Impact of river morphology on extreme flood level prediction: a probabilistic approach

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ABSTRACT: The dike rings along the Rhine in the Netherlands have a level of protection of 1/1250 per year. The design water levels are estimated on the basis of one random variable: the river discharge. Van Vuren & Van Breen (2003) show the existence of large spatial and temporal variation in bed level position in the river Waal. In this paper the impact of river morphology on extreme flood level predictions is investigated. Therefore, the method to compute design water levels is extended with another random variable: the river morphology. The results show that the impact of river morphology on design water levels is limited. A random bed level prior to the design water level computations leads to small changes (order of 0.01 - 0.06 m) in design water levels. The impact of seasonal variations in the river morphology and morphological changes during the flood wave can be neglected.

1 INTRODUCTION

The Netherlands is unique in the fact that a large part of it exists solely because of the presence of dikes along the coast and rivers, (TAW, 1998). Flood protection is therefore embedded in many laws, but is summarized in the Flood Protection Legislation. According to this Legislation the Netherlands is divided in 53 dike ring regions of which each has its own level of protection. The dike rings along the Rhine Branches have a level of protection of 1/1250 per year. This means that river dikes are designed for water levels with a yearly exeedance probability of 1/1250 – the design water level (DWL).

So far, the DWLs are estimated on the basis of one random variable: the design discharge. A 1D hydrodynamic model for the Dutch Rhine branches (Van der Veen, 2001) is used to compute the DWLs. A margin is applied to account for among others wave and wind set-up. The DWLs do not only depend on this discharge and the set-up factors. Uncertainties in the DWLs are introduced with among others the schematization of the hydrodynamic model and the specification of the model input (boundary conditions, initial conditions and model parameters). For example, uncertainties in the model calibration (hydraulic roughness modeling) and the geometrical river schematization (morphological state) may affect the computed DWLs. Each uncertainty source will contribute differently to the exeedance probability of the water levels. Accordingly, each uncertainty source will affect differently the computed DWLs.

In this paper we investigate the impact of river morphology in the river Waal on extreme flood level predictions. Therefore, the DWL computation method is extended. The present situation in the Waal without any additional human intervention is considered. The extended method includes the contribution of two random variables in the DWL computation: the river discharge and the river morphology. The method contains different steps. With the help of Monte Carlo simulation with a 1-D morphodynamic model, a large number of possible morphological states are simulated. These morphological states form the basis of a large number of water levels computations: for each simulated morphological state, water levels are computed for a range of steady discharges. Numerical Integration combines the likelihood of the simulated morphological state and the discharge levels to estimate the probability of the computed water levels. The set of outputs resulting from all computations is used to determine per location along the river a curve showing the exeedance probability of water levels. On the basis of this curve the 'new' water level with a probability of occurrence of 1/1250 per year can be derived. This can be compared with the DWL that is derived with the traditional method using only one random variable: DWL_0. Also, this curve can be used to estimate the 'new' exeedance probability of the DWL_0.

Concerning river morphology two aspects are considered:

1 The effect of variation in the morphological state prior to DWL computations.
2 The impact of morphological changes during the flood wave.

2 DESIGN WATER LEVELS AND MORPHOLOGY

2.1 *Design water levels*

In the Netherlands, the dike rings along the Rhine branches have a protection level of 1/1250 per year (Flood Protection Legislation, 1996). Every five years, the DWLs are revised to adapt for changes in the design discharge, in the river morphology, in the discharge distribution at bifurcation points and in the lateral discharges of tributaries.

Flood protection measures are taken on the basis of the revised DWLs. In the past the dikes were strengthened and heightened in order to protect the Netherlands from flooding. Recently, a new flood protection policy, called Room for the Rivers, has been implemented for the Dutch rivers. Measures other than dike strengthening are considered in order to increase the flood conveyance capacity of the river. Examples of such measures are lowering groynes, repositioning river dikes, establishing detention basins, lowering floodplains and removing summer dikes.

The estimation of DWL is embedded with a number of uncertainties, as shown for instance by Kok et al (2003). Apart from statistical uncertainties which are caused by the limited amount of observed river discharges, also model uncertainties (caused by the fact that the actual probability density from which 'nature generates its realisations' is unknown) can lead to uncertainties of the design river discharges of up to 20% (Van Gelder, 2000). The DWL computation method is only stochastic in a certain way: a design discharge with a yearly probability of 1/1250 is applied. The inclusion of more than one random variable in the DWL computation method may result in a change in the DWLs. In this paper the importance of river morphology on flood level prediction is investigated.

