Risk Analysis, Vol. 33, No. 7, 2013 DOI: 10.1111/j.1539-6924.2012.01932.x

EvacuAid: A Probabilistic Model to Determine the Expected Loss of Life for Different Mass Evacuation Strategies During Flood Threats

Bas Kolen,[1,3,*] Matthijs Kok,[1,2] Ira Helsloot,[3] and Bob Maaskant[1]

Evacuation of people in case of a threat is a possible risk management strategy. Evacuation has the potential to save lives, but it can be costly with respect to time, money, and credibility. The consequences of an evacuation strategy depend on a combination of the time available, citizen response, authority response, and capacity of the infrastructure. The literature that discusses evacuations in case of flood risk management focuses, in most cases, only on a best-case strategy as a preventive evacuation and excludes other possible strategies. This article introduces a probabilistic method, EvacuAid, to determine the benefits of different types of evacuation with regards to loss of life. The method is applied for a case study in the Netherlands for preventive and vertical evacuation due to flood risk. The results illustrate the impact of uncertainties in available time and actual conditions (e.g., the responses of citizens and authorities and the use of infrastructure). It is concluded that preparation for evacuation requires adaptive planning that takes preventive and vertical evacuation into account, based on a risk management approach.

KEY WORDS: Decision making; emergency planning; evacuation; flooding risk management; loss of life; risk analyses

1. INTRODUCTION

Although preventive measures can reduce the probability of flooding, such measures cannot completely eliminate the risk of flooding. A flood in the Netherlands caused by a breach in the flood defense is a low frequency event; however, flooding can occur under many different scenarios.

Evacuation has the potential to save lives,(1) but it can be costly with respect to time, money, and credibility.(2) Evacuation is a possible risk management measure for the threat of flooding. When an evacuation begins too late, not all evacuees can leave the area or reach the desired destination in time.(3–5,1) The response to Hurricane Katrina in 2005 in New Orleans demonstrated that people and goods that can be moved might be saved, but other goods will still be affected by the flood, and economic processes will come to a halt.(6) The costs of an evacuation in the case of hurricanes in the United States can exceed 1 million dollars per mile of coast due to losses in commerce, productivity, and direct losses to goods.(7) Credibility is related to concerns about the information, and it is depleted when there are discrepancies between timely and accurate warnings(8) and the impact and occurrence of false alarms.(9)

In this study, evacuation is defined as the organization and movement of (part of) a population to a (relatively) safe place in the case of a threat.

[1]HKV Consultants, P.O. Box 2120, 8203 AC Lelystad, The Netherlands.
[2]Delft University of Technology, Faculty of Civil Engineering, Delft, The Netherlands.
[3]Radbout University, Nijmegen, The Netherlands.
*Address correspondence to Bas Kolen, HKV Consultants, P.O. Box 2120, 8203 AC Lelystad, The Netherlands; tel: 0031 (0) 320 294242; b.kolen@hkv.nl.

This threat, along with the effectiveness of possible responses, typically will have a high level of uncertainty.

This article focuses on evacuation before the onset of a large-scale flood event. The evacuation results in a number of people exposed to the direct consequences of a flood event at a certain location. Within a critical time window (between early warnings based on forecasts and the onset of the flood event), it may not be possible to remove all inhabitants completely (and in time) due to the number of inhabitants, limited road capacity, and lead time.[3,10] People can reduce the risk of loss of life by moving to relatively safe places, such as shelters, safe havens, or even places prepared at home. Different types of evacuation can be identified based on the moment of the onset of a disaster and the destinations for the evacuees as follows:[11]

(1) Preventive evacuation: from a potentially exposed area to a safe location outside this area.
(2) Vertical evacuation: the organization and the movement of people inside the potentially exposed area:
  (i) Shelters: from home to strong buildings that offer protection for gathered people and goods.
  (ii) Safe havens: from home to areas inside the threatened zone that will not or be less affected.
(3) Shelter in place (or hide): from home to upper levels of residential buildings.

An evacuation strategy is a combination of different types of evacuations. After the onset of a flood event, other types of evacuation occur, such as when people are rescued by first responders or leave the area on their own; however, these are not discussed in this article.

