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Living With Peak Discharge Uncertainty: The Self-learning Dike

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Keywords: Flood Defence; Uncertainties; Climate Change; Adaptation; Rhine; Dike; Risk Analysis.

Abstract: Although river dikes still play a key role for flood protection in the Netherlands there is a growing interest for other measures to deal with larger peak discharges, such as lowering or widening the floodplains. Regardless of the strategy chosen the assessment of its effect on the flood risk depends on the peak discharge statistics. A problem here is that the statistical analysis of peak discharges relies on probability distributions based on the limited time series of extreme discharges. The extrapolation of these distributions are subject to considerable uncertainty, because there is a measuring record of only about 100 years and the natural variability can be expected to change as a result of climate change. This raises the question whether a more direct response to the effects of climate change is possible. The natural variability of the peak discharge changes, the changes in this variability due to e.g. climate change and the new statistical distribution can only be established after the actual change has happened. Even with regular updates of the statistical distributions it is inherent that the actions taken to reduce the flood risk are not anticipatory but delayed. As an alternative, this paper presents an adaptive or so-called self-learning approach to deal with the uncertainty in the peak discharge statistics. The difference with the probabilistic design of flood defense works, which depends on the analysis and prediction of uncertain peak discharges, is that the dike is adapted in direct response to peak water levels exceeding the dike height minus a certain safety margin. The results indicate that, on average, adaptive flood management based on observed peak water levels is at least as safe as a probabilistic approach, which necessarily relies on uncertain discharge statistics. Other advantages of the adaptive strategy are also obvious: the rule of response is simple and easy to communicate to the public, and peak water levels are less difficult to measure. In general the example demonstrates that flood management can be based on a direct response to the effects of climate change, without tedious statistical analysis of peak discharge records.

Keywords: Flood Defence; Uncertainties; Climate Change; Adaptation; Rhine; Dike; Risk Analysis

1.   INTRODUCTION

After the 1953 flood catastrophe in the Southwest the Netherlands decided to follow a probabilistic approach for the design of coastal flood defence works in the Netherlands [Van Danzig, 1956; Vrijling, 2001]. From the 1980s onwards this approach was adopted for the design of the dikes in general [Vrijling, 2001]. The current approach is based on a design water level corresponding to the return period for overtopping of the dikes, which is increased with a freeboard of at least 0.5 m [MTPWWM, 2005a]. By law the design water

levels are re-evaluated every five years to deal with uncertainties with respect to the actual peak discharge variability and changes in the river characteristics. A problem encountered here is that the statistical distributions for the peak discharge are extrapolations derived from limited time series of discharge data. The knowledge about discharges and water levels with a return period of 1250 years is limited because historic data are available for a hundred-year period only. Furthermore, the volume and variability of peak discharges are subject to change due to factors such as climate change and changing upstream flow conditions. Due to climate change the peak flows in the lower Rhine corresponding to return times of 100-1000 years are expected to increase by 5 % or more over the next 50 years [Middelkoop et al., 2001]. As an extreme scenario the design discharge at Lobith could increase from 16,000 m^3s^{-1} to 20,000 m^3s^{-1} in the year 2100 [Middelkoop and Kwadijk, 2001]. In the probabilistic design a change in the discharge regime will only lead to a different design long after the change took place, even if the discharge statistics are regularly updated. It is therefore inherent to this strategy that the actions taken to reduce the flood risk are not anticipatory but following. Here we evaluate the usefulness of the probabilistic dike design policy against the background of the older design philosophy, which was to apply a safety margin on top of the highest water level ever recorded. We refer to this older design philosophy by the term 'self-learning dike', where 'self-learning' refers to the fact that dike adjustments immediately follow actual extreme flood levels. Metaphorically speaking, the dike learns through monitoring actual water levels and adapting according to a simple rule, without applying any statistics. The aim of the analysis is not to challenge the full risk-based approaches (Vrijling, 2001; FLORIS, 2006), but only to compare two different approaches to cope with discharge uncertainty. The two dike heightening strategies differ in the rule that governs the heightening of the dike. The probabilistic approach is based on the Design Flood Level (DFL), which is the water level corresponding to a flood return time of 1250 years, plus a freeboard of 0.5 m. The DFL is calculated on the basis of the historic record 1901-1998, and updated every five years by determining again the peak discharge probability distribution with the additional discharge data added to the existing time series. In the self-learning design strategy the dike height is compared with the highest water level that occurred so far. If this water level exceeds the existing dike height minus a safety margin s, the dike is heightened to the water level plus this safety margin. Obviously, a larger safety margin leads to a safer but more expensive dike design. For this analysis the safety margin has been taken equal to the dike height for the probabilistic dike design (including the freeboard) minus the largest historic water level. This ensures that the initial dike height is identical for both strategies.