Van Vuren & Van Breen (2003) show the existence of large spatial and temporal variation in bed level position in the river Waal. The river's geometrical schematization (morphological state) in the hydrodynamic model used for the DWL computation is derived on the basis of annual bathymetric soundings in the period between April and November – a series of snapshot taken at different points in time. This means that the sampling has a seasonal bias. The geometrical schematization might therefore be an arbitrary choice, as the bed level state in September can be different from the one in February.

Moreover, the riverbed can be very active in the Waal during floods. This leads to a large uncertainty range in the bed level, which affects the predicted height of the flood wave. This important role of morphological changes at high discharge conditions is encountered in many rivers. In the Yellow River, for instance, it is impossible to accurately predict the flood levels without accounting for the morphological changes during the flood (Kemink, 2002).

2.2 *Morphodynamic Sobek Rhine Branches model*

The morphodynamic Rhine branches model (Jesse & Kroekenstoel, 2001), a 1-D Sobek model (WL, 2001), is used to simulate the morphological response and to compute the DWLs. This morphodynamic model solves the 1-D cross-sectionally integrated shallow water equations, distinguishing between the main channel, the flow conveying floodplain and the storage area. In addition the sediment transport rate and the sediment balance equations are used to determine the morphological changes.

In reality many irregularities occurs in the river Waal, such as variations in geometry, in floodplain width, in floodplain vegetation type, in the presence or absence of summer dikes, flood-free areas and storage and conveying parts in the floodplains. Each irregularity acts as a generator for new bottom waves. Irregularities such as variations in river geometry, bottom groynes (Erlecom) and fixed bottom layers (Nijmegen and St. Andries) are included in the Sobek Rhine branches model. The morphological model is calibrated on the basis of bathymetric data in the period between 1987 and 1997. The model predicts for the period between 1997 and 2097 erosion in the upper part (867 km – 915 km) and large-scale sedimentation in the lower part (915km – 963 km) of the Waal. Although some sedimentation is expected because maintenance dredging is not incorporated in the model, the sedimentation cannot be completely explained by the neglect of dredging. The sediment transport is likely underestimated. Therefore, in this study only the upper part of the Waal - Waal section between Pannerdense Kop (km 886) and Tiel (km 915) - is considered next.

2.3 *Design flood wave*

The DWLs are estimated on the basis of the design discharge that has a yearly probability of occurrence of 1/1250. The design discharge is derived is with a statistical analysis on yearly peak discharges out of a range of 100 years of daily discharge measurements at Lobith, where the Rhine enters the Netherlands. This time series is homogenized to compensate for the river regulation works in Germany (canalization works and the placement of weirs). A combination of three probability distributions (a Gumbel distribution, a Pearson-III distribution and a lognormal distribution) is applied to derive the design discharge (Parmet et al, 2002).

The design discharge is revised every five years, recently in 2001. The time series is extended with peak discharges in the period between 1992 and 1998. As a consequence of extreme discharges in 1993 (11039 m^3/s) and 1995 (11885 m^3/s) the design discharge has gone up to 16,000 m^3/s. The relation between the averaged return period T and the river discharge - Q [m^3/s] - at Lobith is described by:

$$
\begin{aligned}
Q &= 1517.8 \cdot \ln(T) + 5964.6 \quad 2 \le T \le 25 \\
Q &= 1316.4 \cdot \ln(T) + 6612.6 \quad 25 \le T \le 10{,}000
\end{aligned}
\tag{1}
$$

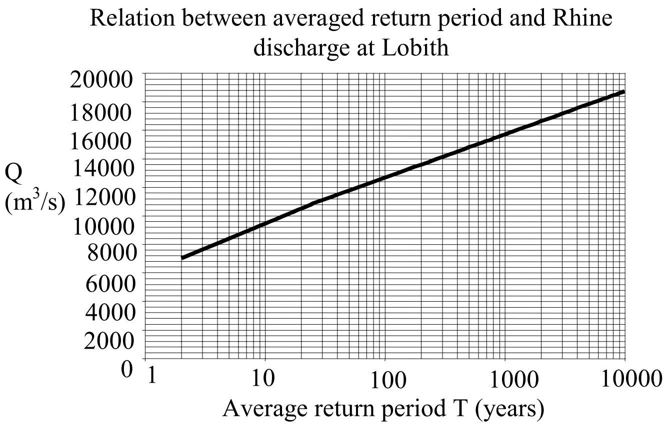

Figure 1. Relation between river discharge at Lobith and the averaged return period.

The wave shape of the design flood wave is derived by upscaling 21 historical flood waves (Klopstra & Duits 1999). The discharge levels of each flood wave are multiplied with the ratio design discharge / peak discharge of the flood wave. The average wave shape (Figure 2) of the resulting 21 upscaled flood waves is used for the traditional DWL computation method.

