncertainty. The main source of uncertainty was shown to be the variability of the roughness values depending on the various possible roughness models.

1 INTRODUCTION

Hydrodynamic river models are applied to design and evaluate measures for purposes such as safety against flooding. These numerical models are all based on a deterministic approach. However, the modelling of river processes involves numerous uncertainties, resulting in uncertain model outcomes. Knowledge of the type and magnitude of uncertainties is crucial for a meaningful interpretation of the model results and the usefulness of results in decision making processes.

The Dutch flood defences along the river Rhine are designed to withstand a flood with a return period of 1250 years. This value is laid down in the 1995 flood protection act (Ministry of Transportation and Management 1995). The water levels that occur during such a flood are computed using the two-dimensional hydrodynamic model, WAQUA, using a design discharge as input. However, uncertainty resides in all parts of this model. To quantify the uncertainty in the design water levels (DWL) we want to estimate the uncertainties in these parts of the model that have the largest contribution to the uncertainty in the DWL.

In this paper we did not focus on the uncertainty of the design discharge being often the largest source of uncertainty (Pappenberger et al., 2006), because the choice of a return period of 1250 years is effectively a way of being precautionary relative to the uncertainty inherent in the extrapolation of the discharge frequency to low exceedance probabilities, whereas uncertainty in the roughness has a real effect in converting that discharge into water levels (Warmink et al. acc). The uncertainty in the design discharge and its effect on the DWL have been studied extensively e.g. by (Silva et al., 2001; Van der Klis 2003; Van Gelder 2008).

Quantification of the uncertainty in the model outcomes is carried out by means of an uncertainty analysis (Morgan and Henrion 1990; Refsgaard et al., 2007). An uncertainty analysis consists of five steps (Van der Sluijs et al., 2005): identification, importance assessment, quantification of the
sources of uncertainty, propagation to the model outcomes and the communication of uncertainty (see Figure 1).

Most uncertainty analysis studies about river models only consider uncertainties in input and parameters, thereby omitting the uncertainties in model structure and model context. Uncertainties in model input and parameters are often easier to quantify, because for model structure and context the model itself and its underlying assumptions should be varied, which is more difficult than varying the input or parameters. Omitting the uncertainties in model structure and context might result in a significant underestimation of the uncertainty in the model outcomes. In the computation of water levels for design conditions, the problem is that these circumstances rarely or never occurred. Therefore, the magnitude of the sources of uncertainty cannot be determined by measurements only, because no or very limited measurements are available. For these reasons the uncertainty in the hydraulic roughness under design conditions might by large and the reconstruction of past large floods may reveal the limits of the model. The uncertainty in the hydraulic roughness results in uncertainties in uncertainties in the DWL, are important for a robust flood safety assessment. Therefore, the aim of this study is to quantify the uncertainties in the hydraulic roughness that contribute most to the uncertainty in the design water levels and quantify their contribution to the design water levels for the 2D hydrodynamic model for the river Waal in the Netherlands.

### 2 STUDY AREA

The river Waal is the largest distributaries of the river Rhine in the Netherlands (Figure 2). At the Dutch-German Border, the river Rhine has an average discharge of 2250 m$^3$/s. In the Netherlands, the river Rhine bifurcates into the Pannerdensch Kanaal and the river Waal. The width of the main

---

**Figure 1.** The five steps in an uncertainty analysis.

**Figure 2.** Study area, (a,b) the location of the river Waal in The Netherlands, (c) WAQUA model for the river Waal. The numbers refer to the river kilometres.
channel of the river Waal between the groynes is 280 m on average (Warmink et al. acc). The cross-sectional width between the embankments varies between 0.5 and 2.6 km (Straatsma and Huthoff 2011). The land cover of the floodplains is dominated by meadows, but recent nature rehabilitation has led to increased areas with herbaceous vegetation, shrubs and forest (Straatsma and Huthoff 2011).

We used the two-dimensional hydrodynamic model, W AQUA, for the river Waal. This model used a staggered curvilinear grid with 148,334 grid cells with a cell size of approximately 40 × 40 m. The water flow was computed by solving the two-dimensional shallow water equations using a finite difference scheme. The W AQUA-Waal model uses empirical roughness equations to approximate energy losses. Figure 2c shows the W AQUA model for the river Waal.