Historically, a large amount of attention has been given to preventive evacuation and almost no attention to other suboptimal but realistic strategies.[12,3,13,14] Examples of these suboptimal strategies are, for example, partly vertical evacuation of people, a preventive evacuation for only areas with extreme high risk, or no evacuation at all and purely a focus on the rescue of people if the flood happens. Most preparations are designed to remove as many people from the flood-prone areas as possible, as demonstrated by the emergency planning of New Orleans. Before Hurricane Katrina in 2005 the cornerstone of hurricane preparedness was preventive evacuation.[15] Although during Hurricane Katrina 20% of the people in New Orleans remained in the city this resulted in a stronger emphasis on preventive evacuation planning. It was decided that shelters of last resort should no longer be used so more people are expected to evacuate preventively.[16]

For the Netherlands, most of the emergency planning documents and exercises strongly focus on preventive evacuation, as demonstrated in the "Waterproef" exercise[17] underlying evacuation planning and literature.[3,4,18] The need to take alternative strategies for preventive evacuation into account is addressed in recent literature. A comparison of the available time from an early warning to the required time for evacuation in the Netherlands[19,1] as well as an analysis of 50 years of flash flooding in Australia[20,14] showed that preventive evacuation is not always the best strategy to save more lives than other strategies, such as vertical evacuation or staying *in situ*. This research concludes that literature about vertical evacuation or staying *in situ* is limitedly available because preventive evacuation is such a well-established means of emergency management. None of these strategies, however, are without risk and it is concluded that more research is needed to guide decision making by emergency managers.[20,14] More understanding of the consequences of alternative strategies for evacuation is needed, including the impact of uncertainties on the nature, knowledge, and consequences of the response.

The reduction of loss of life in an area due to evacuation is defined as the success (benefits) of an evacuation. This reduction depends on a combination of the location and the vulnerability at these locations. In this article, we discuss in Section 2 the interaction between the threat, citizen and authority response, and the physical infrastructure with regard to evacuation. A literature review is reported in Section 3 to illustrate the need for alternative scenarios for evacuation in addition to preventive evacuation. These scenarios can be used in the risk management approach for decision making taking the costs (i.e., the consequences created by evacuation) and benefits (i.e., the reduction of loss of life and damage into account.

In Section 4, a probabilistic method called EvacuAid is described to determine the benefits of different strategies for mass evacuation and measures taking the impact of uncertainties into account.

The method is applied for some dike-ring areas in the Netherlands and discussed in Section 5.

The method is applied for dike-ring areas in the Netherlands to compare a strategy for preventive evacuation and a combined strategy of vertical evacuation with shelter in place. The results and insights are discussed in Section 6. Section 7 contains conclusions and recommendations.

2. EVACUATION: INTERACTION BETWEEN THE THREAT, CITIZEN AND AUTHORITY RESPONSES, AND THE PHYSICAL INFRASTRUCTURE

2.1. Authority Response

In case of a threat based on early warnings or other signals in society authorities and citizens become aware and make sense (understand the threat and willing to act on this information) of the threat. The authorities can influence the effectiveness of evacuation by use of infrastructure and resources by implementing several measures. Traffic management can be implemented that makes networks more robust. For those who evacuate, optimal circumstances are created. Examples are the contraflow system in New Orleans[21] and National Traffic Management in the Netherlands.[22] By implementing these types of measures, the environment and especially the infrastructure can be transformed to create more capacity for mass evacuation.

Mass communication campaigns about risk and calamities can inform the public about the risk and possible measures. The authorities can also add extra attention for special groups, such as people at care institutions, but capacity is limited. These measures will influence citizen response and use of infrastructure. When time is limited a risk-based approach can identify most vulnerable areas and select the most effective measures or strategies. Finally, this might reduce loss of life and damage.

2.2. Citizen Response

Many studies have argued that citizens will act in a rational manner in case of a crisis.[23–25] Citizens will take measures when they feel threatened and evacuate themselves to a place that they think is appropriate for them. Citizens gather nowadays more and more information using multiple sources of information, such as the Internet, radio, television, and social media. This information and also opinions is partly distributed by authorities and by the media, experts, and other citizens using (social) media. Thus, views other than those from the government will be widely available. Authorities can also be aware of this process and support it with extra information. When more information is provided literature shows that citizens act in a more proper way.[26]