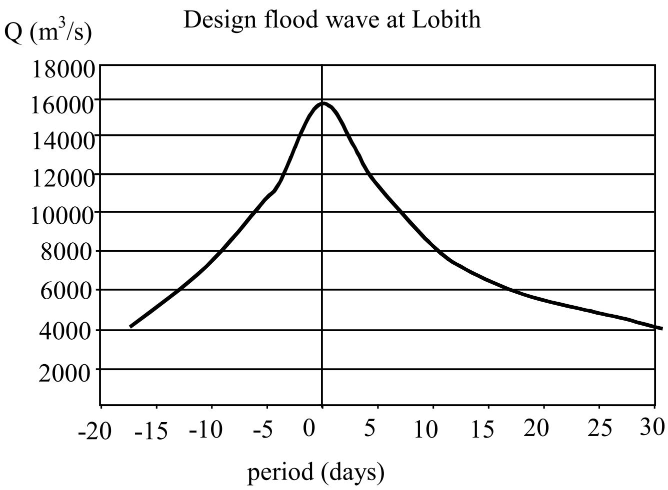

Figure 2. Design flood wave at Lobith.

2.4 *River morphology in the Waal*

Van Vuren & Van Breen (2003) investigated the bed level variation in the Waal in the present situation without additional human interventions. A short summary of their findings is given in this section. The morphological response in the river Waal (Figure 3) is analysed with a 1D-morphodynamic Sobek model of the Dutch Rhine branches (Jesse & Kroekenstoel, 2001). The model shows further evolution of the system without any additional human intervention.

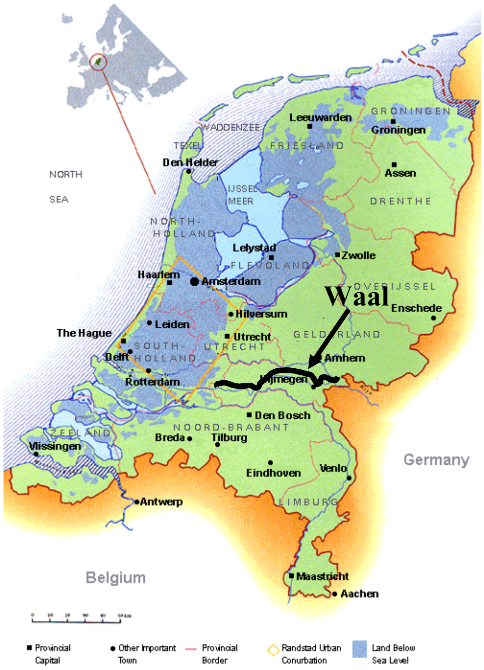

Figure 3. The river Waal in the Netherlands.

The morphological computations are affected by various uncertainties, including uncertainties in the model schematization and uncertainties in the specification of the model input. Monte Carlo simulation is applied to quantify the uncertainties in the morphological response. Van der Klis (2003) and Van Vuren et al (2002) showed that the relative contribution of an uncertain discharge to the uncertainty in the morphological response is one of the most relevant factors. Therefore, the effect of an uncertain river discharge on the uncertainty in the morphological response is analysed. Uncertainties introduced by the model schematization are not considered.

Monte Carlo simulation (Hammersly and Handscomb, 1964) involves a large number of model simulations with statistically equivalent inputs. For each 1D Sobek model simulation a discharge time series of a hundred years duration is randomly generated according to the prescribed probability distribution. This distribution accounts for the seasonal dependency of the discharge and the correlation of the discharge in successive periods. On the basis of the outputs of 500 of these model simulations, the morphological response statistics (e.g. the expected value and 90% confidence band of the bed level change) are analysed.

The results show that a large variation in bed level uncertainty exists in the river Waal: in space (due to irregularities in the river geometry) and in time (due to seasonal variation in discharge).

Figure 4 shows the spatial variation of the morphological response statistics in the main channel after 100 years in January. This figure presents the mean bed level changes and the (size of the) 90% confidence interval of the bed level changes in the Waal section between the Pannerdende Kop (km 886) and Tiel (km 915). The 90% confidence interval means that with a probability of 90% the bed level changes are within this range.