3 UNCERTAINTY

Uncertainty is defined by Walker et al. (2003) as being any departure from the unachievable ideal of complete determinism. They presented a classification matrix based on the classifications by Janssen et al. (1990) and Van Asselt and Rotmans (2002). The classification of Walker et al. (2003) distinguishes between the nature of uncertainty, the location of the uncertainty in the model and the degree of uncertainty.

Two natures of uncertainty can be distinguished: variability (inherent uncertainty) and limited knowledge (epistemic uncertainty). Variability represents the randomness of variations in nature and limited knowledge is a property of the state of knowledge in general or of the modeller. The second dimension is the location where the uncertainties manifest themselves within the model, its context or the input and parameters of the model, which are actually parts of the model itself. The third feature is the degree of uncertainty, which deals with the different levels of knowledge, ranging from complete deterministic understanding up to total indeterminacy (in case we do not know what we do not know). Table 1 shows the classification matrix based on (Walker et al. 2003).

4 IDENTIFICATION AND RANKING OF UNCERTAINTIES

Identification is the first step of an uncertainty analysis. The reliability of the results of an uncertainty analysis strongly depends on the included
uncertainties. An unreliable identification may lead to an unbalanced comparison of the different uncertainties. Therefore, there is a need for a list of unique and complementary uncertainties. Often only uncertainties in model input and parameters are considered, but uncertainties are also present in the context and structure of a model. It is important to be aware of these sources of uncertainty and consider them in uncertainty analysis studies.

Warmink et al. (2010) presented a general method for a structured identification of uncertainties to acquire this list of unique and complementary uncertainties. This method consists of iteratively classifying the sources of uncertainty in the adapted classification matrix of Walker et al. (2003) and in each step more specifically specifying the uncertainties until classification is possible along all three dimensions of uncertainty (see Table 1). It is impossible (and often not feasible) to be complete in the identification of all uncertainties, but by being as accurate and comprehensive as possible, a sound basis is laid for quantification or description of the uncertainties in environmental models for prediction and exploratory purposes.

Expert opinion elicitation was used to identify the uncertainties that contribute most to the uncertainties in the design water levels (DWL) for the river Waal. A Pedigree analysis was used to assure an objective selection of experts (Warmink et al. 2011). Eleven selected experts were asked to list the sources of uncertainty that contributed most to the uncertainty in the design water levels (DWL) for the Dutch river Waal using the method described in Warmink et al. (2010) and state their relative importance.

Table 1 shows the iterative classification for two sources of uncertainty in the W AQUA model for the river Waal: the main channel roughness and the vegetation roughness. These sources were identified following the method described in the previous section. Initial identification led to sources that consisted of multiple classes of uncertainty. These sources were described in more detail until all sources of uncertainty could be uniquely classified. Table 2 shows the sources of uncertainty that were identified by the experts. The experts were asked to express the magnitude of the uncertainty as the effect in cm's on the DWL, which was used to determine their relative importance. The results are presented in Figure 3 (from Warmink et al., 2011), where the circles refer to the individual expert opinions and the plus signs show the average uncertainty for each source.

The aggregated expert opinions showed that the design discharge (that is the discharge that corresponds to a return period of 1250 years) and the empirical roughness model that is used to determine the roughness of the main channel contribute most to the uncertainty in the design water levels. The ranking of the uncertainties from important to less important was strengthened by the combination of qualitative and quantitative information from the expert opinions about the uncertainties (Warmink et al. 2011). The values for the uncertainty in design water levels stated by the experts should not be used directly, but merely as an indication. Other sources of uncertainty that were considered to be important by the experts are the uncertainty due to the vegetation classification error (source 3), the weir formulation that is the energy losses due to acceleration of water flow over weirs (source 4), the calibration data (source 5) and the uncertainty due to the
vegetation roughness model (source 7), see Table 2 and Figure 3.

5 QUANTIFICATION OF UNCERTAINTY

As the next step of the uncertainty analysis, the main sources of uncertainty were quantified, namely the uncertainty due to the bed form roughness model, the vegetation classification error and the vegetation roughness model. As stated previously we did not focus on the uncertainty in the design discharge.