Without a call for evacuation by the authorities, people can initiate an evacuation spontaneously. The perception of the risk is not by definition equal to the real risk; therefore, areas that will not be exposed can evacuate in what is called a shadow evacuation.[27,28] The response of the public can reduce the capacity of an infrastructure, such as an overload of a highway and extra trips that cause interference with other routes and people can spread over more cars resulting in a higher traffic load or vice versa. The impact of overload of infrastructure becomes clear not only during normal traffic jams, but also when more people evacuate than is necessary in case of a spontaneous evacuation or shadow evacuation. This could influence the average travel speed and departure curve during an evacuation, resulting in less effective use of the road network. Also a higher load to road networks outside the evacuation zone will decrease the outflow rate of the threatened area because others use road capacity. This necessity is also illustrated by the contra-flow system of New Orleans, where traffic management had to be implemented in the states of Louisiana and Mississippi.[15]

2.3. Impossibility to Control All Stakeholders in a Mass Evacuation

In case of a large-scale disaster, such as flooding in the Netherlands, many stakeholders will be confronted by the same threat and have to deal with the same resources and infrastructure.[1] The day-to-day objectives of rescue workers might interfere with measures to minimize loss of life and damage during a mass evacuation. Traffic control by police forces, for example, could increase time needed for evacuation. The same applies for citizen response. The theory of distributed decision making, defined as design and coordination of connected decisions,[29,30] describes how multiple decisions in a situation with multiple interests of organizations and citizens are connected. In modern democracies responsibilities of the government are spread over several independent organizations in such a way that a central body can almost not control it. Therefore, it cannot be assumed that a decision by one of the authorities will be exactly in line with the decision of others, even when these decisions are guided by laws.[31] Also in case

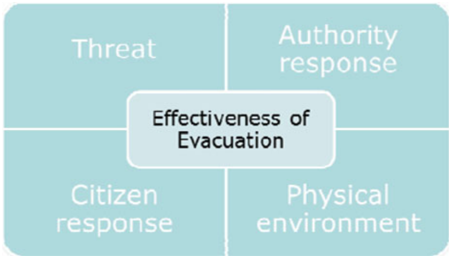

Fig. 1. Evacuation related to a society.

of a crisis, their purpose is to fulfill own tasks and responsibilities.

2.4. Conceptual Framework of Evacuation

To describe an evacuation of a system, four elements can be distinguished that influence the effectiveness of evacuation (Fig. 1):(32)

(1) Threat: depending on the lead time, probabilities for water levels, breaches, threatened area, and possible impact; the size can be large or small, also the lead time can vary between days to unexpected events.
(2) Citizen response: depending on the risk perception of citizens, available information, available means, animals, family situation.
(3) Authority response: depending on the risk perception of decisionmakers, experience from real events, training or exercises, information management, quality of emergency planning.
(4) Physical environment: depending on the demographics, infrastructure and available means for rescue workers, and ability to take mitigating measures.

In the case of a flood threat, citizens and authorities will act on the actual perception of the threat and consequences of possible measures. Citizens and authorities have to make sense about the situation before they start to act. Measures can be influenced positively or negatively by other measures and the consequences of them. These (consequences of) measures can influence the physical environment (e.g., traffic management or traffic jams, accidents, fallout of services) or influence risk perception (e.g., communication).

Evacuation scenarios can be developed that combine the four elements. These scenarios can describe the benefits of evacuation given the assumed conditions. The result of an evacuation is determined by comparing the required time to execute an evacuation strategy and the available time.(4,3,18) Evacuation models combined with models for loss of life can be used to describe the benefits of evacuation scenarios. These models take into account the local characteristics of the system that are affected by the event.

In reality, each condition is uncertain. Knowledge about the impact of these uncertainties and the probability of them can be used to get insight into the relevance to influence these conditions by measures. These can be used to develop and compare different strategies for evacuation during emergency planning or during decision making in case of a threat. When emergency planning is based on deterministic planning, measures can perfectly be designed to the expected scenario. However, the reality does often not meet the predefined scenario.(33) Emergency plans that describe only the desired situation are called fantasy documents in the literature.(34) When uncertainties are taken into account the measures can be selected that result in better evacuation and less loss of life for all or most possible scenarios.

3. A REVIEW OF MODELS FOR EVACUATION AND LOSS OF LIFE ESTIMATION

3.1. Literature Review of Evacuation Models and the Use of Uncertainty

Evacuation models are used as instruments for evacuation planning. These models can be used to calculate the consequences for evacuation for the required time, traffic load and congestion on routes, and the impact of behavior for several scenarios. A scenario for evacuation describes the logistic progress and the number of people that reaches the intended destination over time based on a set of chosen boundary conditions and a predefined road network. For each scenario, the model is based on a set of assumptions, such as the population that evacuates, the capacity of the infrastructure, and the decisions of the authorities, first responders, and the public. Evacuation models can be divided into three types:(35,36)

(1) Dissipation rate models use an aggregate state formula to estimate the evacuation time based on the size of an area and its population density. These models are also called macro models.

