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Kolen, Bas; van Gelder, P. H.A.J.M.

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Risk-Based Decision-Making for Evacuation in Case of Imminent Threat of Flooding

Bas Kolen [1,2] **and P.H.A.J.M. van Gelder** [2,3,*]

[1] HKV Consultants, Elektronicaweg 12, 2628 XG Delft, The Netherlands; B.Kolen@hkv.nl
[2] TU Delft Safety and Security Institute, Delft University of Technology, Jaffalaan 5, 2628 BX Delft, The Netherlands
[3] Section of Safety and Security Science, Department of Values, Technology and Innovation, Faculty of Technology, Policy and Management, Delft University of Technology, 2628 BX Delft, The Netherlands
* Correspondence: p.h.a.j.m.vangelder@tudelft.nl

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Abstract: It is important for decision-makers in emergency response situations to determine the scope, scale, timing, path and resettlement area of an evacuation decision when there is an imminent threat of flooding. In this paper, a method called the "Evacuation Diagram" is described to support risk-based evacuation planning and decision-making. In case of an imminent threat of flooding, we refer to the conditional risk, which is the risk given the forecasted water levels and potential consequences during the next days of the event. Given the threat and potential costs and benefits, evacuation decisions have to mitigate this conditional risk. Since evacuation can be costly, decision-makers have to make a trade-off between costs and benefits. In this research we present a method using a cost–benefit analysis approach, in which we adopt the "Dutch flood risk approach" to define the required strength of levees based on flood risk considerations. The "Evacuation Diagram" method is derived from analytical derivations, based on differential weighing of costs and benefits, which have an impact on a binary choice (or a set of discrete choices) as to whether to instruct an area to evacuate or not. Basically, this is an analysis of behavioural decision-making under risk, investigating how a cost–benefit analysis can yield higher cost effectiveness in risk reduction for human lives lost during possible evacuation incidents. The method is applied to a Dutch case study and the results are compared to the outcomes of the largest evacuation exercise ever held in the Netherlands, called 'Waterproef'. It is concluded that the risk-based evacuation method, as presented in this paper, provides useful insight into collective and authoritative evacuation order decisions.

Keywords: flood risk; evacuation; probabilistic analysis; cost–benefit-analysis

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1. Introduction

Floods are often described as the most deadly of all natural disasters [1]. Flood risk is defined as the product of the probability of flooding and the consequences of flooding. The consequences are often expressed as the economic costs and loss of life. Both indicators are important and are to be considered when discussing acceptable (or tolerable) risk or decisions to evacuate. This definition is commonly accepted in the flood risk literature [2,3]. Alternative definitions describe the risk in terms of hazard, vulnerability and exposure [4,5]. Both approaches for defining risk lead to similar outcomes, as they both consider the occurrence of a hazard (the probability) and the consequences (vulnerability, exposure) of a given occurrence.

Sunstein [6] states that quantitative analysis of the risks is indispensable to a genuine deliberative democracy. Risk analysis can compare different (competing) strategies. Different competing strategies or measures can be compared using a rational approach (which may be risk-seeking or risk averse) based on the benefits (as risk reduction) and the costs (investments) of these alternatives [7]. Flood scenarios which describe the development of a flood given the size of a breach and characteristics of an area are already used in the field of risk-based approaches to define the optimal strength of a levee system [8–10].

Different approaches for flood risk management have been adopted in various parts of the world. A flood risk management strategy can consist of measures which can be categorised in multiple layers as prevention with levees, land use planning, building codes, insurance and emergency management. A multiple-layer safety approach, such as that followed in the Netherlands, consists of three layers: (1) prevention, (2) land use planning, and (3) emergency management [11]. For the US (see, for example, [12]) and for Canada (see, for example, [13]), similar approaches are referred to as 'multiple lines of defence'. The concept of multiple-layer safety distinguishes the probability of flooding as well as the consequences. Therefore, the risk as the probability x consequences is the central element, and such an approach can be used to evaluate flood risk management [14]. Kolen and Kok [15] describe a cost–benefit approach (CBA) to define the optimal mix of measures to reduce flood risk based on using a multiple-layer safety approach. The costs refer to the investments required by the measures, and the benefits correspond to the reduction in the flood risk. These studies express risk in terms of the costs of loss of life per year and are used to develop policy and design the multiple-layer safety system.

The valuation of human life is sometimes addressed as unethical because a life is worth much more than its economic value; hence, life is invaluable. However, it does have an economic value [16,17], as shown by its use in investment decisions in several fields of expertise [18–20]. For the Netherlands, the use of the economic value for the loss of life in risk assessments is accepted by the Dutch Parliament to define the optimal levels of flood defences [21].

In this study, we focus on a situation where there is a threat of flooding. We speak of the conditional risk, the risk given the forecasted water level during the threat event. The strength of the levees and the available infrastructure, houses and the number of emergency personnel is a given. In this paper, we focus on the call for evacuation. Evacuation is defined as the process of alerting, warning, deciding, preparing, departing and (temporarily) holding people, animals, personal belongings and corporate stock and supplies from an unsafe location at a relatively safer location given the actual circumstances [22]. As for the design of multiple-layer safety systems and corresponding evacuation decisions, a quantitative analysis of the risks is also indispensable to a genuine deliberative democracy.