2. METHODOLOGY

A comparison between the probabilistic flood prevention strategy and the self-learning strategy has been carried out for the case of the border gauge Lobith of the Rhine river. The endangered dike ring 48 "Rijn and Ijssel" has a total length of 57 km. In case of flooding the worst case estimate of the flood damage is 6.8 billion euro [Eijgenraam et al., 2005]. The two dike heightening strategies are compared for three different scenarios for the peak discharge statistics:

1. current peak discharge statistics without including uncertainty;
2. peak discharge statistics with uncertainty included;
3. gradual climate change trend with slowly increasing peak discharges.

In fact scenario 2 reflects the knowledge uncertainty related to limited data and scenario 3 reflects the intrinsic uncertainty due to a lack of knowledge due to climate change.

The results of the simulations are compared on the basis of the average number of dike overtopping instances, the average number of times the dike has to be heightened, and the total extra height added to the initial dike height during the 100-year simulation.

The comparison of the different dike heightening mechanisms is based on extension of the historical discharge data for the gauge station at Lobith. A time series of the yearly

maximum discharges for the period 1901-1998 [Parmet et al., 2001] was used. The complete time series has been homogenised so as to represent the river condition of 1977 [Lorenz and Kwadijk, 1999; Parmet et al., 2001]. The homogenised peak discharge data have been used to derive the parameters for the Gumbel Extreme Value distribution with the cumulative probability distribution:

$$F(Q) = \text{Pr}ob\ (q_{max} \leq Q) = \exp(-\exp(-b(Q-a))) \qquad (1)$$

where Q is the peak discharge in m^3s^{-1} and a and b are the moment estimators for the parameters of the Gumbel distribution. The stationary Gumbel distribution is justified here because statistical analysis using the Spearman ranking test did not reveal a significant trend in the historic discharge time series. In addition application of the probability plot correlation test statistic [Stedinger et al., 1993] to the discharge data proved that the historic discharge data can be described with a Gumbel distribution. For the simulated extension of the peak discharge time series in the first two scenarios there is no significant trend as well. For the scenario with a gradual climate change the probability distribution becomes non-stationary [Khaliq et al., 2006]. In this case the Gumbel parameters a and b are made time dependent by means of multiplication with a common factor, which ensures the chosen design discharge is reached after 100 years.

For the initial year of the simulation the values $a = 5170\ m^3s^{-1}$ and $b = 6.584 \times 10^{-4}\ m^{-3}s^{-1}$ were determined from the rescaled discharge data to ensure that the 1250-year design discharge corresponded to the value of 16,000 m^3s^{-1} at Lobith, which was agreed upon in 2001 [MTPWWM, 2005b]. The return period for a peak discharge Q is then given by

$$T(Q) = \frac{1}{P(Q)} = \frac{1}{1 - \exp(-\exp(-b(Q-a)))} \qquad (2)$$

Once the representative Gumbel probability distribution was established the parameters were used to simulate an artificial 100-year time series following the historic period. For each year the new discharge is simulated by:

$$Q(t) = F^{-1}(x_t) \qquad (3)$$

where $Q(t)$ is the discharge in year t, $F^{-1}(x)$ the inverse of the cumulative distribution function of Eq. (1) that is determined from the extended discharge record, and x_t a random uniform number in the range [0,1]. To obtain a reliable estimate of the probability of overtopping during the 100-year period the simulations were repeated 100,000 times. This number of iterations ensures that the values of μ and σ for the simulated discharge approach the parameters of the Gumbel distribution within less than 1.5 %. For any year the water level corresponding to the discharge is determined from the known stage-discharge relationship (Figure 1) for the gauge station at Lobith, which is an extrapolation of the stage-discharge relationship based on [Schielen, 2007, Van den Brink et al., 2007]. This water level is first compared with the existing dike height to determine whether overtopping of the dike crest occurs. Depending on the dike management strategy chosen the water level is also used to adapt the dike when necessary. The results of the simulations are used to determine the average probability of overtopping during a 100-year period for each combination of the dike strategies and discharge scenarios.
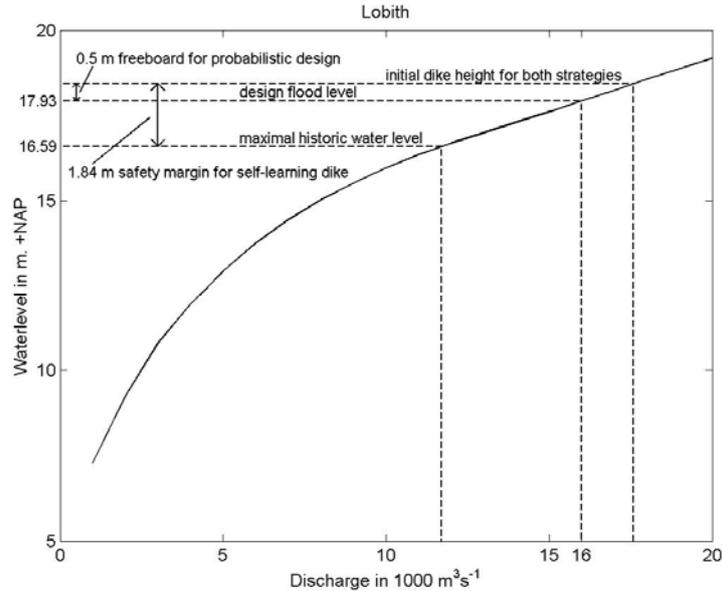
Figure 1. Stage-discharge relationship for the Rhine gauge station at Lobith based on [R.J.M. Schielen, 2007; N.G.M. Van den Brink et al., 2007].