Table I. Evacuation Models

Name	Category
Hans and Sell[37]	Dissipation rate model
EMBLEM (empirically based large-scale evacuation estimate method)[38]	Manual capacity model
Evacuation calculator (static traffic model) (also part of National Evacuation Module Netherlands)[18,39]	Dissipation rate model
Dynamic planning module of National Evacuation Module Netherlands[40]	Manual capacity model
Traffic module (dynamic module)[18,39]	Manual capacity model
OREMS (Oak Ridge method evacuation modeling system)[38]	Micro simulation model
FIRESCAP[41]	Micro simulation model
INDY[42]	Manual capacity model
SPOEL (serious gaming for mass evacuation)[43,44]	Manual capacity model
DSS ESCAPE[45]	Micro simulation model
EVAQ[46]	Manual capacity model
Life Safety Model[47]	Micro simulation model

(2) Manual capacity models use techniques to allocate the population on the (road) network while taking the road capacity into account. These models are also called "meso" models.
(3) Micro simulation models simulate the evacuation process on the network at a micro (or individual) level. Each individual is modeled, and there is a detailed description of the road network.

An overview of several available models is given in Table I.

None of the known evacuation models accounts for the probabilities for the scenarios needed to assess the benefits of evacuation. The "Evacuation Calculator" distinguishes different strategies for evacuation related to a best-case and worst-case event and presents the results as additional scenarios.

The probability of each scenario is related to the threat, use of infrastructure, and when and how measures are taken by authorities and citizens. Validation of models is, in most cases, not possible because data for mass evacuations are limited. Because of the lack of data expert judgment has to be used to identify optimistic, realistic, or pessimistic scenarios. Optimistic and pessimistic scenarios for evacuation can be developed based on the made assumptions about these four elements in the introduced framework for evacuation.[18]

The available evacuation scenarios of the Netherlands indicate that the required time varies from hours for small areas to many days for large dike-ring areas.[4,48,49,3] Many types of incidents, such as car accidents and incorrect route choices, can occur during an evacuation. For evacuation planning, a shortage of available means for rescue services must be considered, which limits the possibility to take action.[50] The number of means for rescue workers are not designed for low frequency flood events but for events with a return period of about 10 years in the Netherlands.[51] The uncertainties in the four elements (see Fig. 1) in the conceptual framework for evacuation require a probabilistic evacuation model to get inside the expected value, uncertainties, and effectiveness of measures.

3.2. Loss of Life After a Flood

None of the evacuation models calculate the expected loss of life. Loss of life in flood risk analyses is often based on the number of people reduced by the number of people that evacuated preventively. For those who remain in the area it is assumed that these are at home.[52,53] Literature has shown that the probability of loss of life is related to the local conditions and age of persons.[54–56] Literature has also clearly demonstrated that the loss of life is related to the different locations (as in a car, or in a home, or shelter) inside the exposed area.[54,57,20] The willingness to evacuate depends on the way the message is sent out by the government. When public officials are aggressive in issuing evacuation notices, over 90% of the population will evacuate.[58] However, when too many people participate in the evacuation, the effectiveness of road use can decline because more congestion can occur.[13] No functions for loss of life are currently available in the literature for different locations within the exposed area (e.g., people who are in shelters or cars when exposed).

3.3. Principles for Probabilistic Evacuation Planning Based on the Results of the Literature Review

A probabilistic evacuation model does not currently exist. This type of model determines an expected value and the uncertainty in the impact or benefits of evacuation as the number of evacuees who reach their location and loss of life. Necessary elements of these models include the expected value and uncertainty bounds of the following elements (see Fig. 1): (1) citizen response, (2) response of the authorities, (3) use of the physical environment, and (4) the threat itself.