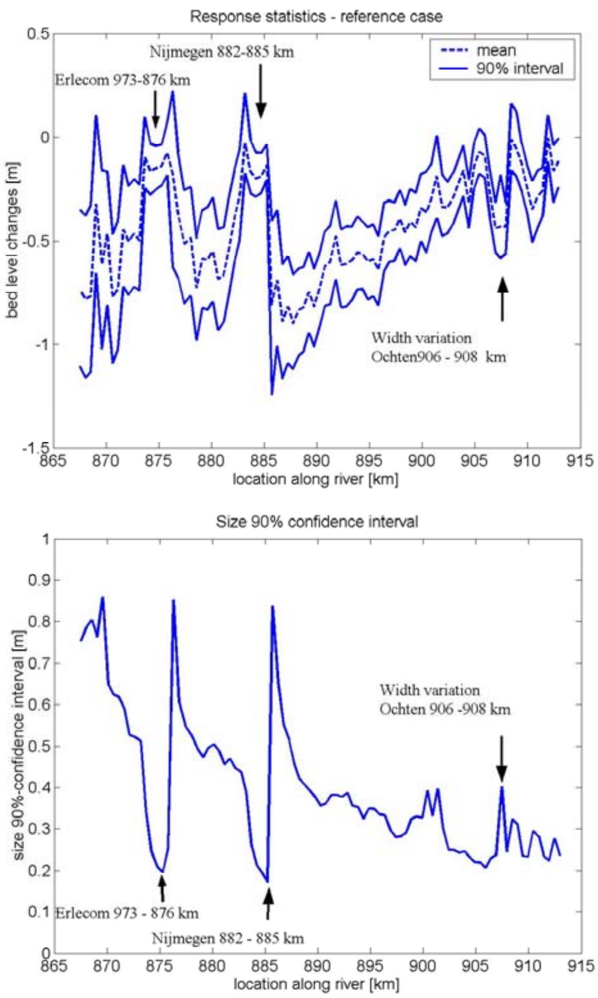

Figure 4. Spatial variation of statistical properties of the bed level change after 100 years in the Waal section between Pannerdense Kop (km 886) and Tiel (km 915).

Figure 4 illustrates that the irregularities in the river, such as width variation and man-made structures (such as riverbed protection), in combination with an uncertain river discharge lead to an uncertain morphological response. Each irregularity in the river acts as a generator of new bottom waves. At locations with large discontinuities, a local increase in bed level variability is observed – reflected by an increase in the 90% confidence band in the panel of Figure 4.

At Erlecom (km 873-876) submerged groynes and at Nijmegen (km 882-885) an armoured layer are present in the bend of the riverbed. These constructions are designed for navigation purposes. In the model the river bed constructions are schematized as fixed bed layers imposing a lower bound on the bed level. At both locations the morphological response after 100 years shows a bar in the riverbed and a reduction of the confidence band. The fixed layers prevent further erosion, while they lead to extra erosion and bed level variability downstream.

Figure 4 indicates the locations with large variation in the floodplain width: Hiensche waarden and Affendensche waarden (km 898-901); Ochtense Buitenpolder (km 902-906) and Willemspolder and Drutense waard (km 906-913). At these locations an increase in the size of the confidence band is noticed. E.g. a large open water area exists between km 906 and km 908 in the floodplain "Willemspolder" (Figure 5). An increase in floodplain width results in sedimentation. A decrease leads to erosion. At the transition points this results in an increase in bed level variability and hence to a larger size of the confidence band.

Figure 5. River section "Willemspolder" (km 906 - 908) with large variation in the floodplain width (courtesy of DON).

In Figure 6 the temporal variation of location 907.4-km in the floodplain "Willemspolder is shown. At this location, the temporal variation in morphological response statistics is considerable. This temporal variation reflects the seasonal variation of the river discharge. At this transition from a narrow to a wide cross section (see Figure 5) sedimentation in the main channel takes place. The seasonal fluctuation of the 90%-confidence band is significant. The largest 90% confidence interval is found in the high water period. The smallest interval is found in the low water period. The 95%-percentile strongly oscillates, while the 5%-percentile is more or less constant. This can be explained by the fact that during discharges higher than the bankfull discharge bottom waves (sedimentation) are initiated in the main channel. These bottom waves migrate downstream and (partly) decay during discharges lower than the bankfull discharge. Therefore, the seasonal variation in the 5%-percentile is limited. At other locations along the river with small irregulari ties this temporal variation is less (or hardly noticeable).

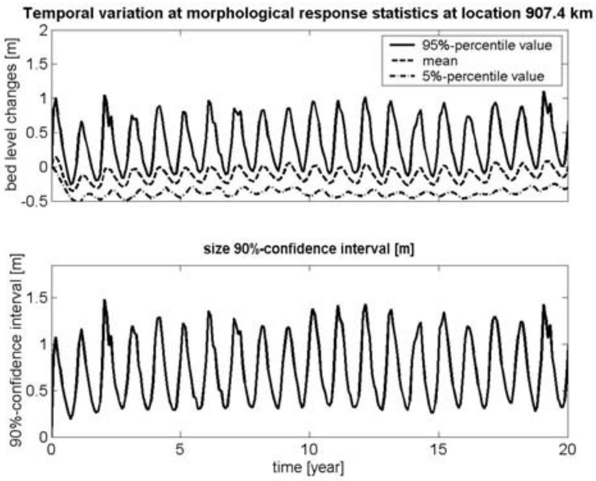

Figure 6. Temporal variation of statistical properties of the bed level change in the Waal at location 907.4 km in the Willemspolder.