In this research, we describe a method, called "Evacuation Diagram", for risk-based decision-making in case of a threat of flooding, as a part of an integrated flood risk management strategy. The method supports evacuation planning and decision-making when there is a threat of flooding. The method is developed for the Netherlands, based on a similar CBA approach as used to define the flood risk management strategy and the strength of the Dutch levees. The results of the method are reflected in the decisions made during the exercise Waterproef, the largest flood risk exercise ever in the Netherlands.

It is noted that the proposed method in this paper is primarily a tool for situations where (1) there is large uncertainty about flooding, and (2) it is not clear in advance whether the entire evacuation can be successfully completed. The proposed method does not prescribe the decision, but it gives the decision-maker a handle to substantiate the decision and to explain it (afterwards). It makes it possible to prepare decisions prior to extreme events by comparing multiple alternatives and different parameter settings.

2. Decision-Making for Evacuation

The key driver for these decisions is a risk-averse policy that aims to reduce the numbers of fatalities. However, evacuation can be costly with respect to time, money, and credibility [23]. In addition, evacuation can even worsen the scenario when people move to a more dangerous place (as, for example, when they are exposed while walking or driving in a car).

Prior to landfall of hurricane Harvey, the Houston mayor decided not to evacuate preventively but to inform people to prepare themselves at home. This decision was made based on the available forecasts and the potential impact of evacuation. A preventive evacuation of 6.5 million people could have resulted in a higher risk. An earlier evacuation prior to hurricane Rita in 2005 resulted in 100 fatalities. With hindsight, the number of fatalities in Houston due to Harvey was estimated at 78 [24].

When an evacuation starts too late, not all evacuees may be able to leave the area or arrive at a safe destination in time [25–28]. For the Netherlands, a completed successful preventive evacuation is almost not possible because of the limited lead time [29].

In the case of the threat of flooding, citizens, companies and authorities will act on the (perceived) threat and the consequences of the possible measures. Human interventions can reduce the consequences of a flood. For example, during hurricanes and flooding, people and movable goods might be saved through evacuation [2]. The effects of human interventions could be seen during Katrina along the Louisiana and Mississippi coast based on the results of contra flow [30], decision-making [31] and the loss of life [32], as well as during the flood of 1953 in the North Sea Area [33,34] and Xynthia in France [35,36]. The costs of evacuation due to hurricanes in the United States can exceed one million dollars per mile of coast as a result of losses in commerce and productivity, as well as direct losses [37]. Credibility relates to concerns about the quality and sources of information, the discrepancy between timely warnings and later but more accurate warnings [38], and the impact of false alarms [39].

Planning documents describe responsibilities and how measures have to be executed. Planning documents also describe criteria when warnings have to be issued to inform people or other organisations. However, the dilemma for decision-makers is when to call for evacuation in a real event and how to deal with the (uncertain) information. Therefore, the implicit value of a human life is finite. Choices in emergency management are made based on (implicit) trade-offs between the reduction of the risk of loss of life and the costs of these measures. There is a need for explicit relationships between the costs of measures and the benefits to supporting decision-making for emergency services.

A call for evacuation in case of a threat of flooding is in many places in the world a once-in-a-career, or even -lifetime, decision, or even less. Therefore, these high-impact decisions will have enormous consequences based on whether the flood occurs or not. Also, the experience of dealing with the information and circumstances in order to make decisions is limited. In reality, the process of decision-making is sometimes subjective, and multiple criteria are taken into account. From a risk-management perspective, such a decision to call for evacuation can be seen as a similar decision to defining the optimal level for the strength of the levee system using a cost–benefit approach.

The decision-making process for mass evacuation is characterised by short reaction times and requires consideration of the probability of a certain impact, possible life-and-death situations and the economic impact. Decision-makers have to decide which information to use, and they have to assign value to information [40]. Decision-makers (in multiple teams) and crisis managers can simultaneously provide multiple frames of reference about a certain phenomenon. This is called ambiguity, which in some literature is described as uncertainty [41,42]. Other literature states that ambiguity is not a part of uncertainty but that 'Ambiguity is removed on the level of words by linguistic conventions' [43]. The risk of linguistic problems increases when the risk perception or awareness is limited. Because of the present on-going struggle for risk awareness for flood risk management by decision-makers [14] and low risk perception of the public [44], ambiguity might impact decision-making for evacuation. If ambiguity is considered to be a linguistic problem, it can be prevented by devoting enough effort towards it.

Kolen and Helsloot [45] showed that Dutch decision-makers (and crisis managers) respond (very) differently to the same flood risk information with regard the call for evacuation. The same decision-makers, however, adopted a nationwide flood risk approach to define the standards for the strength of the levees [46]. The call for evacuation, therefore, is influenced by ambiguity. A better understanding of risk, costs and benefits and heuristics and biases can improve judgments and decisions in cases of uncertainty [47,48] also shows the need to support decision-makers in cases of crisis management with risk-based information.

