Determining the time available for evacuation of a dike-ring area by expert judgement

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ABSTRACT: The possibilities open to preventive evacuation depend on the time available and the time required for evacuation. If the time available for evacuation is less than the time required, complete preventive evacuation of an area is not possible. This can occur if the threatening flood is difficult to predict or if the area that has to be evacuated has few access roads and the evacuation requires a considerable amount of time. To determine the influence of preventive evacuation, it is necessary to estimate the time available and required for evacuation including the uncertainties involved. This paper focuses on these issues, especially on the time available for evacuation. Because there are almost no observations on the time available, we have had to rely on expert judgement. In addition, the results of this study provide a basis for further discussion. The results give an administrator insight in the time available and required for evacuation of his dike-ring area.

1 INTRODUCTION

Improved management of flood disasters is necessary to decrease the consequences of flooding. This can be achieved through the early warning of the people to be affected and various other preparatory measures. For an overview of risk management of large-scale floodings in the Netherlands, see Vrijling (2001) and Waarts and Vrouwenvelder (2004). One of the consequences of floods is loss of lives. According to Loster (2000), floods account for about one third of all natural hazards and cause more than half of all fatalities due to natural hazards all over the world. It is possible to influence the number of lives lost by carrying out a successful evacuation of the area before the flood occurs (preventive evacuation).

In the Flood Risks and Safety (Floris) project, initiated by the Netherlands Directorate-General for Public Works and Water Management (DWW, 2003), a study is carried out to determine the effect of preventive evacuation on the number of lives lost by a threatening flood. To determine this influence, it is necessary to estimate the time required and available for evacuation including the uncertainties involved.

The time required for evacuation is the time required for decision making, the preparation (initiation, warning and response) and the transportation out of the area. With the time available for evacuation, we mean the period between the moment that the safety of the flood defences can no longer be guaranteed and the moment one or more flood defences will actually collapse. The different phases of the time available for evacuation and the time required are shown in Figure 1.

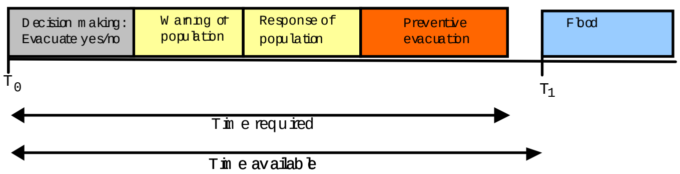

Figure 1. Time available and required with T_0 the moment when the safety of the flood defences can no longer be guaranteed and T_1 the moment where one of the flood defences actually collapses.

To date, little is known about the time available and required for evacuation. The possibilities open to preventive evacuation depend on the time available and the time required for evacuation. In a study carried out by HKV Consultants for the Road and Hydraulic Engineering Institute (DWW) of the Netherlands Ministry of Transport, Public Works and Water Management, more insight is gained into the possibilities for evacuation by quantifying the time available and required for evacuation (Barendregt and van Noortwijk, 2004). In this study, the estimation of the time necessary for evacuation is gathered on the basis of information and experience gained through previous evacuations. To determine the time available for evacuation we had to rely on expert judgement, because there are almost no observations of this event.

The time available for evacuation depends on the possibilities for flood forecasting (several hours or days ahead) and the failure mechanisms. In the study, an estimation procedure is provided for the time available which includes the uncertainties. We use the judgements of experts to determine the time available for evacuation, taking into account the difference in impending threat, such as sea, lake and river (Meuse, Rhine, IJssel, Vecht), and the failure mechanism. The expert judgements are obtained through interviews. The result is an estimation of the time available for evacuation (in hours) with an uncertainty interval. The answers provided by the experts are combined and discussed.

The outline of this paper is as follows. The definition of the time that is available for evacuation is given in Section 2. The procedure for obtaining probabilistic estimates of the time available from experts is explained in Section 3. Next, the results of the expert judgement study are presented in Section 4, and they are evaluated and discussed in Section 5. The length of time required for evacuation is discussed in Section 6. Recommendations are formulated in Section 7. Some pictures of the 2002 flooding of the Danube river in Austria are shown in Figures 2-4 and 6.

Figure 2. Danube flood, Emmersdorf an der Donau, Austria, August 13, 2002 (Photography: J.M. van Noortwijk).