5.1 Bed form roughness model uncertainty

The quantification of the uncertainty due to bed form roughness was carried out by (Warmink et al. acc). They selected five roughness models of (Van Rijn 1984), (Vanoni and Hwang 1967), (Engelund 1977), (Haque and Mahmood 1983) and (Wright and Parker 2004) that predict the bed form roughness based on measurements of bed form and flow characteristics. The measurements from (Wilbers and Ten Brinke 2003) and (Julien et al. 2002) were used, which were measured during three large flood waves. The predicted roughness values for each of the five roughness models were extrapolated to the design return period of 1250 years. Also, the 95% confidence intervals were computed for each model. The variation of the data around the fitted distributions gave a measure for the uncertainty of each roughness model, while the differences between the extrapolated roughness values gave the uncertainty between the roughness models. Figure 4 shows the resulting distribution of the roughness at the design return period, where the colours refer to the different roughness models. The combined 95% confidence interval of the Nikuradse roughness ($k_n$) for the main channel of the river Rhine under design conditions ranges from 0.32 m to 1.03 m and showed a positively skewed distribution, with $k_n = (n/0.04)^{6}$, where $n$ is the Manning roughness coefficient (Van Rijn 2011).

5.2 Vegetation classification error

Straatsma and Huthoff (2011) quantified the uncertainty due to the vegetation classification error. This classification error of the Rhine branches was determined by Knotters et al. (2008) as “map purities”. Table 3 shows a part of the aggregated map purities table that Straatsma and Huthoff (2011) constructed from the field measurements of Knotters et al. (2008). This table shows the percentages of the vegetation types on the total map that were correctly classified. The map purities sum up to one per row. The authors noted that the overall classification accuracy was low, only 69% of the ecotopes were correctly classified. In total 81% of the surface area in the WAQUA model is taken into account. The remaining 19% was assumed deterministic as this consisted of a large number of vegetation types with small coverage. The classification error should be interpreted as a maximum value (Straatsma and Huthoff, 2011), which results in an estimate of the maximum uncertainty range in DWL.

Other sources of uncertainty concerning the vegetation roughness were quantified previously by Straatsma and Huthoff (2011). These uncertainties were related to the mapping scale that is used for discretization of the vegetation types and the vegetation characteristics (e.g. height and density). These uncertainties proved to have little effect on the design water levels. Straatsma and Huthoff (2011) computed the 68% confidence intervals of the mapping scale and the vegetation characteristics to be 5 and 1 cm, respectively.

5.3 Vegetation roughness model uncertainty

Warmink et al. (acc) computed the uncertainty due to the vegetation roughness model. They considered four models of (Klopstra et al. 1997), (Van Velzen et al. 2003), (Huthoff 2007) and (Baptist et al. 2007). All models predict the energy losses above the canopy of the vegetation using a rigid cylinder approach (Petryk and Bosmajian 1975). The four models are equal for non-submerged vegetation. For submerged vegetation, the former three models predict an exponential decrease of the roughness with increased submergence of the vegetation, while the Baptist model effectively yields a constant roughness with water depth.

![Figure 4. Uncertainty in the hydraulic roughness due to bed forms under design conditions. The different colours represent the five bed form roughness models.](image-url)
We computed the effects of the three sources of uncertainty on the DWL using the WAQUA model for the river Waal (see Figure 2c) in a Monte Carlo Simulation setting. The upstream boundary condition was set as the design discharge for the river Waal. The water levels in the downstream part of the river Waal are influenced by the backwater effect due to the fixed downstream boundary condition. The results showed that the downstream 25 km (up to Zaltbommel) are dominated by this effect. Therefore, the uncertainties in this region are underestimated and unreliable and this section is not considered in the sensitivity analysis. The results are presented as the histograms of the water depths at a single location at river kilometre 893 (close to the city of Ewijk, see Figure 2), which is 67 km upstream of the downstream boundary condition.