Kolen and Helsloot [45] identified, in a survey among Dutch decision-makers and crisis managers, the most critical parameters for the call for evacuation. Although many factors will influence the decision for evacuation the probability of a flood, the costs and benefits (including fatalities) were the most important parameters. Also, during hurricane Harvey, the tradeoff between the probability of the event and the costs and benefits of evacuation was made by the Mayor of Houston (resulting in the call not to preventively evacuate) [24]. When the flood risk approach has already been adopted to define the strength of the levees, this approach can also be used to support emergency planning and the call for evacuation.

3. Methodology "Evacuation Diagram"

Different objectives to minimize the risk for a society can be defined as follows:

1. To minimize the risk of loss of life.
2. To minimize the economic risk.
3. To minimize the total risk considering the combination of economic risk and risk of loss of life.

The key question is how to define the conditional probability of flooding with respect to a call for evacuation. The objectives above can result in different conditional probabilities of flooding to call for evacuation; therefore, the objective has to be defined clearly.

The benefits for evacuation are described as:

1. $s_0 - s_1$ as the number of prevented loss of life by evacuation. s_1 is defined as the number (persons) of lives lost in the case of a flood event with evacuation, s_0 is defined as the number (persons) of lives lost in the case of a flood event without evacuation;
2. C_1 as the value (Euro) of the goods that are saved by evacuation.

As previously mentioned, an evacuation can be costly as well, and the following variables are introduced to describe the costs:

1. s_2 as the number of lives lost because of evacuation (these also occur when the flood does not occur for example in car accidents of hospital evacuation);
2. C_2 as the costs (Euro) of the evacuation because of the limitations of economic and social processes and economic costs of the use of equipment and resources (this is estimated by the reduction of the added value to the gross regional product).

P_t is defined as the 'conditional probability of flooding' in t days given the forecasts of hydraulic loads and the strength of the defence system. Uncertainties in the probability of flooding are not taken into account, yet, in this example. The 'conditional probability of no flooding' (P_0) is equal to:

$$P_0 = (1 - P_t) \tag{1}$$

If the objective is to minimise the risk of loss of life, a call for evacuation is made when the expected costs of no evacuation ($P_t s_0$) are larger than the expected costs of evacuation ($s_2 + P_t s_1$):

$$P_t s_0 > s_2 + P_t s_1 \tag{2}$$

Which can also be described as when:

$$P_t > \frac{s_2}{(s_0 - s_1)} \text{ with no evacuation when } RightHandSide(RHS) > 1 \tag{3}$$

When the objective is to minimise the economic risk, it should be decided in favour of evacuation when the benefits of the prevented damage in case of a flood are more than the economic costs of evacuation (because economic processes will stop because of evacuation), while taking the conditional probability of flooding into account:

$$P_t C_1 > C_2 \quad (4)$$

Therefore, the decisions to call for evacuation with the objective of minimising the economic risk is made when:

$$P_t > \frac{C_2}{C_1}, \text{with no evacuation when } RHS > 1 \quad (5)$$

When the combination of economic risk and human life is taken into account in the cost–benefit analysis, the relationship between the economic risk and the risk of loss of life becomes clear. Information can be generated that offers insights into the costs incurred to prevent the loss of life. Each casualty is economically valued as V. The combination of costs for the loss of life and economical damage results in a call for evacuation when:

$$P_t > \frac{s_2 V + C_2}{((s_0 - s_1)V + C_1)}, \text{ with no evacuation when } RHS > 1 \quad (6)$$

When risk aversion (which can be part of a rational approach) is known in advance, it can be taken into account in the approach as well. Therefore, a factor is introduced to reflect the willingness to evacuate to prevent the loss of life (f_1) and damage (f_2). This results in:

$$P_t > \frac{s_2 V + C_2}{((s_0 - s_1)V f_1 + C_1 f_2)}, \text{ with no evacuation when } RHS > 1 \quad (7)$$

The value of f_1 and f_2 can be defined in advance and taken into account during emergency planning to take risk aversion into account. These values can be determined by presenting various scenarios to decision-makers and inferring their risk aversion from their preferences, as shown, for instance, in [49]. If necessary, a parameter for risk aversion can also be added to the loss of life because of evacuation. However, because of the subjective elements of decision-making and because of the judgment process in a real event (it has to be taken into account that other decisions can be made [40]. Using the "Evacuation Diagram" method, decision-makers can make trade-offs with other parameters.

Application of the above method as a function of time, and taking uncertainties into account, results in typical hyperbolic-shaped "Evacuation Diagram", as illustrated in Figure 1. The Evacuation Diagram shows the expected value of the conditional probability of flooding when calling for evacuation given the reduction of loss of life and economic consequences in case of a flood and the consequences caused by evacuation. The amber bandwidth represents the impact of uncertainty and describes the zone in which the costs and benefits are comparable for evacuation and no evacuation. The red and green zones are beyond the bandwidth of uncertainty. When the probability of a flood in a certain event combined with the prevented loss of life is in the red zone, a call for evacuation has to be made based on an economic approach. The green zones indicate situations when no call for evacuation has to be made based on an economic approach. The evacuation diagram shows that when more loss of life can be prevented by evacuation, the call for evacuation can be made with a lower probability of flooding. The evacuation diagram also shows that when fewer people can be saved, the level of probability of flooding at which a call for evacuation should be made increases.