2 TIME AVAILABLE FOR EVACUATION

To determine probabilistic estimates of the time available for evacuation, we are interested in the predictability of a flood. The predictability of a flood can be expressed in 'time' including the possible uncertainty. The predictability of a flood depends on the type of threat (sea, river, lake) and the failure mechanism. For this reason, we have subdivided the time available for evacuation in the following two phases:

1. the time between prediction of a critical situation and failure initiation (overload) of the flood defence, and
2. the time between failure initiation and actual collapse of the flood defence.

A critical situation is a situation in which the flood defences are threatened by the initiation of failure (overload) due to an applied critical water level. Because of this critical water level, a failure mechanism will be set in motion and can result in the actual collapse of the flood defence. In most disaster management plans, a critical situation is defined by the occurrence of an extreme water level, the alarm stage. If this water level is reached and a further increase is expected, it concerns a threatening disaster and areas must be evacuated. For example, the alarm stage for the river Rhine at Lobith is 17.65 m+NAP (normal Amsterdam level), which corresponds to a discharge of about 15,000 m^3/s.

With failure initiation of the flood defence, we mean the moment at which a failure mechanism initiates due to the hydraulic load (water level, wind). Some failure mechanisms do not directly result in flooding because of the presence of some reserve strength. The flood defence collapses when water enters the area and the area is inundated.

Failure of the flood defence is the result of the occurrence of one or more of the following failure mechanisms (Vrijling, 2001; Steenbergen et al., 2004):

- wave overtopping and overflow,
- uplifting and piping,
- inner slope failure,
- damage of revetment and erosion of dike body,
- failure in closing movable flood defences,
- erosion of dunes.

The flood defences are subject to hydraulic loads, such as high river discharges, extreme winds or a combination thereof. Large river discharges result in high water levels, which can be even higher because of wave overtopping due to extreme wind. In the upper-river branches, high water levels mainly cause the hydraulic load on the flood defences. The wind is relatively less important in the upper-river area.

The hydraulic load in the lower-river area consists of a combination of high river discharges in the Rhine and the Meuse, and high water levels caused by storms on the North Sea. In addition to the wind, the hydraulic load of the flood defences of the IJssel and the Vecht estuaries are high water levels caused by high river discharges from the upper river and the lakes below. The hydraulic loads on the flood defences of the lakes are high water levels at the lake and/or wind. The water levels on the lakes are influenced by the wind, the discharges to the lakes, and the possibilities of sluicing at sea. Water levels and wind waves caused by storm tide and extreme wind velocities determine the hydraulic load of the flood defences along the coast.

Because of the difference in threats, the following water systems are distinguished:

- Upper river: leveed Meuse and Rhine;
- Lower river: Meuse and Rhine branches;
- IJssel estuary and Vecht estuary;
- Lakes: IJssel lake and Marker lake;
- Sea and estuary: North sea, Wadden sea and Western Scheldt.

3 OBTAINING EXPERT JUDGEMENT

This section explains how the expert opinions are gathered, what the experts' fields of expertise are, and how the uncertainties in the time available for evacuation are elicited.

3.1 *Obtaining individual and group information*

Different methods can be used for an expert judgement investigation (Cooke, 1991; Cooke and Slijkhuis, 2003). The experts can be approached individually or a workshop/expert meeting can be organised. Each method has its advantages and disadvantages. The advantage of the individual approach method is that all experts are heard. Furthermore, it is possible to take into account the reliability of the expert. The disadvantage of this method is the time it takes to interview all the experts individually.

In an expert meeting, the basis is that 'two heads are better than one'. An advantage is that consensus can be reached easily. Furthermore, an expert meeting has a positive effect on creating support for the decisions that will eventually be made. On the other hand, during an expert meeting it is possible that not all the opinions are heard. Therefore, we chose for the individual approach.

The opinions of the experts were gathered by interviewing them according to a questionnaire. This questionnaire is based on currently available information (literature study) and was reviewed by a number of technical experts. In this way, a well-founded questionnaire was compiled for gathering the necessary information with regard to time and associated uncertainty. The questionnaire was sent to the experts prior to the interview so that they were able to prepare for the interview.

The questionnaire was divided into two parts. In Part 1, the subject was flood forecasting. The expert was asked to estimate how long in advance a critical situation (water level) can be predicted with a given uncertainty per water system. The subject of Part 2 was the failure initiation and collapse of the flood defence. The experts were asked to estimate the duration from the moment a failure mechanism is initiated and the flood defence fails until the moment the flood defence actually collapses. It is assumed that the failure of the mechanism concerned is initiated by high water.