Four sets of Monte Carlo simulations were carried out with 500 simulations each. One set of 500 simulations was carried out for each of the uncertainty sources: the bed form roughness, vegetation classification error and vegetation roughness model, separately. The fourth set of simulations was carried out with all three sources of uncertainty set variable. For the bed form roughness we used the samples as a uniform and constant roughness value for the main channel, randomly selected in the distribution shown in Figure 4. For the vegetation classification error, the approach by Straatsma and Huthoff (2011) was followed, where the map purities determined the probabilities that an vegetation polygon was classified correctly. For each polygon in the vegetation map, a random number was drawn from a uniform distribution, and based on the ecotope probability assigned a new vegetation code to each of the polygons. Five hundred samples were used for the Monte Carlo Simulation, so 500 realisations of the vegetation map were generated. These maps were recoded to WAQUA roughness codes and used as input for the WAQUA model.

For the vegetation roughness models, we randomly drew one of the selected models and applies it to compute the roughness.

Table 3. Part of the purity matrix for classification of vegetation in the Rhine distributaries, after Straatsma and Huthoff (2011). The rows show the vegetation type on the map and the columns show the field reference data.

<table>
<thead>
<tr>
<th>Description</th>
<th>Groyne field / sand bar</th>
<th>Stone protection</th>
<th>Build-up area / paved</th>
<th>Agricultural area</th>
<th>Production meadow</th>
<th>natural grass / hay land</th>
<th>Dry herbaceous veg.</th>
<th>Reed</th>
<th>Reed-grass</th>
<th>Sedgeweed bush</th>
<th>Willow plantation</th>
<th>Thorny shrubs</th>
<th>Softwood production forest</th>
<th>Hardwood forest</th>
<th>Sedgeweed grass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equivalent grain roughness types</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Groyne field / sand bar</td>
<td>85.7%</td>
<td>80%</td>
<td>91.6%</td>
<td>78.2%</td>
<td>4.9%</td>
<td>21.3%</td>
<td>0.3%</td>
<td>0.2%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stone protection</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Build-up area / paved</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Agricultural area</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Production meadow</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Natural grass / hay land</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Submerged vegetation (grass-type)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pioneer vegetation</td>
<td>53.1%</td>
<td>24.4%</td>
<td>7.6%</td>
<td>15%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Production meadow</td>
<td>0.5%</td>
<td>2.2%</td>
<td>51.7%</td>
<td>32.5%</td>
<td>6.7%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Natural grass / hay land</td>
<td>0.7%</td>
<td>2.5%</td>
<td>2.2%</td>
<td>33.3%</td>
<td>43.1%</td>
<td>7.7%</td>
<td>2.7%</td>
<td>5.5%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Submerged vegetation (herb-type)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dry herb. vegetation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reed-grass</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reed</td>
<td>9.9%</td>
<td>2.3%</td>
<td>4.3%</td>
<td>1.7%</td>
<td>7.6%</td>
<td>22%</td>
<td>52.8%</td>
<td>3.9%</td>
<td>2.2%</td>
<td>58.9%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sedgeweed grass</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

6 PROPAGATION TO WATER LEVELS

We computed the effects of the three sources of uncertainty on the DWL using the WAQUA model for the river Waal (see Figure 2c) in a Monte Carlo Simulation setting. The upstream boundary condition was set as the design discharge for the river Waal. The water levels in the downstream part of the river Waal are influenced by the backwater effect due to the fixed downstream boundary condition. The results showed that the downstream 25 km (up to Zaltbommel) are dominated by this effect. Therefore, the uncertainties in this region are underestimated and unreliable and this section is not considered in the sensitivity analysis. The results are presented as the histograms of the water depths at a single location at river kilometre 893 (close to the city of Ewijk, see Figure 2), which is 67 km upstream of the downstream boundary condition.

Figure 5 shows the distributions of the water depths due to the three sources of uncertainty separately and in combination. Combining the three main contributions to the uncertainty in the DWL resulted in a 95% confidence interval of 68 cm, which is significant in view of Dutch river
management practice. The effect of the individual sources was 49, 34 and 12 cm for the main channel roughness, classification error and vegetation roughness model, respectively.

