CALCULATING FLOOD RISK IN OBIHIRO USING A RISK BASED APPROACH – FROM PROBABILITY OF DISCHARGE TO PROBABILITY OF DIKE FAILURE

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ABSTRACT

In 2016 Hokkaido was hit by various typhoons which led to floods in the city Obihiro and the surrounding catchments. These events raise questions about what kind of floods can be expected in a future, uncertain trough climate change. The Dutch risk based approach (VNK2) offers a method to deal with these uncertain future scenarios. The challenge however is applying the approach to a specific Japanese river system.

Typhoon induced rainfall events around Obihiro will lead to flash floods in the relatively steep rivers. The strength of the dikes protecting the surrounding area depends on the type of flash flood. For overflow higher water levels or floods with longer durations lead to a higher chance of failure. Flash floods can also lead to large erosion. This can degrade the stability of the dike or even erode it completely.

The flood risk in Obihiro is assessed by combining the probabilities of extreme water levels with the strength of the dikes under these conditions. Since the strength dependents on the water level this leads to a complex risk assessment. At the end of the research in fall 2020, we expect to have an understanding of Japanese failure modes in a probabilistic context, and use this information to calculate flood risk now and in the future.

Keywords: Flood risk, dike failure, overtopping, climate change

1. INTRODUCTION

Why use a probabilistic approach for assessing flood risks, when deterministic methods can also give useful answers? That is the main question indicating the relevance of this study. The answer is that uncertainties are inevitable when assessing extreme events under a future climate. In these predictions there are a lot of variables that are difficult to estimate. The question is how to handle these uncertainties. The first option is including conservatism by adding safety margins, an option that does not provide insight. Another possibility is trying quantifying the uncertainty. For this the uncertainties need to be estimated in some way, a tedious process. The advantage is however a more substantiated answer (so likely also better), and more insight in the processes that might cause flooding.

Within the current research we apply the Dutch VNK method (Jongejan et al., 2011) to the Tokachi and Satsunai River flowing around Obihiro, a city in east Hokkaido. The research is carried out by the Japanese parties Docon, River Center Hokkaido and Hokkaido University, and the Dutch parties HKV Consultants, Deltares and Rijkswaterstaat. Work package 1 (WP1) focuses on climate change and hydrology. WP3 aims to quantify the damage as a result of flooding. WP2, carried out by Docon and HKV is the connection factor between WP1 and WP3, in which the hydrology is connected to flood risk. This article is about WP2 and explains the probabilistic method used in the research. Since it is a pilot study, the focus is mainly on applying a methodology, rather than creating definite results.

In the current flood risk approach the failure of a dike is determined rather binary: when the water level during a flood exceeds the design water level of the dike, a breach is assumed to occur that will flood the hinterland. The comparison between a water level and the dike height is a very useful one, since it is an easy understandable measure. If the water level is somewhat higher than the dike it will fail, and when it is sufficiently lower, it will not fail. In WP2 we try to determine the flood probabilities for the water levels in between, where the occurrence of dike failure is uncertain. This relation between water level and failure probability follows a logistic model we; a conditional failure probability given the load. In the Netherlands such model is often called a “fragility curve”.

A high water level itself does not cause failure. It is the overflowing water that results in high flow velocities and subsequently erodes the inner revetment and the dike body until the dike breaches. Other failure mechanisms, for example like instability causing sliding, are not considered in this article. The approach is however adaptable to these mechanisms as well.

2. METHODS: APPLYING CONDITIONAL FAILURE PROBABILITIES

In the description of failure due to overtopping from the previous paragraph, a number of uncertainties can be identified. High discharges are the results from heavy rainfall, and will lead to a high water level. What height the discharge and the resulting water level will be, is however uncertain. Each flood wave is different, and the geometry of the river might change from time to time, causing different water levels than we expect from our model. Considering the dike, we might also be uncertain about the exact height of the dike. And if the water would flow over the dike, at what flow velocities does erosion start? Also if the hydrograph is wider, the volume of overtopping might be larger.

All these factors add to the total uncertainty in the estimated flood levels. To quantify the uncertainty the failure probability distribution conditional to the load is determined. This relation is called a fragility curve. The current (deterministic) approach is actually already a very simple version of such a fragility curve, in which the failure probability is 0 for all values below the design water level, and 1 above this critical level. If we consider the described uncertainties, the failure probability gradually increases from 0 somewhere below the crest level, to 1 above it, when we are certain the dike fails.

The main sources of uncertainty we assume to be the hydrograph (course of the discharge and water level in time) height and width, and the critical flow velocity for which the revetment fails. To determine the water levels that lead to failure we need some relations additional to the hydrographs. Figure 1 shows these components: the discharge statistics and probability of a hydrograph type (from WP1), and the resulting water levels which follows from modeling done by Docon.