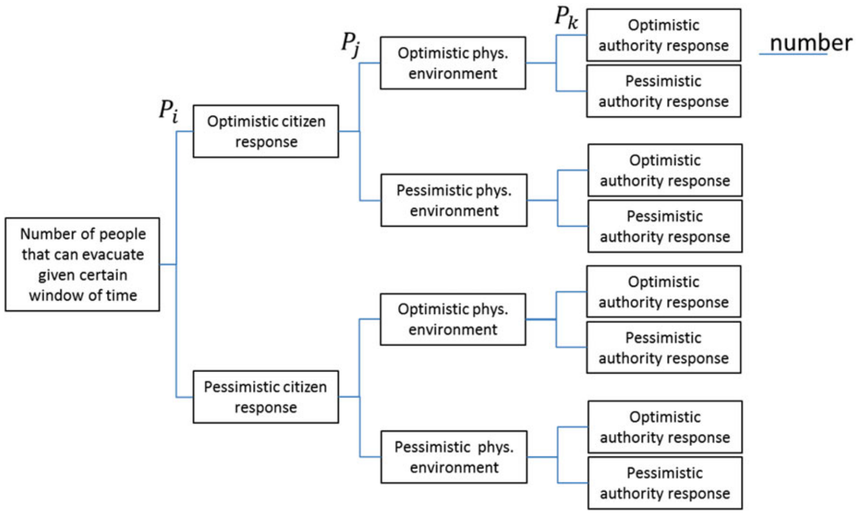

Fig. 2. Concept of the probabilistic model. The probabilities P_i, P_j, P_k show the way the probability for the most optimistic situation can be defined as an illustration for the concept.

This probabilistic model could be used for emergency planning and crisis management. The model will, for example, assess that it can be impossible to reduce loss of life to zero even when all measures have been implemented perfectly. When all measures are implemented optimally and the response of citizens and authorities is optimal the expected loss of life is not equal to zero. Improvements in evacuation can only be made after investments in additional infrastructure (e.g., roads) and additional emergency equipment (e.g., personnel or resources) to create more capacity for evacuation (note that the existing road capacity or emergency services are often not designed for low frequent mass evacuations).

Various scenarios can be developed for evacuation that represents classes of all significant known events. The probability of these scenarios are determined using data (as uncertainties in forecasting) and expert opinions with event trees.[48,3]

Fig. 2 shows the concept of such a probabilistic model. The number of people who can evacuate in a certain amount of time depends on the interaction between citizen response, response of authorities and physical environment, and optimistic or pessimistic conditions.

To evaluate the impact of different strategies for evacuation, the mortality rate has to be related to different locations inside a flood zone. Although no literature is available that relates the location and water depth to a function of loss of life, a subjective estimate is made based on previous experiences, such as Katrina. The expected number of people who can, or cannot, evacuate can be defined when the available time is known; the combination with the mortality rates results in the expected loss of life.

Therefore, all information is available to develop a probabilistic model for evacuation to determine the success of different evacuation strategies as a function of time. The number of people who evacuate from an area as a function of time is needed, which means that all type of evacuation models can be sufficient. Because of the calculation time, a dissipation rate model is used to get an understanding about the effectiveness of evacuation and the impact of uncertainties and effectiveness of measures. A more detailed model that will increase calculation time and needs more data can give additional information about the evacuation that is not required for a strategy choice. These models can be used to optimize evacuation when the strategy choices have been made.[13] The costs of different strategies for evacuation can be related to the benefits (the reduction of loss of life). Decisionmakers can evaluate the need for possible strategies for evacuation and compare them with other measures that reduce the risk (as measures that reduce the frequency of disasters). However, all scenarios should be used very carefully because these models are not validated because of the lack of events.

4. METHODOLOGY EVACUAID

4.1. Purpose of Method

The EvacuAid method determines the benefits of various alternative strategies for (mass) evacuation for planning purposes as well as during a crisis. The results of EvacuAid are based on