Van Vuren and Van Breen (2003) concluded that large-scale floodplain lowering in combination with summer dike removal lead to more bed level variability than in the present situation without any additional human interventions.

3 METHOD

3.1 *Proposed methodology for DWL computation*

The extended method not only includes the discharge as a random variable. It includes the 'uncertain' river morphology as well. The method covers that a peak discharge in combination with a particular morphological state may result in water levels that are higher or lower than the DWLs derived with the traditional computation method. The extended method involves the following steps (Figure 7):

1 With the help of Monte Carlo simulation with the 1-D morphodynamic Sobek model for the Rhine branches, a large number of morphological states are simulated (similar to section 2.4). In this study 500 morphological simulations are performed.

2 The simulated morphological states form the basis of a large number of water level computations with the 1-D morphodynamic Sobek Rhine branches model. For each simulated state, water levels are computed for a range of steady discharges between 13,000 m^3/s and 20,000 m^3/s, with a discretisation step of 500 m^3/s. This results in 15 water level computations per simulated morphological state:

$$Q_i = 13{,}000 + i \cdot 500 \quad \text{for } i = 0, \ldots\ldots, 14 \tag{2}$$

3 Numerical Integration combines the probability of the two random variables. The likelihood of the simulated morphological state and the discharge levels is combined to estimate the probability of the computed water levels. The probability of each simulated morphological state is the same:

$$P(\text{Morphological State}_j) = \frac{1}{N} \quad \text{for } j = 1, \ldots\ldots, N \tag{3}$$

in which N is the number of morphological simulations with the Sobek Rhine branches model (in the Monte Carlo simulation).

The probability of the discharge level Q_i is derived with the help of formula (1):

$$\begin{aligned} T(Q) &= \exp\left(\frac{Q - 6612.6}{1316.4}\right) \\ F_Q(Q) &= P(Q \le Q) = \frac{1}{T(Q)} = \exp-\left(\frac{Q - 6612.6}{1316.4}\right) \\ P(Q_i) &= F_Q(Q_i + 250) - F_Q(Q_i - 250) \end{aligned} \tag{4}$$

The multiplication of the probability of the simulated morphological state_j and the probability of the discharge level Q_i lead to the combined probability of the water level computation:

$$P(\text{Water level}(i, j)) = P(\text{Morphological State}_j) \cdot P(Q_i) \tag{5}$$

Equation (5) holds since the morphological state j is considered independent of the discharge i.

4 The set of outputs resulting from all computations is used to determine per river location a curve showing the exeedance probability of water levels.

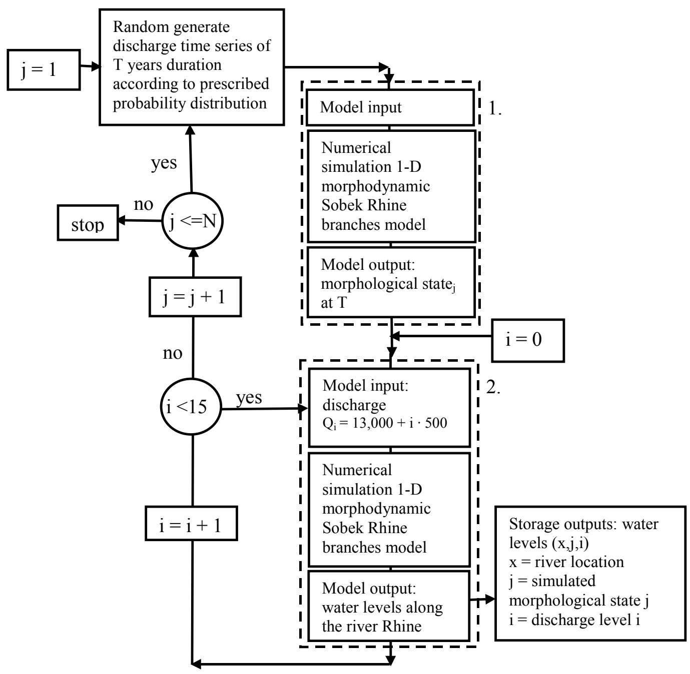

Figure 7. Design water levels: computation method with the random variables: discharge and bed level.