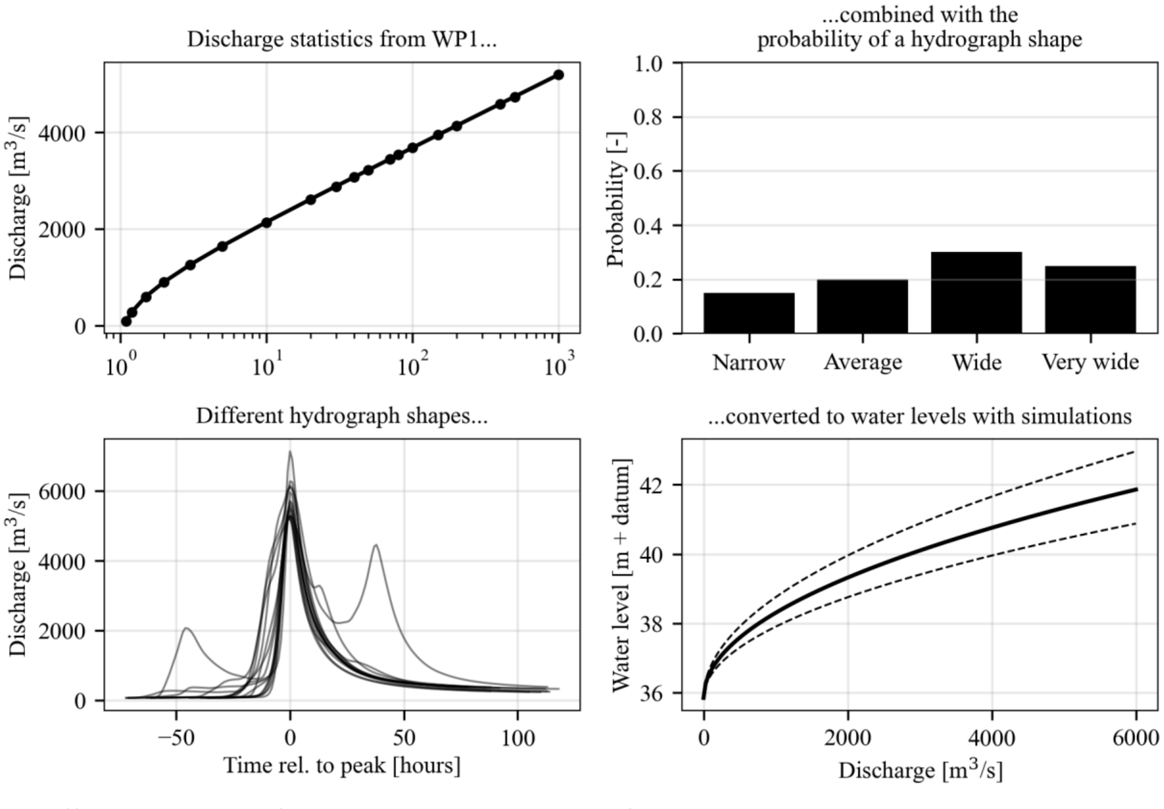

Figure 1. Different components for determining the probability of water levels and durations.

The first row in the figure contains the two random variables (discharge height and shape), the second row the actual hydrographs and the conversion to water levels. To get the actual failure probability of the dike, these water levels are combined with the resulting overtopping velocities and volumes. The full process from hydrograph to failure probability is given in the steps below. These steps are similar to current practice in the Netherlands, as described in (Geerse, 2011):

1. Based on the statistics derived from work package 1, determine a number of hydrographs to simulate. Select them based on two classes, width (duration) and height (maximum discharge). The number of simulated hydrographs does not need to be very large; only hydrographs relevant for failure and with sufficient distinction between less extreme and more extreme events. For example 4 discharge levels

and 4 hydrograph shapes. Determine the probabilities of each class based on the result from work package 1.

$$P(q|w) = P(Q > q_1|w) - P(Q > q_2|w) \tag{1}$$

In which $q \in q_1, q_2$ is a representative discharge for the class, and w denotes the hydrograph shape.

2. Convert the discharges to water levels, preferably with a hydrodynamic simulating. If this is not possible it might also be sufficient to use a similar older existing simulation, or a rating curve.
3. Determine the failure probability of the dike as a function of the overtopping flow velocities:

$$P(u > u_{crit}|q, w) \tag{2}$$

In which u is the overtopping flow velocity and u_{crit} is the critical overtopping flow velocity. The relation can be refined for different overtopping volumes (durations of high flow velocity).

4. Combine the probability of a hydrograph with the failure probability conditional to this hydrograph

$$P_{fail} = \int f(w) \int f(q) \cdot P(u > u_{crit}|q, w) \mathrm{d}q\mathrm{d}w \tag{3}$$

5. The different hydrograph shapes are divided into discrete realizations. De different discharge levels will also be summarized numerically, perhaps for accuracy after interpolation:

$$P_{fail} = \sum_{i=0}^{4} P(w_i) \sum_{j=0}^{n} P(q_j) \cdot P(u > u_{crit}|q_j, w_i) \tag{4}$$

These steps result in a calculated failure probability. In case of climate change scenario only the discharge statistics need to be updated in order to calculate the future failure probability.

3. RESULTING FLOOD PROBABILITIES AND CONSEQUENCES

At the moment of writing the methodology for WP2 has not been worked out into full detail. Also the discharge statistics from WP1 are not yet finished. Docon has however simulated a lot of different floods for different breach locations around Obihiro. Together with historical discharge statistics and available rating curves, we have an abundant source of information for which we can work out the steps described in the method. Note however that the presented results are still preliminary and will change in the final version.