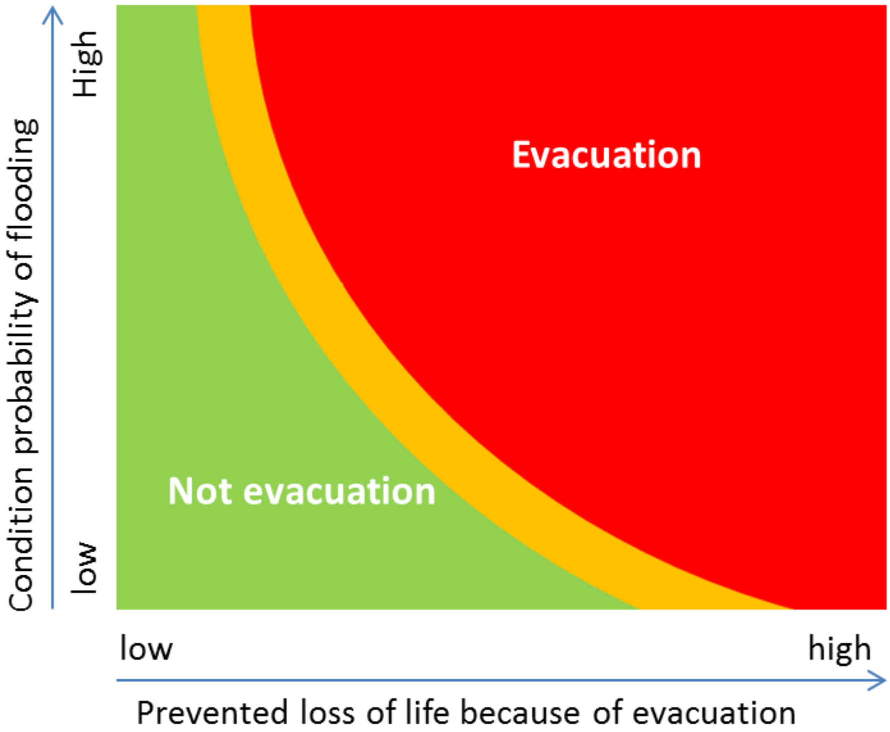

Figure 1. Evacuation diagram (after Kolen 2013).

4. Case Study: Evacuation Decision for Polders in The Netherlands

4.1. Introduction

The Dutch Delta has a low frequency of flooding because of dikes, dunes and structures, and criteria for flood protection are set by law. This is to protect large areas that represent a high economic value. Two-thirds of the total number of people live in a flood-prone area, and 70% of the Gross Domestic Product is earned in flood-prone areas. Risk assessments show that flooding is considered to be the disaster with the highest consequences in the Netherlands [50]. Furthermore, earlier research showed that the risk of flooding is relatively high compared to other possible incidents [14].

In October 2016, the Dutch parliament decided to embrace a new approach to flood risk, which was implemented in the Water Act on 1 January 2017. Two central new elements are (1) that the new approach takes into account the potential loss of life due to catastrophic flooding, and (2) that the new standards are defined based on a probabilistic assessment [46]. The standards for flood defences in the Water Act [11] are therefore based on the acceptable flood risk for the protected areas; for each levee, a minimal probability of failure is defined [46,51]. The standards for these areas are based on two principles:

1. Everyone has to be given the same minimum level of protection: the basic level of protection, expressed as Local Individual Risk (LIR). LIR is defined as the probability of flooding × mortality × (1 − evacuation fraction). The LIR may not exceed 1/100,000 per year.
2. Where the impact of flooding is very high, a lower probability of flooding (or a higher level of protection) is appropriate, the standards are based on societal risk and a Societal Cost–Benefit Analysis (SCBA).

The low frequency of flooding also means that there is almost no real (or out-dated) experience with evacuation, but the risk persists. The public perception of the flood risk is very low [44,52], as is the level of attention to this issue from decision-makers and policy-makers, which also tends to decline over time [14]. An evacuation in the Dutch Delta is a complex operation because of the size of the threat, the available lead time, uncertainties, and the high density of people involved in relation to the road capacity [25,45]. It is, therefore, known that for some areas, a preventive evacuation cannot always by completely executed.

Forecasts of expected water levels are made by the KNMI and Rijkswaterstaat in the Netherlands. Forecasts result in an expected water level, with a margin of uncertainty [26] or even expected probability of flooding. Using predefined trigger values, warnings and alarms will be issued after interpretation by experts or using automatic systems. In the end, crisis management structures can be put into place and decisions for evacuation can be made.