For a fair comparison of both dike heightening strategies it is necessary to include both the costs of dike heightening and the prevented flood damage. A cost-benefit analysis has recently been carried out for dike ring 48 in the framework of the project "Room for the River" [Eijgenraam, 2005]. The investment costs of heightening the dikes along the complete 57 km length of the dike for dike ring 48 have been obtained by extrapolation of the investment costs given in Table 3.6 and Appendix C of [Eijgenraam, 2005]. For dike ring 48 the fixed investment costs are 0.5×10^6 euro, whereas the variable investment costs are 1.2×10^6 euro per km length of dike for an extra dike height of 50 cm, 1.8×10^6 euro per km length of dike for an extra dike height of 75 cm, and 3.0×10^6 euro per km length of dike for an extra dike height of 100 cm, respectively [Eijgenraam, 2005].

3. RESULTS

The performance of the two dike heightening strategies has been evaluated based on the three different discharge scenarios (Table 1). All results are based on the synthetic discharge record for the period 1998-2098. The difference between the standard and second scenario is that in the latter scenario the parameters a and b in Eq. 1 are not constant but drawn randomly in a range that has been deducted from the discharge data.

Table 1. Average performance of the probabilistic (A) and self-learning (B) dike heightening strategy for the three discharge scenarios over the 100-year simulation period.

	standard		with uncertainty		climate change	
	A	B	A	B	A	B
# dike overtoppings	0.024	0.021	0.034	0.030	0.047	0.037
# dike adaptations	2.13	1.00	2.40	1.09	3.62	1.40
extra height per adaptation	0.07	0.48	0.07	0.51	0.07	0.51
total extra height	0.14	0.48	0.17	0.55	0.24	0.71

The results indicate that, on average, the self-learning dike performs better in terms of safety and requires less adaptations of the dike height. The average extra height per adaptation and total extra height after 100 years, however, are larger for the self-learning dike. Adaptations to the dike height that are relatively small are less desirable because of

the relatively high fixed costs of dike heightening. To reduce the number of dike height adaptations one could add an extra margin of, for example, 0.5 m to the dike height when it is adapted.

Table 2 shows the discounted costs aspects for both dike strategies, based on the average of 100,000 simulations. The average flood damage is based on a 2 % yearly economic growth rate as used by Eijgenraam [2005]. The Net Present Value is based on an effective discount rate of 4 % [Eijgenraam, 2005] and determined from:

$$NPV = \sum_{t=1}^{100} \frac{C(t) + D(t)}{(1+r)^t} \qquad (4)$$

where $C(t)$ are the investment costs in year t, $D(t)$ is the flood damage in year t, and r is the discount rate. For the probabilistic design the fixed investment costs are larger than for the self-learning dike, whereas the variable costs of dike heightening are smaller. As expected the flood damage due to dike overtopping is smaller for the self-learning dike due to the higher safety level. The total expected costs (sum of investment costs of dike heightening and flood damage) are always a bit smaller for the self-learning dike. Compared with the damage incurred without dike heightening the total costs are only lower for the self-learning dike for the scenario with climate change. From a purely economic perspective this would mean that dike heightening is not necessary for most of the combinations shown in Table 2, but this changes if safety is taken into account.