The water levels due to uncertain main channel roughness show an almost normal distribution around the mean. The histogram of the input samples (Figure 4) shows a positively skewed distribution. Skewness is the third moment of a distribution and is a measure of the asymmetry of the data around the sample mean. The skewness of the roughness samples was 0.68, while the skewness of the water levels, based on these samples was 0.15. This showed that high roughness values for the main channel do not necessarily result in extreme water levels, but are partly compensated by a higher discharge through the floodplain regions.

The uncertainty due to the classification error was spatially distributed and caused positive outliers in the design water levels, due to clustering of rough vegetation types (Warmink et al. acc). These outliers increased the uncertainty, especially if they occur simultaneously with a high bed form roughness. Including the uncertainty due to the choice of the vegetation roughness model resulted in only a small increase of the uncertainty in design water levels.

7 DISCUSSION

In practice the roughness in models is calibrated to fit measured water levels. Besides the absolute value of the modelled water levels also the uncertainty will be influenced (probably reduced) by calibration. However, because calibration is carried out on the highest measured discharge wave, which is only 75% of the design discharge, the extrapolation also introduces uncertainty. The absolute magnitude of the uncertainty is therefore difficult to quantify. We carried out a detailed and rigorous analysis of the uncertainties. Therefore, the order of magnitude of the uncertainty will be representative for the Dutch river Waal. However, it is noted that we did not account for the effect of calibration. Therefore, this estimate should be considered as an order of magnitude. But it is the best estimate that is currently available.

Our detailed uncertainty analysis showed that it is not necessary to quantify all sources of uncertainty, because only the most important sources determine the majority of the uncertainty in the DWL. It is not expected that the final uncertainty range of 68 cm will change significantly if the uncertainties due to the vegetation mapping scale and vegetation characteristics are included. Also the uncertainties due to weir formulation and the calibration data will only slightly increase the final uncertainty range. Depending on the required accuracy of the uncertainty analysis the number of uncertainties to be included in the analysis can determined. This significantly reduces the complexity of the uncertainty analysis. However, it is of main importance to reliably identify and rank the sources of uncertainty. Because omitting a major source of uncertainty may result in significant underestimation of the final uncertainty range.

8 CONCLUSIONS

The objective of this study was to quantify the uncertainties in the design water levels for the Dutch river Waal in the Netherlands. The first four steps of an uncertainty analysis have been carried out from identification of the uncertainties to the quantification of the combined effect of three important sources of uncertainty in hydraulic roughness on the design water levels (DWL). It is concluded that:

- It is possible to explicitly quantify the uncertainties in a complex model factor such as the hydraulic roughness, including uncertainties in the model structure.
- Besides the uncertainty in the design discharge, the bed form roughness and the vegetation classification error contribute the most to the uncertainty in the design water levels. Their effects are in the order of magnitude of 49 cm and 34 cm on the design water levels.
- The combined effect of bed form and vegetation roughness uncertainty on the water levels is 68 cm, which is significant in view of the Dutch river management practice.
- Identification and ranking of the sources of uncertainty in a model is essential for a reliable uncertainty analysis.

The thorough analysis of uncertainties in this study ensured that the reported uncertainty ranges are the best estimates of uncertainty in the DWL, even though we did not account for the effect of calibration. This study shows that the uncertainties in a modelling study can be made explicit and the process of uncertainty analysis helps in raising the awareness about the uncertainties and it enhances the communication about the uncertainties in a model between decision makers and modellers. Furthermore, the results show which measures can be taken to reduce the uncertainties and what benefits in terms of reduced uncertainty in water levels can be accomplished.

ACKNOWLEDGEMENTS

The research reported in this paper was supported by the Technology Foundation STW, applied science division of NWO and the technology program of the Ministry of Economic Affairs. We thank the Dutch
Centre for Water Management for providing the WAQUA model to do the analysis. Furthermore, the authors thank Deltures for the use of their facilities. This research was also supported by the Flood Control 2015 program. For more information please visit http://www.floodcontrol2015.com.

REFERENCES


Gevoeligheidsanalyse en onzekerheidsanalyse: een inventarisatie van ideeën, methoden en technieken. Technical report, Rijksinstituut voor volksgezondheid en milieuhygiëne, Bilthoven. (in Dutch)


Validatie van de ecotopenkaarten van de rijkswateren. Technical report, Alterra, Wageningen, the Netherlands.


164