4.2. Numerical Examples

In this section, the methodology is illustrated by some numerical examples for dike ring 14 in the Western part of Holland in the case of a call for preventive evacuation due to coastal flooding (Figure 2). The relation between the conditional probability of flooding and the consequences are defined for all three objectives as discussed in the methodology.

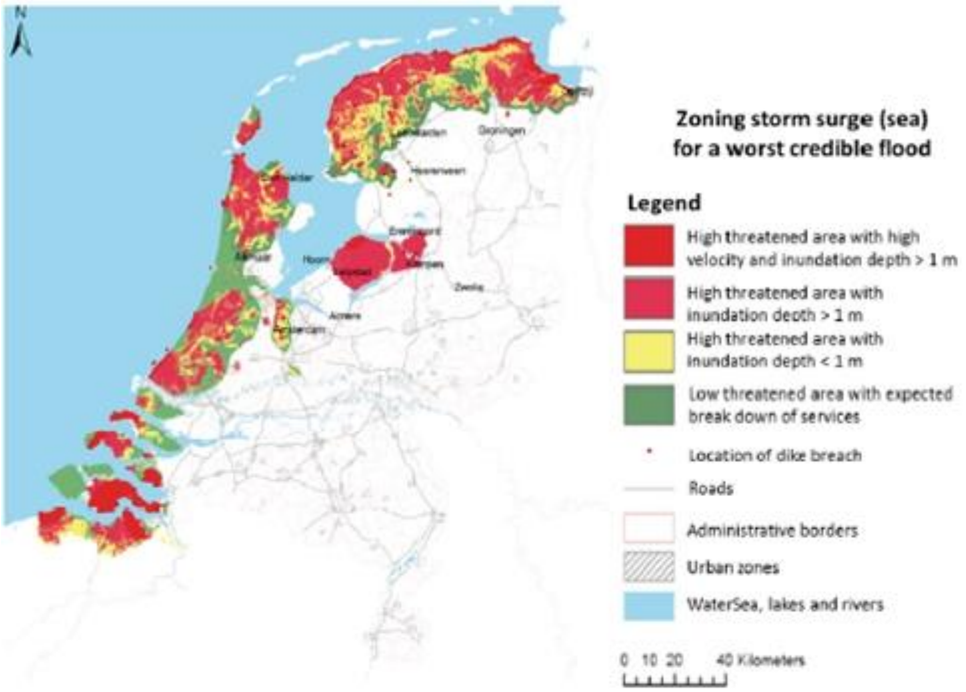

Figure 2. Map of the areas with the worst credible floods in the Netherlands (Source: [53]).

The following numerical values of the parameters are chosen, focusing on the Dutch situation of flooding and preventive evacuation.

- $V = 6.7$ M; the value for the loss of life V for the Netherlands is based on [54], based on econometric considerations.
- $s_2 = 25$ persons; the number of lives lost due to an evacuation (in reality, this is related to the number of people that evacuate, with special attention paid to people with special needs). Although no figures are known regarding the loss of life due to evacuation in the Netherlands, it is expected, based on international experience, that some loss of life will occur because of traffic accidents during evacuation and evacuation of hospitalized people (in dozens of threatened hospitals). It is expected that s_2 depends on the number of hospitals and the condition of patients who have to be evacuated, and further (empirical) research is recommended here to determine its sensitivity to the overall outcomes.

- $C_2 = 6000$ M; it is assumed that an evacuation including the return of the people will stop economic processes for a week and affect approximately 50% of the Netherlands. The total Gross Domestic Product of the Netherlands in 2010 was 590 Billion € [55]. The costs of evacuation are estimated at 1% ($1/52 \times \frac{1}{2}$) of the Gross Domestic Product.
- Because of the limited possibilities of evacuating all people, most effort will be given to reducing loss of life. In addition, movable goods can be evacuated to reduce damage. Because of uncertainty in the damage reduction, an optimistic and pessimistic assumption is taken into account:
  - For the optimistic assumption C_1 is 10% of the total damage in the case of a flood. For a worst credible flood on the western coast, the damage is estimated at 120 Billion € [56]; C_1 is therefore 12,000 M€;
  - For the pessimistic assumption, C_1 is 0.01% of total damage in the case of a flood; C_1 is 12 M€;
- Risk aversion is not taken into account, f_1 and f_2 are equal to 1.

Table 1 shows that the objective to 'minimise loss of life' results in different decisions for evacuation than the objective to 'minimise costs' or when the economic value for loss of life is taken into account. In the case when the prevented loss of life, and therefore the economic value of life, is far more than the economic damage, an optimistic or pessimistic assumption of C_1 has less influence on P_t to call for evacuation. When the number of prevented losses of life is 6000 persons, the minimal conditional probability of flooding to call for evacuation increases by only 3 percentage points (from 12% to 15%), while the prevented damage C_1 decreases from 12,000 M€ to 12 M€. When the number of lives lost declines, the prevented economic damage C_1 becomes more significant. For example, when the number of lives lost that is prevented is (only) 1000 persons, the minimal conditional probability of flooding to call for evacuation is 33% when C_1 is optimistic and 92% when C_1 is pessimistic.