Figure 3. Danube flood, Emmersdorf an der Donau, Austria, August 13, 2002 (Photography: J.M. van Noortwijk).

3.2 *Fields of expertise of experts*

After interviewing each expert individually, the answers were combined, analysed and discussed with a number of specialists. In total, eight experts were interviewed. These experts were selected according to expertise, background, and area of work, etcetera. The experts were asked to answer the questions based on their experience and knowledge (see Table 1).

Table 1. Fields of expertise of the experts.

	Expertise
Expert 1	High water situations on the lower-river branches, the sea and estuary
Expert 2	High water situations on the upper-river branches
Expert 3	High water situations IJssel/Marker lake and IJssel/Vecht estuary
Expert 4	High water situation Dutch rivers 1995
Expert 5	Risk analysis and structural reliability
Expert 6, 7, 8	Failure mechanisms

The experts indicated that it was difficult for them to answer questions that were not related to their expertise and daily work activities. Therefore, only the answers of one or two experts were available per question.

To analyse the answers, we took the expertise of the experts into consideration. That is, the results were based on the answers provided by the expert with the expertise related to the question concerned. Next, the results were compared with the remaining answers and were sometimes adapted after consultation with the DWW.

3.3 *Uncertainty in time available for evacuation*

The expert was asked to supply answers in terms of time (hours) and uncertainty bounds. However, it is possible that the moment of failure is not accurately estimated. The uncertainty in the time available was determined by the uncertainty in the time to failure initiation (e.g. extreme water level) as well as the uncertainty in the time until the collapse of the flood defence caused by the initiated failure (e.g. damage of revetment and erosion of dike body). Besides the prediction (in time [hours]), the expert was asked to estimate the uncertainty interval.

The uncertainty is taken into account in the questionnaire by asking the expert for the median (50th percentile), as well as his/her 5th and 95th percentile. The 5th percentile has a probability of non-exceedance of 5%. It means that in one out of twenty cases, the time available for evacuation is less than the 5th percentile. For the 95th percentile, the expert is asked to estimate the time for which, in one out of twenty cases, the time is longer than the 95th percentile. For convenience, the 5th and 95th percentile are called the 5% lower "bound" and 95% upper "bound".

Figure 4. Flooding of the Danube river near Melk, Austria, August 13, 2002 (Photography: J.M. van Noortwijk).

4 COMBINING EXPERT JUDGEMENT

The aim of the expert judgements was to estimate the time available for evacuation (in terms of hours) with an uncertainty interval (an upper and lower bound). By means of a questionnaire, expert estimates are gathered on:

1. how long in advance a critical situation (water level) can be predicted (called the prediction time),
2. how much time it takes from failure initiation until the actual collapse of the flood defence for the different failure mechanisms per water system (called the failure time).

The following assumptions are made:

- a critical situation is a situation in which a critical water level initiates a failure mechanism,
- the critical situation will last for some days,
- the flood defence will collapse, water will enter the area and the area will be inundated.

To determine the time available for evacuation, the expert judgements on prediction time and failure time need to be combined. To combine the 5%, 50% and 95% quantiles of the prediction time with the 5%, 50% and 95% quantiles of the failure time, we have to make an assumption about the statistical (in)dependence of the prediction and failure time. It is expected that a shorter (or longer) prediction time not definitely result in a shorter (or longer) failure time. That is, the prediction time and the failure time can be assumed statistically independent.

Given the assumption of independence, the next step is to combine the results. The combination of uncertainties of symmetrical uncertainty bounds is straightforward under the assumption of normal distributions. Uncertainty bounds are symmetric when the difference between the 50% and 5% quantile and the 50% and 95% quantile are identical. In this situation, the assumption can be made that the prediction time and the failure time both have a normal distribution. With the assumption of statistical independence, the sum of the prediction time and the failure time also has a normal distribution, where the expectation equals the sum of the individual expectations and the variance equals the sum of the individual variances (see, e.g., Mood et al., 1974, Chapter 5).

However, it appears that not all uncertainty bounds are symmetric. For asymmetric bounds, the method for symmetric uncertainty bounds can be used by approximation.

To determine the 50% quantile of the sum of the prediction and failure time, the 50% quantiles of the prediction time and the failure time can simply be summed. For the combination of uncertainties (5% and 95% quantiles) in the prediction time and failure time, it is not possible to simply add the individual quantiles. In this situation, complete dependence would hold and the uncertainty would be too large.