Table 2. Comparison of the average costs over 100 years in million euro of dike heightening and average expected flood damage in million euro for both dike strategies for the three scenarios.

	standard		with uncertainty		climate change	
	A	B	A	B	A	B
total fixed costs	22.7	8.2	24.6	9.0	27.1	9.8
total variable costs	4.6	17.5	5.4	21.3	5.7	21.9
total flood damage	74.8	69.5	107	98.8	122	106
costs per adaptation	12.8	25.5	12.5	27.9	9.0	22.6
total expected costs	102	95.1	137	129	155	138
total expected costs without dike heightening	85		123		147	

Figure 2 below shows the year-by-year development of the average costs of dike heightening, number of dike overtoppings, flood damage, and total expected costs for both dike strategies for the climate change scenario with a gradual increase of the design discharge to 18,000 m³s⁻¹. The gradual increase of the peak water levels (due to climate change) is directly reflected in a gradual increase of the dike height for the self-learning dike. Therefore, the average costs per year are constant for this strategy. For the probabilistic design the costs decrease first due to the increased safety level and then increase due to the effect of climate change on the discharge statistics.
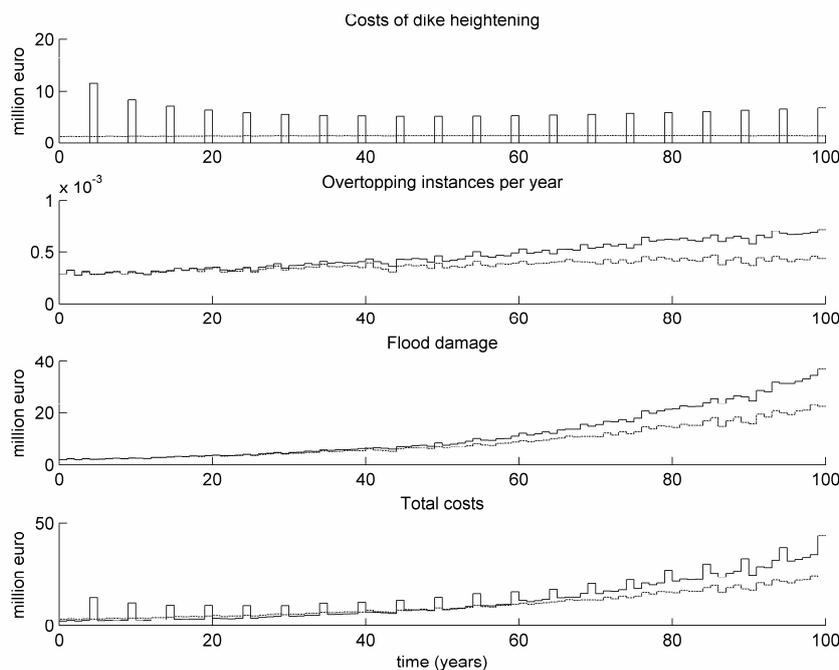
Figure 2. Average investment costs of dike heightening, number of overtopping instances, flood damage, and total expected costs for the probabilistic strategy (solid line) and the self-learning dike (thin line) over the 100-year simulation period. The discharge statistics correspond to a gradual increase of the design discharge from 16,000 to 18,000 m^3s^{-1}.

4. CONCLUSIONS

The effectiveness of the probabilistic dike design strategy has been compared with the self-learning dike strategy on the basis of the average number of overtopping instances over a 100-year period. The results of the simulations clearly indicate that the safety level and total expected costs of the self-learning dike are somewhat lower than for the probabilistic design, although the self-learning dike requires larger adaptations. Under conditions of uncertain or gradually changing discharge statistics, the average safety performance of the self-learning dike is also better than for the dike based on a probabilistic design. We acknowledge the relevance of other dike failure mechanisms and the importance of analysing how effects of flooding can be reduced in addition to examining methods to reduce flooding probabilities. Nevertheless, any flood security policy will need to include some policy towards dike heights. The approach of the self-learning dike can also be applied to other measures such as floodplain lowering or dike shifting with the same response criterion. If the water level exceeds the dike height minus the safety margin, for example, the dike is shifted backwards over such a distance that the water level for the corresponding discharge is lowered to the critical level. However, to estimate the appropriate distance it is necessary to have information on the stage-discharge relationship. Three important advantages of the self-learning dike are:

- the use of a simple rule for response which needs recording of peak water levels only and is easier to implement;
- no dependency on uncertainties in the extrapolation of discharge statistics, nor on the use of an uncertain discharge–water level relationship;
- in terms of safety communication towards the protected population the rule of the self-learning dike is more transparent.

Without challenging the full risk based or cost-benefit approaches (Vrijling 2001; Eijgenraam, 2006; FLORIS, 2006) the general conclusion is that for Lobith, on average, the self-learning dike is at least as safe as the probabilistic design. In comparison to the risk-based approach the merit lies in the more simple and direct response mechanism to uncertainties related to the discharge statistics. In a risk-based approach probability is accounted for, but the uncertainties in the statistics are usually not explicitly included.

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