On the basis of the exeedance probability curve the 'new' water level with yearly a probability of oc currence of 1/1250 can be derived. This can be compared with the DWL that is derived with the traditional method using only one random variable: DWL_0. Also, this curve can be used to estimate the 'new' exeedance probability of the DWL_0.

3.2 *Cases*

Three cases are considered to analyse the impact of river morphology on extreme flood level prediction.

In Case 1 'Long-term variation in morphology' the impact of stochastic morphological changes over a longer period - years - is considered. The model scheme in Figure 7 is run through for different points in time T:

$$T = t_0 + k \cdot \Delta T \quad \text{for } k = 1,.....,4$$

in which t_0 is the starting point of the morphological simulation, ΔT is a period of 5 years.
The morphological changes during floods are not included. The simulated bed level state at time T is held fixed during the water level computations.

In Case 2 'Seasonal variation in morphology' the impact of seasonal variation in the morphological state prior to the water level computation is considered. The model scheme in Figure 7 is run through for different points in time T:

$$T = t_0 + 5 + k \cdot \Delta T \quad \text{for } k = 1,.....,12$$

in which t_0 is the starting point of the morphological simulation, ΔT is a period of 1 month.
Similar to Case 1, the morphological changes at high water conditions is not considered.

Case 3 'Morphology during floods' is similar to Case 1. The morphological changes during flood circumstances are considered in this case. The simulated bed level state at time T is not held fixed during the water level computations, but morphodynamic changes at high water conditions are included.

4 RESULTS

For the three cases the model scheme in Figure 7 is used. For each case this resulted per future moments in a set of computed water levels and corresponding probabilities. These are used to derive a curve showing the exeedance probability of water levels per river location, see for example Figure 8.

The DWL_0 in this curve represents the design water level at time t_0 that is derived with the traditional method using only one random variable. The curve is used to derive the 'new' water level with a yearly exeedance probability of 1/1250 and 'new' exeedance probability of the DWL_0. In Figure 8 it is shown that the DWL (at location 892.3 at time t_0 + 2*T) will decrease with 0.06 m. The exeedance probability of the DWL_0 decrease from 1/1250 to 1/1450.

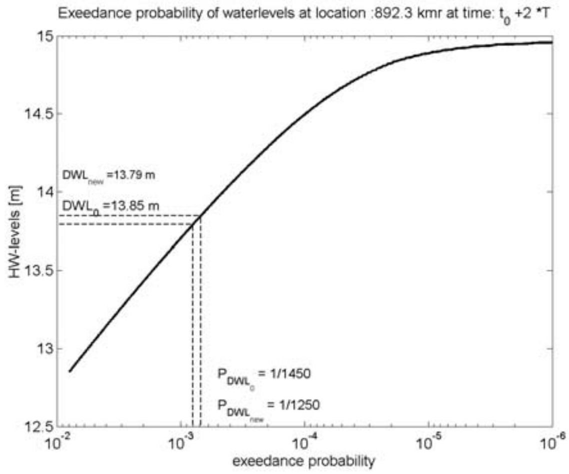

Figure 8. Exeedance probability of water levels at location 892.3 km at time $t_0 + 2 \cdot T$ for Case 1.

4.1 *Case 1: 'Long-term variation in morphology'*

The results of case 1 (Figure 9 and Figure 10) shows us that the influence of a random bed level on the DWL is not high. This is partly the result of a negative trend in the bed level: it is expected that in the future the bed level will be lower that the current situation (Figure 11). This trend has a positive impact on the DWL: these water levels will also be lower. The uncertainty in the bed level can, however, increase the DWL. In the calculations we combine these two affects.

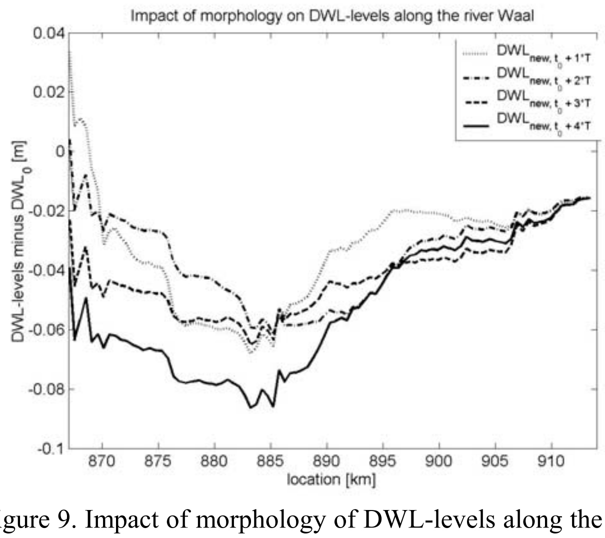

Figure 9. Impact of morphology of DWL-levels along the river Waal: change in DWL level with respect to DWL_0.