Next, the mathematical formulas are derived for combining the uncertainty bounds of the prediction and failure times under the assumption of normality. Let X be the prediction time with mean μ_X, standard deviation σ_X, 5th percentile $x_{0.05}$, 50th percentile $x_{0,50}$, and 95th percentile $x_{0.95}$. Similarly, let Y be the failure time with mean μ_Y, standard deviation σ_Y, 5th percentile $y_{0.05}$, 50th percentile $y_{0,50}$, and 95th percentile $y_{0.95}$. With the assumption of independence, the 5th percentile of the sum ($Z = X+Y$) of the prediction time (X) and the failure time (Y) is approximated as follows (Mood et al., 1974, Chapter 3):

$$z_{0.05} = \mu_{X+Y} + \Phi^{-1}(0.05)\sigma_{X+Y} =$$
$$= x_{0.50} + y_{0.50} - \sqrt{[x_{0.50} - x_{0.05}]^2 + [y_{0.50} - y_{0.05}]^2},$$

where $\Phi(x)$ is the cumulative distribution function of the normal distribution with zero mean and unit variance. For the 95th percentile of the sum of the prediction time and the failure time, we get analogously:

$$z_{0.95} = \mu_{X+Y} + \Phi^{-1}(0.95)\sigma_{X+Y} =$$
$$= x_{0.50} + y_{0.50} - \sqrt{[x_{0.95} - x_{0.50}]^2 + [y_{0.95} - y_{0.50}]^2}.$$

These formulas for the 5th and the 95th percentile of the sum of the prediction time and the failure time are exact when the uncertainty interval given by the experts is symmetric and normally distributed. If the uncertainty intervals are not symmetric, the abovementioned method can be applied by approximation. The advantage of this analytic approach is that (asymmetric) probability distributions do not have to be fitted on the percentiles of X and Y, which then have to be combined with, for instance, a time-consuming Monte Carlo simulation.

5 EVALUATION AND DISCUSSION

The results of the expert judgment study are given in Table 2. In this table, an overview is provided of the estimates related to the time available for preventive evacuation with uncertainty interval, depending on the water system and the type of failure mechanism.

The results provide a rough estimate of the time available for preventive evacuation. It helps crisis managers to gain more insight into the deliberation process of '(partial) evacuation in the event of a threatening flood'. The answers given are rough estimates and provide an order of magnitude. Besides this, particularly in relation to the time between failure initiation and collapse, the experts' estimates vary considerably. The experts' estimates are analysed and discussed with the specialists to obtain these results.

Extreme river discharges in the Netherlands can be predicted up to several days ahead, whereas extreme sea water levels have a much shorter prediction time of about 6 to 10 hours. River stage predictions are more accurate for the Rhine than for the Meuse. The prediction times of the critical situation can be increased for the coastal and the lake area. In those areas, the models for predicting high water levels are being improved at present. An improvement in the forecast of water levels along the coast and lakes will also have an influence on the prediction times in the lower-river area.

In the estimation of the time from failure initiation to collapse of a flood defence, the experts' estimates differ strongly. For some failure mechanisms (wave overtopping and overflow, uplifting and piping, erosion of dike body, not closing structures), the experts gave the answer 'infinite' for the 95th percentile. In this study, we assume that the flood defence then collapses. That is why the 95th percentile is then determined by the maximum duration of the hydraulic load at high water. For the upper rivers, we assume (following the experts) a maximum high water period of 4 days (96 hours). For the lower rivers, we assume a maximum high water period of 2 days (48 hours). The smaller maximum high water period of 2 days is due to the influence of sea storms, which can only be accurately predicted about 6-10 hours in advance. Because sea water levels are more difficult to predict, the answers of the experts differ considerably.

To determine the failure time, the estimates can be improved by organising an expert meeting to confront the experts with the differences in their estimates. Furthermore, more insight into the failure times for particular failure mechanisms can be gained by means of experimental and model research into the way the flood defence system fails.

Based on the expert judgement study, it can be concluded that it is difficult for the experts to give the prediction horizon and the accuracy. The answers provided by the experts differ strongly in a few cases. They provide an initial indication of the available time for evacuation and are useful for gaining insight into the evacuation process for the development of policy studies and disaster management plans.

Because there are almost no observations of the available time, we have had to rely on expert judgement. In addition, the results of this study provide a basis for further discussion. The results give an administrator insight into the time available for evacuation of his dike-ring area. The probability of failure is not included. It is up to the administrator/crisis manager to point out which failure mechanism has the largest probability.