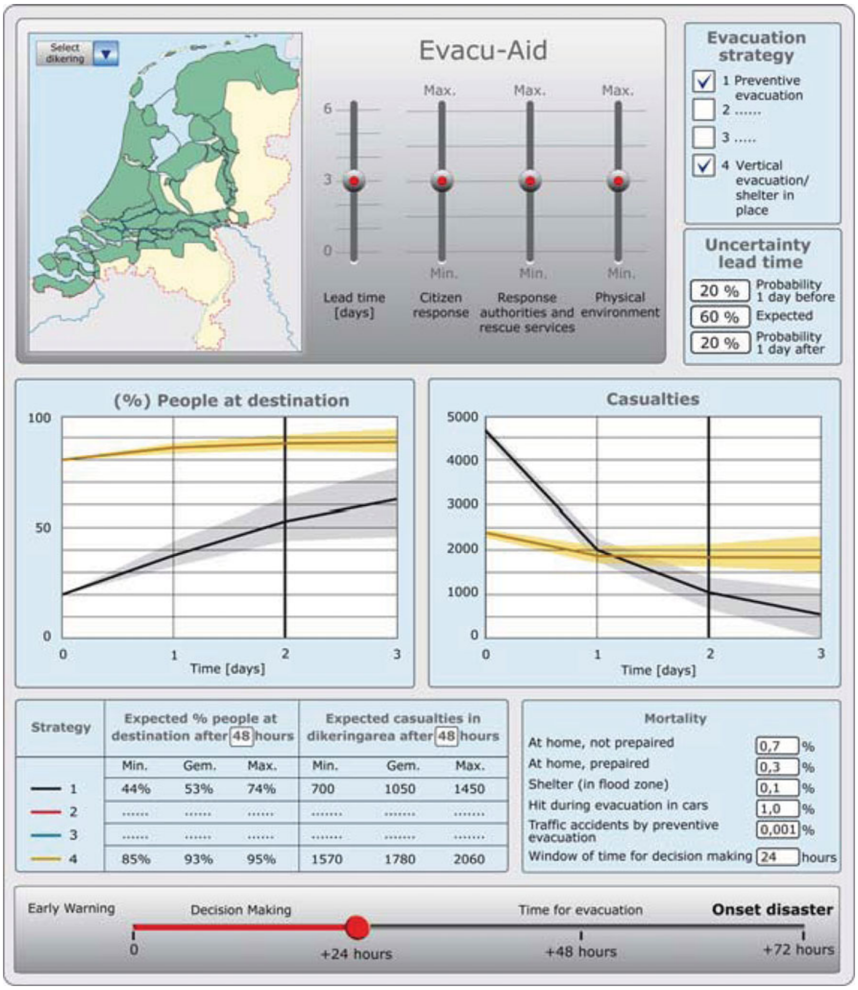

Fig. 3. EvacuAid interface.

predefined evacuation scenarios based on local characteristics. When information is known about the status of the four elements of evacuation in the conceptual framework of evacuation and the mortality rates, an assessment can be made for several strategies of evacuations based on the interaction of these elements. This assessment is shown as a function of time in the graphs in Fig. 3. The timeline below shows the time needed for decision making and implementation of measures and the time for evacuation itself. At the dashboard on top of this figure the assessment of the four elements can be added for a selected dikering area.

Different strategies for evacuation can be compared to select the preferred strategy given the actual circumstances. The method focuses on the selection process for an evacuation strategy before the actual start of an evacuation. Until that moment, measures can still be implemented adequately (e.g., traffic management), and the chosen strategy can be communicated to the public and first responders before they begin with their evacuations. Effectiveness of these measures can decline over time due to the (autonomous) response of citizens and local or regional authorities. Because they use already limited resources and infrastructure, starting their evacuation might reduce the possibility of implementing other logistical measures. This window of time between the early warning and when evacuation will start by autonomous response is called the transition phase.[31] This transition phase is shown in Fig. 4 by window of time covered in the thick box.

EvacuAid was developed to compare different strategies for evacuation during this transition phase. EvacuAid supports decisionmaking about possible strategies as vertical, preventive evacuation, or no evacuation at all and shows the effectiveness of implementing these measures. The method can be

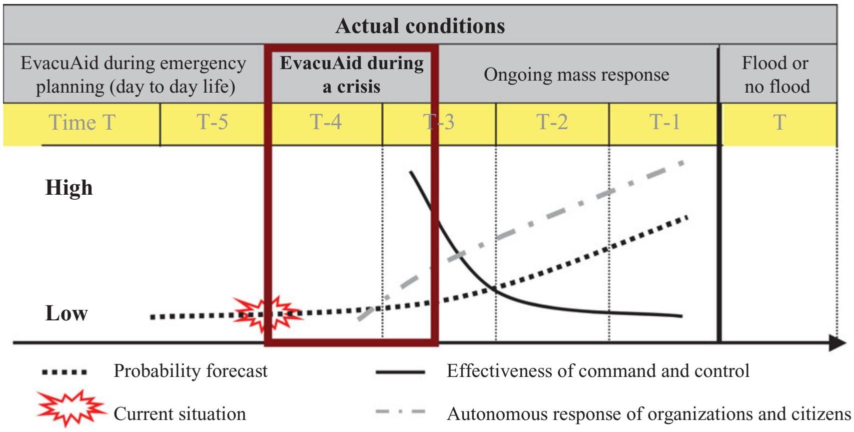

Fig. 4. Focus area of EvacuAid during the transition phase in emergency planning and the decision-making process during a crisis. (Rectangle indicates transition phase from normal to evacuation phase.)

applied for emergency planning because the possible situations based on uncertainties are taken into account. In case of a crisis the method can also be applied to support decisionmakers with strategy choices and the moment when to call for evacuation. Calculation time on a personal computer is less than a minute. After recognition of a threat emergency planners can estimate the actual conditions of the four elements and mortality rates and estimate the impact of the measures. The consequences can be presented to decisionmakers. The results of EvacuAid can be related to other parameters for realistic decision making such as the costs of the evacuation, disruption of the economy, and the probability of the threat. The results can also be used for communication to the public.