Figure 2 shows the different steps in calculating the failure probability. The left figure shows 4 distributions for the critical flow velocity. The distributions show the flow velocity for erosion will start when exceeded, leading to dike failure (Vrouwenvelder, 1999). In the final method these distributions are replaced with Japanese research on the erosion limit, like (Fukuoka and Fujita, 1990). The resulting fragility curves for these preliminary results are shown in the second figure. The higher the water level (vertical axis), the higher the failure probability is. The right figure shows the design water level for this dike, which is lower than the actual dike height. Note that the dike height and water level are also uncertain. These uncertainties can be incorporated in the fragility curves as well.

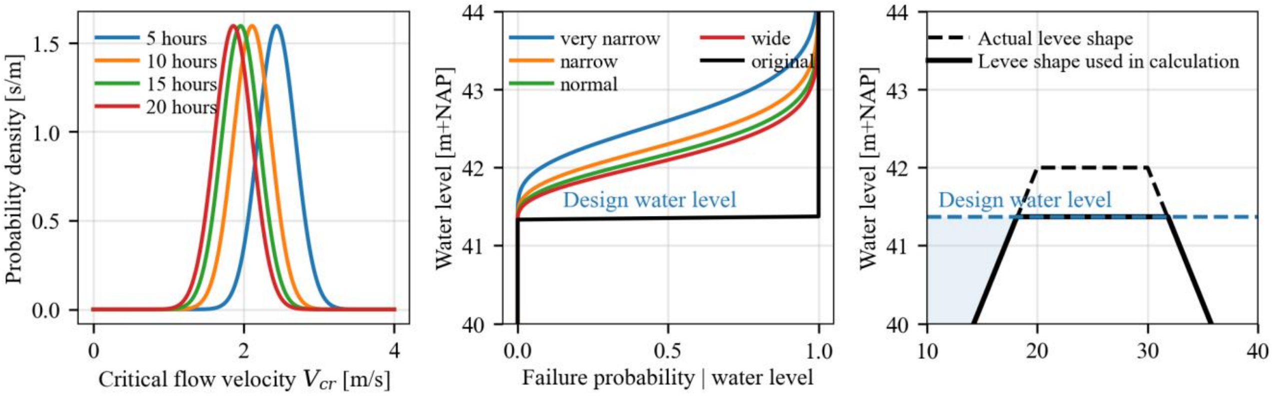

Figure 2. Different steps in the results.

By combining the hydrograph classes and the fragility curves, the failure probability can be determined for this first approach. In the example we calculated a once per 1000 years failure probability when using the design water level, and a once per 3000 years failure probability when using the fragility curves in Figure 2.

4. DISCUSSION OF PRELIMINARY RESULTS, HOW TO IMPROVE

The results presented so far are only preliminary. We saw that the failure probabilities from the probabilistic assessment are smaller than the deterministic assessment. This makes sense since the probabilistic approach assumed that the dike only fails for water levels higher than the design water level. Looking at the fragility curves there is quite a lot of spread in the water levels, for a 5 hour overtopping duration, the failure probability is only 50% when there is more than 1.5 meter overtopping water. This seems an unlikely result. Adding the velocity of the water in the direction of the river flow may lead to more realistic results. Additionally the uncertainty in the modeled water level should be taken into account, as well as using the actual dike height instead of the design water level. In the coming months of the research we aim to sharpen the described approach.

An additional factor for the total failure probability is looking at other failures along the river. When an upstream dike fails, it reduces the load on downstream dikes. Taking this into account gives a more realistic flood probability. This is particularly important for WP3, in which the flood risk is quantified. Not taking this into account could for example lead to estimating two simultaneous floods, while the first flood reduces the water levels such that the second flood will no longer happen.

In this article only failure due to overtopping is considered. Other failure mechanisms such as instability (sliding), piping (due to seepage) or erosion due to lateral flow might be relevant causes of dike failure (Uno et al., 1988; Tabata et al., 2015). Adding these failure mechanisms in the approach will lead to better estimates of flood risk for the catchment, and an approach that is applicable to other Japanese rivers as well.

5. CONCLUSIONS

A probabilistic approach leads to more insights in the mechanisms that lead to dike failure. It likely gives better estimates of flood risk. The results so far are preliminary, but they indicate lower probabilities of flooding than in the deterministic case.

The method worked out in this study is a framework for applying a probabilistic approach to calculate flood risk. For now only the failure mechanism overtopping is included since this is the most relevant for the Obihiro pilot area. By adding additional failure mechanisms the calculations might be refined, and the method is easier applicable to other locations throughout Japan.

ACKNOWLEDGMENTS

This project is funded by Partners for Water, Docon, River Center Hokkaido, Hokkaido University, Rijkswaterstaat, HKV Consultants and Deltares. Work package 2 is led by Docon, assisted by HKV. Additional to the second author U. Fumihiko, also his Docon colleagues T. Yoshida, N. Omura and S. Masuya contributed to the work presented in this article.

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