The expert judgement to estimate the time available should not replace research. Of course, experimental and model research is still recommended to improve the estimates.

Table 2. Estimates of time available for evacuation with uncertainty interval depending on water system and failure mechanism.

	Time Available for Evacuation [hours]																								
	Failure Mechanism	Overtopping/ Overflow			Uplifting and Piping			Inner Slope Failure			Erosion of Dike Body			Piping Large Structure			Piping Small Structure			Not Closing Structure			Dune Erosion		
Type of Threat	Quantile	5%	50%	95%	5%	50%	95%	5%	50%	95%	5%	50%	95%	5%	50%	95%	5%	50%	95%	5%	50%	95%	5%	50%	95%
Upper River	Rhine	35	60	147	30	54	147	35	60	87	86	120	154	34	60	87	30	54	79	33	58	147	-	-	-
	Meuse	46	60	147	41	54	147	46	60	87	93	120	154	44	60	87	41	54	79	44	58	147	-	-	-
Lower River	Rhine Branches Lek Hagestein	35	60	103	36	60	103	28	52	77	69	96	130	34	60	87	30	54	79	35	60	103	-	-	-
	Rhine Branches Waal Werkendam	15	24	61	19	24	61	11	16	27	47	60	86	13	24	39	12	18	29	15	24	61	-	-	-
	Rotterdam	13	22	59	17	22	59	9	14	25	45	58	84	11	22	37	10	16	27	13	22	59	-	-	-
	Meuse Lith	22	36	74	24	36	74	16	28	41	55	72	99	20	36	53	17	30	43	22	36	74	-	-	-
	Meuse Dordrecht	15	24	61	19	24	61	11	16	27	47	60	86	13	24	39	12	18	29	15	24	61	-	-	-
	IJssel Estuary Hattem	19	36	74	14	30	74	19	36	53	53	72	99	18	36	53	14	30	43	18	34	74	-	-	-
	IJssel Estuary IJssel-Ketelmeer	12	24	62	8	18	62	12	24	41	45	60	87	11	24	41	8	18	31	11	22	62	-	-	-
	Vecht Estuary Dalfsen	12	21	58	9	15	58	12	21	36	44	57	83	10	21	36	9	15	26	11	19	58	-	-	-
	Vecht Estuary Ramspol Barrier	12	24	62	8	18	62	12	24	41	45	60	87	11	24	41	8	18	31	11	22	62	-	-	-
Lake	IJssel Lake	9	18	62	12	21	62	7	16	29	45	60	87	11	24	41	8	18	31	7	16	29	-	-	-
	Marker Lake	9	18	62	12	21	62	7	16	29	45	60	87	11	24	41	8	18	31	7	16	29	-	-	-
Sea	North Sea	10	15	58	16	21	33	20	33	59	32	45	60	10	21	36	9	15	26	12	21	58	19	25	31
	Wadden Sea	10	15	58	16	21	33	13	21	36	32	45	60	10	21	36	9	15	26	12	21	36	-	-	-
	Western Scheldt	10	15	58	16	21	33	20	33	59	32	45	60	10	21	36	9	15	26	12	21	58	-	-	-

6 TIME REQUIRED FOR EVACUATION

The time required for evacuation mainly depends on the availability of an evacuation plan, the number of people to be evacuated and the available infrastructure. Rough estimates of the first three phases have been determined using literature study and expert judgment without uncertainty bounds (see Table 3 adapted from Frieser, 2004). For the rivers Rhine, Meuse, Vecht and IJssel, the total time to initiate evacuation is about 10 hours (decision making: 4 hours; warning of population: 3 hours; response of population: 3 hours). It is possible that the different phases overlap.

Table 3. Estimates of time required to initiate evacuation.

Water System	Time required to initiate evacuation [hours]	
Evacuation Process	Rivers	Lakes and Sea
Decision Making	4	2
Warning Population	3	2
Response Population	3	2
Total	10	6

For the IJssel lake, Marker lake, North sea, Wadden sea, and Western-Scheldt, the initiation time of evacuation is 6 hours (decision making: 2 hours; warning of population: 2 hours; response of population: 2 hours). The reason that the time to initiate evacuation is less for the lakes and sea than for the rivers is that the available time for preventive evacuation is also less. River floods can generally be better predicted in advance than sea and lake floods.