When the available time is reduced for evacuation, fewer people can be saved, and $(s_0 - s_1)$ will be reduced. As time passes and the number of people that can be saved $(s_0 - s_1)$ is reduced, the minimal conditional probability of flooding to call for evacuation increases.

Table 1. Numerical examples for P_t to call for evacuation.

Objective: Minimise Loss of Life					
Prevented loss of life $(s_0 - s_1)$	100	500	1000	2000	6000
Minimal value for P_t in %	25%	5%	2.5%	1.3%	0.4%
Objective: minimise economic risk; Minimal value for P_t in %:					
Minimal value for P_t in % for optimistic prevented economic damage (C_1 is 12,000 M€)			50%		
Minimal value for P_t in % for pessimistic prevented loss of economic damage (C_1 is 12 M€) in %			No evacuation		
Objective: minimise economic risk including economic value for loss of life					
Prevented loss of life $(s_0 - s_1)$ in persons	100	500	1000	2000	6000
Minimal value for P_t in % for optimistic loss of economic damage (C_1 is 12,000 M€) in %	49%	40%	33%	24%	12%
Minimal value for P_t in % for pessimistic prevented loss of economic damage (C_1 is 12 M€) in %	No evac.	No evac.	92%	46%	15%

When the range between the optimistic loss of economic damage and pessimistic prevented loss of economic damage (as in Table 1) is considered, a bandwidth in the evacuation diagram can be defined. Figure 3 shows the evacuation diagram for the objective to minimise the economic risk including economic value for loss of life. For the examples, it is shown that when more loss of life can be prevented, the prevented damage influences the minimal conditional probability of flooding to call for evacuation. When fewer people can be saved, the estimation of the prevented damage becomes more significant. The examples also show that in some cases, it is better not to decide for evacuation; for example, when the loss of approximately 1000 lives can be prevented and the prevented damage by evacuation is 12 million €, the decision is not to call for evacuation. Alarm criteria in emergency planning, however, are to alarm in case of a threat.

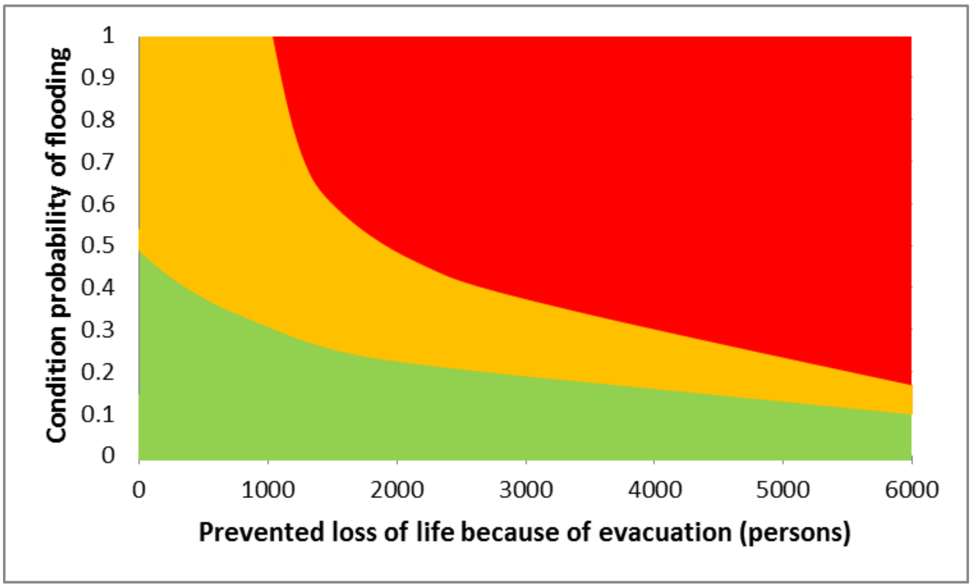

Figure 3. Evacuation diagram for numerical example of the Dutch dike ring no. 14.

Taking subjective arguments into account, the factors f_1 and f_2 can be used (and defined in advance). As described in this section, the model presents a linear relationship between the economic value for the loss of life V and f_1 and between the damage prevented by evacuation C_1 and f_2. When higher values are given to the prevented loss of life (which is expected because emergency plans give the highest priority to reducing loss of life, above critical infrastructure and above economic damage) the conditional probability of flooding for when to call for evacuation is reduced (see Table 2).

Table 2. Sensitivity analysis for numerical examples for the objective of minimising the economic costs, including the value of the loss of life.