For use in emergency planning, the actual conditions of the next event are uncertain. On the basis of statistics and expert judgment, probability distribution can be defined to provide an overview of the range of possibilities.

The method cannot be applied in this form for an on-going evacuation. One can also question if such a model is relevant because the effectiveness of decision making and coordination will be limited in this situation. In the case of an on-going evacuation, it will be difficult to switch to another evacuation strategy. Only the switch to a stop of an on-going evacuation and finding a nearby shelter without the use of the logistic system seems possible. The combination of decision making, large-scale operational measures, reallocation of means and rescue workers, and citizen response without creating a gridlock may be impossible. Available information and the effectiveness of coordination are limited during these circumstances with regards to a reduction in loss of life.

4.2. Mathematical Description

This method can be applied for different evacuation strategies, such as a preventive evacuation, a vertical evacuation, or a combination of both. Table A1 in the appendices shows a list of all parameters in the model.

The number of people D_τ that, given a strategy for evacuation, can move within the available timeframe for evacuation τ to the desired location depends on:

- The number of people who can leave the area in this period H_τ.
- The number of people who move to possible shelters V_i . V_1 is the number of people who stay at home and take no extra precautions; V_2 is the number of people who stay at home and take precautions; and V_3 is the number of people in a public shelter.

D_τ is defined as:

$$D_\tau = H_\tau + \sum_{i=1}^{3} V_i. \tag{1}$$

The timeframe for transportation during the evacuation τ depends on the period T_3 between the expected moment of impact and the moment of detection of the threat. This period is reduced by the window of time needed for decision making and implementing measures T_1 and the window of time that extreme weather will limit the possibility for mass evacuation T_2.

Note that τ can be expressed as follows, which describes the time to execute an evacuation:

$$\tau = T_3 - T_1 - T_2. \tag{2}$$

The number of people who can leave the area in this period, H_t, is defined by an evacuation model. Within the evacuation model, six state variables x are included in a road network N_τ that is used to define the number of people who can evacuate in period τ. This results in the following expression:

$$H_\tau = N_\tau(x_1, \ldots, x_6), \qquad (3)$$

where x_1 is the departure curve (% of people who will depart as a function of time), x_2 is the number of people in a car, x_3 is the average travel speed, x_4 is the actual road capacity, x_5 is the flow out rate at exit point, and x_6 is the route choice.

Equation (3) describes gives the conceptual description of H_τ. In the framework of evacuation we have defined four elements. The consequences of evacuation are defined in our model assuming the occurrence of the flood. Therefore, H_τ can also be defined using contribution and interaction of the elements "measures of citizens C," "the measures of authorities A," and the "efficiency of the use of physical environment I." In a mathematical description C, A, and I are a subset of $H_\tau.(C_\tau \subseteq H_\tau, A_\tau \subseteq H_\tau, I_\tau \subseteq H_\tau)$.

C, A, and I are therefore also a function of $N_\tau(x_1, \ldots, x_6)$. Moreover, H_τ also depends on the actual conditions and measures as foreseen in case of a threat. The parameters k,l, and m describe the actual conditions for C, A, and I on an ordinal scale of 1–5 (1 = extreme positive, 3 = average, 5 = extreme negative). The weights $W_{1,k}$, $W_{2,l}$, and $W_{3,m}$ describe the performance of C, A, and I, which results in the following expressions for H_τ:

$$H_\tau = W_{1,k}C_\tau + W_{2,l}A_\tau + W_{3,m}I_\tau \qquad (4)$$

$$W_{1,k} + W_{2,l} + W_{3,m} = 1 \qquad (5)$$

The total loss of life L depends on the number of people at a certain location multiplied by a unique mortality rate n_i for these locations. For H_τ, the mortality rate n_H is assumed to be equal to fatal car accidents. The number of people who did not reach the desired location R_t is the difference between the total number of people in an area and D_τ; the mortality rate for this group is n_R. The total loss of life in a strategy is the following:

$$L_\tau = \left(H_\tau n_H + \sum_{i=1}^{3} V_i n_{V,i} + R_\tau n_R \right). \qquad (6)$$