Figure 9 and 10 show that the influence of the random bed level results in higher safety, but this depends on the location along the river. The maximum change is 0.08 m, and this influence is not very large.

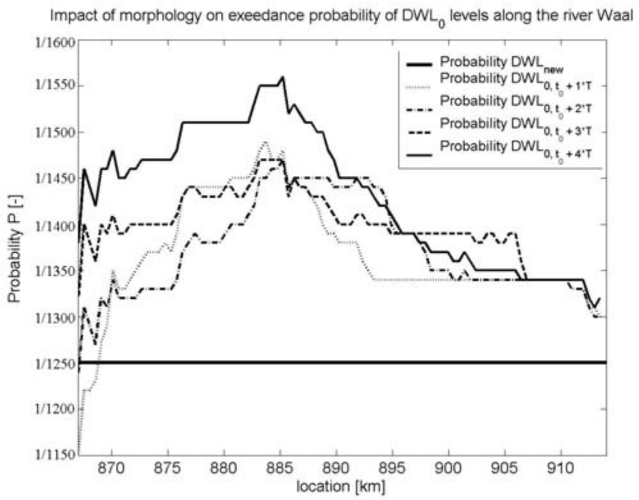

Figure 10. Impact of morphology on exeedance probability of the DWL_0 levels along the Waal.

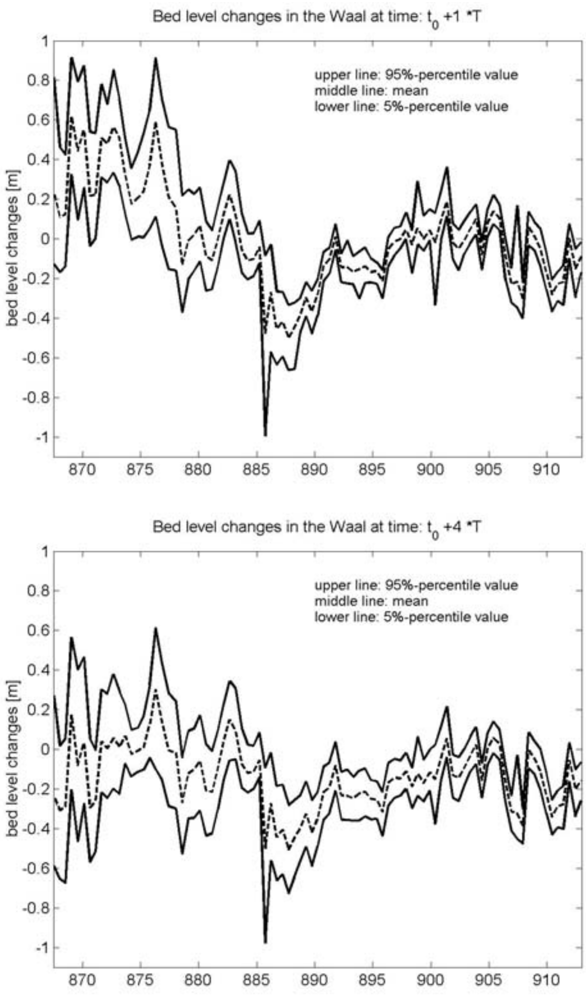

Figure 11. Spatial variation of the statistical properties of the morphological response in the Waal at time t_0 + T and $t_0 + 4 \cdot T$.

Figure 12 shows the DWL_{new} derived with the extended method and some DWL computations derived with the traditional method (using only one random variable, the design discharge) for single simulated morphological states at time $t_0 + 3 \cdot T$. The figure illustrates that each simulated morphological state results in slightly different DWLs. The difference depends on the location along the river and is in the order of 0.01 m.

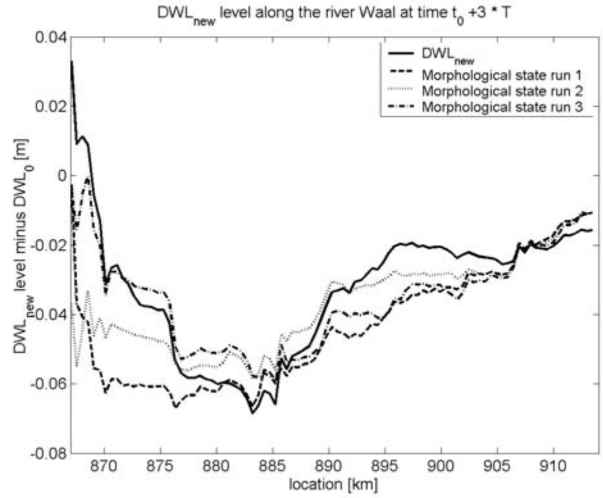

Figure 12. Impact of morphology of DWL-levels along the river Waal: change in DWL_{new} levels and DWL levels of single morphological simulations with respect to DWL_0.