Prevented loss of life ($s_0 - s_1$) in persons	100	500	1000	2000	6000
Minimise loss of life when f_1 and f_2 are equal to 0.5					
Minimal value for P_t in % for optimistic loss of economic damage (C_1 is 12,000 M€)	97%	80%	66	49%	24%
Minimal value for P_t in % for pessimistic prevented loss of economic damage (C_1 is 12 M€)	No	No	No	92%	31%
Minimise loss of life when f_1 and f_2 are equal to 2					
Minimal value for P_t in % for optimistic loss of economic damage (C_1 is 12,000 M€)	24%	20%	16	12%	6%
Minimal value for P_t in % for pessimistic prevented loss of economic damage (C_1 is 12 M€)	No	92%	46	23%	8%

4.3. Exercise Waterproef

Training and exercises are used to develop and maintain experience with emergency management. Research shows that training and exercises to stimulate the correct response have to be based on plausible scenarios [57]. Although an exercise is a constructed situation and not developed for scientific research, lessons can be learned for the top strategic decision-making process for mass evacuation by taking the circumstances of the exercise into account. Evaluation of the exercises gives a unique and realistic view of national crisis management in reality because these exercises are so large that they cannot be controlled by the supervisors of an exercise (higher and lower control) [58].

Waterproef was the first national exercise on flooding and mass evacuation, and was held after a two-year program of improvements for flood preparedness by the national Task Force Flood Management [59]. In this section, we reflect, using the developed method, upon the decision for evacuation made during the Dutch exercise Waterproef for coastal flooding. It was decided to postpone the call for complete evacuation until the next day and wait for the development of the threat. Because of the impact of the evacuation on economic processes and society, decision-makers decided to delay the call for evacuation and to monitor the further development of the threat.

The general feeling after this exercise was that people learned a lot and the preparation for flooding was improved. Reducing loss of life in the case of a flood is the top priority in Dutch emergency plans. However, in Dutch flood risk analyses, the costs also are taken into account. Therefore, we compare the decision in the exercise with the objective of minimising the total risk (based on economic damage and loss of life). The case 'Waterproef' illustrates the difficulties faced by decision-makers in dealing with uncertainties and in working with an integrated approach [59,60]. The decision-making process was not rational, and was dominated by perceptions and also by some emotions.

Using the evacuation diagram, we can reflect on the call for evacuation during Waterproef from the perspective of a cost–benefit analysis (as also used in Dutch flood risk management strategies). At the moment of decision-making during the exercise, the parameters were [53]:

- P_t was estimated at 40–45% by the water authorities.
- $s_0 - s_1$ was estimated by the National Operational Team at 8000 people if the call for evacuation was made; only 2000 fatalities would occur in case of the flood. When no decisions were made by the authorities regarding evacuation, the loss of life was estimated at 10,000 people (minimum strategy) in the case of a flood. Also, a strategy of partial evacuation was presented, reducing the number of lives lost to 4000 people.
- C_1 and C_2 were not quantified in the exercise; neither information regarding the consequences was given to the decision-makers. During the crisis meetings, the issue of credibility related to the fear of a call for evacuation not followed by a flood was discussed by the decision-makers.
- s_2 was not quantified in the exercise. s_2 is not taken into account in this analysis because it is outnumbered by far by the number of lives lost in the case of a flood.

Although the costs of evacuation and prevented damage were not made explicit, the reason not to evacuate can be explained using the model. In the model, this can be explained by the willingness to evacuate to prevent the loss of life (f_1) and damage (f_2), as well as the parameters that describe the costs C_1 and C_2. Although no costs were taken into account, the perceived costs can be considered as the value against evacuation. Given P_t of 40%, V = 6.7 M€ and the 8000 casualties that could be prevented, the economic value of C_2 (assuming f_1 and f_2 are equal to 1) can be determined. We assume a bandwidth based on the value of C_1. C_2 is

- 21,000 M€ when C_1 is 12 M€ which is a pessimistic approach;
- 26,000 M€ when C_1 is 12,000 M€ which is an optimistic approach.

Based on the expected value of C_2 in case of the flood scenario, the perceived value of C_2 during Waterproef was 5 less than expected value of C_2 in case of a flood, as estimated at 120,000 M€ by [56].

The minimal conditional probability of flooding to call for evacuation based on the circumstances during Waterproef using our model are far below the probability used in the exercise. When these costs are assumed to be zero, for simplicity, f_1, f_2 are assumed to be equal to 1, P_t to call for evacuation is 0.31%. When the value for C_1 and $C_2$are as in the numerical examples, P_t to call for evacuation is 9% (when C_1 is 12,000 M€) or 12% (when C_1 is 12 M€). The bandwidth for the 'optimal' P_t is far less the value for P_t (40–45%) as used in the exercise. In other words, the call for evacuation should already have been made if decision-makers had given the same value for human life in case of an imminent threat, as in the design of the levee system to reduce the probability of dike failure per year.

This conclusion seems to be in conflict with the top priority of decision-makers to save lives [35], as set out in many planning documents [61]. Three possible explanations can be given:

1. The priority of saving lives is only relevant for the planning document; in real events, this priority is less relevant. However, this seems to conflict with the expectations of the public and the messages sent out by decision-makers and the experiences of many other disasters.
2. The assumed economic value of human life (6.7 M€) is too high. However, this seems to be in conflict with research that has been carried out on the value of human life and flood risk assessments in the Netherlands. When C_1 is 12,000 M€, the perceived economic value of human life is 0.4 M€, and when C_1 is 12 M€, the perceived economic value of human life is 1.9 M€. This economic value of 0.4 M€ of a life is outside the scope of the bandwidth as presented in the literature for flood risk management in the Netherlands [54]. This value for human life is also far less than, for example, the economic value for human life in traffic, which was 2.6 million euro in 2009 [62].
3. The lack of information on the costs of evacuation, in combination with the awareness among decision-makers about the large consequences of evacuation and with the load of information about the benefits, created a circumstance in which the call for evacuation was delayed in order to wait for more accurate information. Also, the limited understanding (or different interpretation) of risk could have influenced the outcome of the decision-making process because different opinions could be given.