The estimates in Table 3 represent the minimum times required for evacuation per phase. For every phase, conditions were provided which must be satisfied in order to achieve the minimum time required. These conditions are based on experiences with earlier evacuations. If one or more conditions are not fulfilled, the time required for evacuation will generally be larger.

The duration of the preventive evacuation itself can be calculated by a decision support system called the Evacuation Calculator (EC) developed by the University of Twente in the Netherlands (van Zuilekom et al., 2005). During a preventive evacuation, there is no actual flooding and a lot of the usual traffic modelling assumptions can be applied. On the basis of a traffic model, EC computes the percentage of the number of people that are evacuated from a dike-ring area as a function of time.

The time available and required (incl. the duration of the evacuation itself) must be combined to determine the fraction of the people that can be preventively evacuated at a given time (see Figure 5). The duration T_i represents the time required to initiate the evacuation (decision making, population warning and population response) and T_e the time required to transport all the people (100%) from the dike-ring area. The time required for evacuation is the sum of T_i and T_e. The time available is graphed by means of the vertical line A. The time required for the actual evacuation is shown by the time-dependent function. From this figure, we can easily obtain the fraction of people that are preventively evacuated (f_e) at the time of collapse of the flood defences. The order of magnitude of the total time required for evacuation (decision making, population warning, population response, and preventive evacuation) is roughly 2 days.

Recent data on the time required for evacuation come from the high water levels of the Rhine at the end of January and the beginning of February 1995. During this high-water situation, a peak discharge at Lobith was measured of 12,060 m^3/s as well as a peak water level of 16.65 m +NAP. This turned out to be the highest observed discharge since 1926. Because there was doubt about the stability of some dikes, about 250,000 people and all livestock were evacuated from the threatened dike-ring areas during one week.

In 1995, the time it took until the decision was made to evacuate lasted 16 hours. This is much larger than the time for decision making of 4 hours estimated by the experts. Possible reasons for this difference are: (i) the situation was not ‘urgent’ and (ii) the time could be shorter if all the parties would have been well prepared. The estimate of 4 hours holds for exceedance of the alarm stage of 17.65 m+NAP, whereas only 16.65 m+NAP was measured. Apparently, the high-water situation of 1995 was not sufficiently severe to require immediate action. The 1995 flood showed that also water levels less than the alarm stage can create a necessity to evacuate. In 1995, the total time required for evacuation was 44 hours.

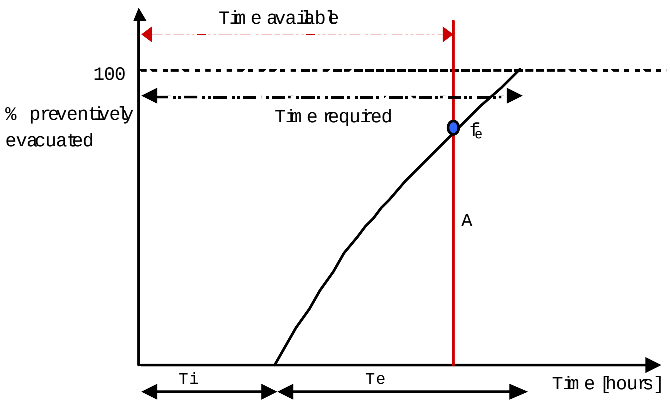

Figure 5. Percentage of people that are evacuated as a function of time.

7 RECOMMENDATIONS

For further research, we recommend:

- Organising an expert meeting to confront the experts with the diversity in their answers in order to obtain better substantiated data.
- Improving the estimates by combining observations of historical failures, like the movement of the dike in Wilnis and the collapse of the dikes in Zeeland in 1953, with existing experiments.
- Improving the failure models by performing more experimental and model research on the way in which flood defences fail due to different failure mechanisms, the emphasis being on the time from failure initiation to collapse of the flood defence.
- Improving the flood forecasting models. For the coastal zone, the most important uncertainty is the wind speed and direction. For these two threats, flood forecasting is currently being improved.
- Improving the communication between the organisations that predict the water levels and the water boards and administrators. In the upper-river area, the water boards and the organisations forecasting the water levels are currently in consultation about the possibilities of improving the flood forecasting times. The water boards indicated their wishes regarding the required accuracy of the prediction time.
- Monitoring and updating the available information about the prediction time and the failure time as soon as new flood disaster data becomes available.

Figure 6. Flooding of the Danube river, Kemmelbach, Austria, August 13, 2002 (Photography: J.M. van Noortwijk).

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