4.2 *Case 2 'Seasonal variation in morphology'*

Figure 13 shows the impact of seasonal variation in morphology on DWL computations. The figure illustrates that the impact of seasonal variation in morphology is small: order of less than 0.01 m. It seems that the seasonal bias in the morphological river state does affect the DWL computation.

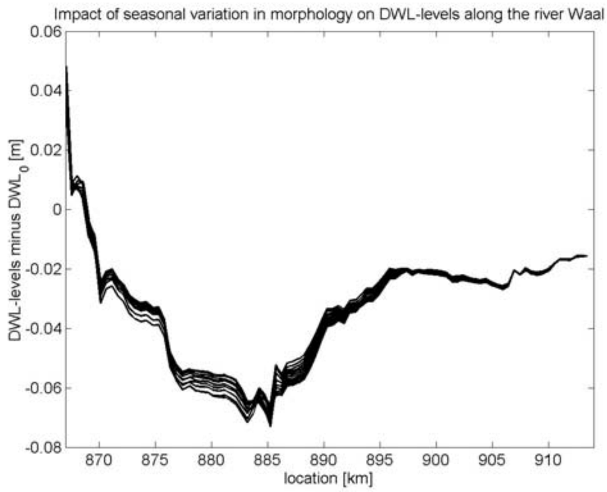

Figure 13. Impact of seasonal variation in morphology on DWL computations: each line represents the change in DWL with respect to DWL_0 in one month after 5 years.

4.3 *Case 3 'Morphology during floods'*

The morphological changes during floods have little impact on DWL computations. Figure 14 shows difference between the computed DWL levels if morphological changes during floods are neglected and if they are considered in the DWL computation. Considering morphological changes at high water conditions results in slightly higher DWLs - order of less than 0.01 m.

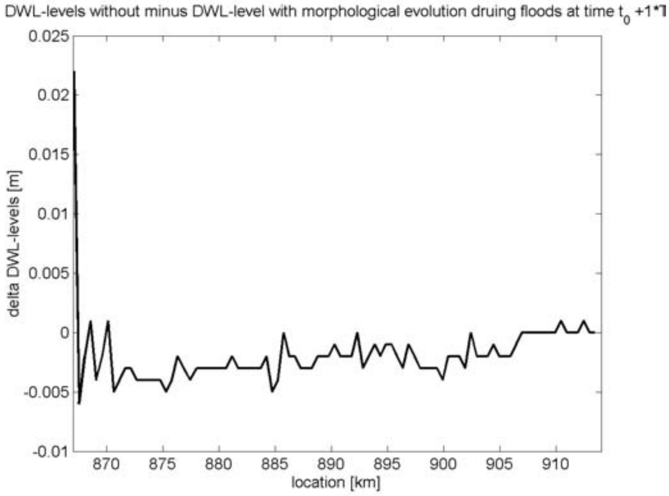

Figure 14. Impact of morphological changes during flood circumstances: difference between DWL levels if morphological changes during floods are neglected and considered.

5 CONCLUSIONS

In this paper the traditional DWL computation method is extended. The extended method includes the contribution of a second random variable: the river morphology. The impact of a random bed level on the DWL is not high. The large spatial and temporal variation in the bed level position, investigated in Van Vuren & Van Breen, depends very much on the location along the river. The contribution of the uncertainty in these local bed level patterns to DWLs is reflected smoothly. The large-scale negative trend in the bed level has more impact on extreme flood levels.

This paper shows that:

– Each morphological state prior to DWL computations results in DWLs that differ in the order of 0.01 - 0.06 m.
– Over a longer period - years - a negative trend in the bed level in the Waal section between Pannerdense Kop (km 886) and Tiel (km 915) has a positive impact on the DWLs in this section. The DWLs will decrease.
– The impact of seasonal variation in the morphology can be neglected. In the traditional DWL computation method the geometrical river schematization is derived on the basis of annual bathymetric soundings. These sounding have a seasonal bias. However, this will hardly affect the DWL computations.
– The impact of the morphological changes during floods on DWL computations is hardly noticeable.

In this paper we investigated the impact of one random variable (the variability of the discharge) on the bed level. Other random variables such as the uncertainty in the morphological process equations and the influence of the bed level might also be important. We recommend to investigate these influences on the variability of the bed level and the resulting consequences on the DWLs.

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