Information management was one of the main improvements recommended in the evaluation of the exercise [60], although this recommendation was mainly focused on the way organisations share information, and not on how to deal with risks and interpreted statistics to minimize the risk. Therefore, it can be questioned as to whether the risk will be reduced by better procedures for sharing information when the correct information is not shared.

Combined with the limited experience with flooding and evacuation in the Netherlands, ambiguity among decision-makers, and the fact that risk information was not on the decision table or prepared in planning documents, we recommend performing further research regarding the costs and benefits of evacuation and to educate emergency planners and decision-makers for dealing with risk information.

5. Concluding Remarks

This research developed a risk-based decision model to support the planning and decision-making process for evacuation in case of a threat of flooding. The model assesses whether the decision to call for an evacuation has to be made or not, and is based on the costs and benefits of evacuation and the probability of a flood. The model can be used to reduce ambiguity and offers a guideline for dealing with statistics and uncertainty in case of a threat of flooding. In the model, a risk aversion factor, which is rational when used consistently, can be taken into account.

This research also shows that an understanding of risk, probabilities and consequences is important for decision-makers (and emergency planners and developers of exercises). This research also shows that choices based on a 'wrong' (learned) understanding of the information can increase the risk of loss of life. Because of the role of ambiguity and the lack of experience among decision-makers with evacuation and flooding in many delta areas, and specifically in the Netherlands, this is likely to occur; it is recommended that support instruments such as evacuation diagrams be developed. This also contributes to standardisation in risk management and resilience frameworks as recommended by [48,63].

The method for emergency management and evacuation has added value when a flood risk strategy is in place. Emergency management can be developed on the principles of the risk-based approach which is used for land use planning and levee management. The risk becomes the central element of emergency management. This is relatively new, because in many emergency documents, procedures are more important, and many emergency documents are symbolic [64,65]. During Harvey, the call for evacuation (as made by the major) could be explained better by an evacuation diagram. During Waterproef, an evacuation diagram could have shown to the decision-makers that a call for evacuation (using the risk-based approach) should already have been made. The time needed to decide for evacuation can be reduced by evacuation diagrams, which in the case of a situation with limited time can be very effective in reducing loss of life. The evacuation diagram, however, does not prescribe the call for evacuation, but gives the decision-maker a tool to evaluate costs and benefits.

Waterproef illustrates the importance of balancing information about costs and benefits with the interpretation and guidance of experts. Real-world decision-makers are operating under information limits (severe in many cases), and an optimal evacuation strategy presupposes far more complete information (about the costs of evacuation and the risk) than is typically present in real crisis situations. During Waterproef, the focus of the presented information was on the benefits of evacuation. Information about evacuation costs was not presented, and the interpretations of the probability of flooding and the evacuation costs were made by the decision-makers themselves. The risk model shows that less value was given to loss of life by decision-makers than was expected based on values used in flood risk analyses by the same authorities. However, because of risk aversion, it was expected that more value would have been given to loss of life.

It can be questioned whether exercises with scenarios such as that in Waterproef contribute to the preparedness of decision-makers or crisis organisations for flooding or reduced flood risk. Although the literature shows the benefits of training and exercises, when the decision-making process, as learned during the exercise, is put into practice in the case of a less ideal and more realistic event, the expertise learned might not contribute to a reduction in loss of life but to an increase of loss of life. Effective emergency planning and exercises that aim to reduce risk damage and loss of life therefore require the use of realistic scenarios.

The method described above is applied to evacuation decisions. However, the method can also be applied to support decisions for other measures in case of a threat of flooding (or other threat-driven disasters) as the moment to activate crisis management structures, when to warn people or industry, etc.

Criteria to activate emergency planning and different phases that indicate the status of the situation of flooding and mass evacuation are in many cases based on forecasts of water levels which are lower than the level when failure is expected. This implies, as part of good planning, that the frequency of evacuation (because of a threat of flooding) is higher than the frequency of a flood. A decision of evacuation not followed by a flood is often defined as a false alarm. When a flood occurs but no warning is issued while forecasting was available, it is called a missed call. It can be discussed as to whether the definitions of false alarms and missed calls are correct when decisions are based on defined criteria using (early) warnings with thresholds based on a better-safe-than-sorry philosophy. Decisions based on defined thresholds or frameworks taking uncertainties into account are not considered to be false, regardless of whether the flood occurs. A decision is only false when it is based on incorrect information (e.g., forecasting models) or when procedures are not used correctly.

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