The model described in the previous formulas is based on a deterministic approach. However, at the moment of planning or decision making these parameters are uncertain because the future is not known. Taking the uncertainty in these variables into account results in better insight into the effectiveness of evacuation. Probabilistic analyses for the use of emergency-inundation areas along rivers showed that in less then 20% of the events the decision could be made as foreseen in a deterministic approach.[33] Therefore, these variables are described as discrete variables that can have a selective number of values and a probability of occurrence.

The available time for evacuation τ is uncertain because of the uncertainty of forecasts and uncertainty in the moment of dike failure. Therefore, three classes are defined for τ: t_1 describes the upper value of the period; t_2 describes a lower value of the period; and t_3 describes the expected value of the period, and P_1, P_2, and P_3, respectively, describe the probability for these moments. This results in the following expression:

$$\tau = \sum_{i=1}^{3} (t_i P_i - T_1 - T_2) \text{ in which } \sum_{i=1}^{3} P_i = 1. \qquad (7)$$

The uncertainties are modeled with a stochastic discrete variable, which can have three values: expected value and a pessimistic and optimistic value. In Table II the uncertainties in the scenarios are presented. These results in 10 scenarios: the first scenario is the scenario with the expected values, in other scenarios one expected value is changed by one of the uncertainties. The table shows the variable that will be changed in the most likely situation to estimate the required time for evacuation and loss of life. These variables describe the willingness to evacuate, the load on the road network and the capacity, the use of this road network related accidents and experience of drivers and are related to the quality of measures that are implemented. For example, when more effort is paid to crisis communication, the scenarios that are based on a better citizen response become more important.

The state variable x_6 is related to the use of exits of the road network. It can have three values described as optimistic, pessimistic, or medium scenarios for evacuation. For each other state variable $(x_1, \ldots, x_5)$, an optimistic $x_{6,1}$, pessimistic $x_{6,2}$, or expected $x_{6,3}$ route choice is defined as a specific class with a unique probability $P_{5,1}$, $P_{5,2}$, and $P_{5,3}$. The probabilities of $P_{5,1}$, $P_{5,2}$, and $P_{5,3}$ are 0.2, 0.2, and

Table II. Uncertainty in State Variables ($x_1, \ldots, x_5$)

Variable	Expected Value in the Most Likely Scenario	Uncertainties in Additional Scenarios	
x_1 Departure curve	Total departure in 16 hours	Total departure in 8 hours	Total departure in 16 hours
x_2 Number of people in a car	2.19 people/car (based on inhabitants/number of cars)	3 people/car	1 people/car
x_3 Average travel speed	20 km/hour	40 km/hour	2 km/hour
x_4 Actual road capacity	All roads are available	Breakdown of 1 highway	Breakdown of 1 local route
x_5 Flow out rate at exit point	0.2	0.3	0.1

0.6, respectively, when k, l, and m have a value of 2, 3, or 4. When k, l, and m have the value of 1, the probabilities of $P_{5,1}$, $P_{5,2}$, and $P_{5,3}$ are 0.6, 0.1, and 0.3, respectively, and when k, l, and m have the value of 5, the probabilities of $P_{5,1}$, $P_{5,2}$, and $P_{5,3}$ are 0.1, 0.6, and 0.3, respectively. When uncertainties are modeled with a stochastic discrete variable Equation (3) can be expressed as Equation (8):

$$H_\tau = N_\tau \left(\sum_{i=1}^{3} P_{5,i}(x_1, \ldots, x_6) \right) \text{ in which } \sum_{i=1}^{3} P_{5,i} = 1. \quad (8)$$

The probability of each scenario j is related to the parameters C, A, and I and the actual conditions on a scale of 1 to 5 for k, l, and m and their respective probabilities $P_{6,j,k}$, $P_{7,j,l}$, and $P_{8,j,m}$. H_τ can be defined using Equation (4) using Equations (9)–(11) for C, A, and I:

$$C_\tau = \sum_{j=1}^{10} P_{6,j,k} \left(N_\tau \sum_{i=1}^{3} P_{5,i}(x_1, \ldots, x_6) \right) \quad (9)$$

$$A_\tau = \sum_{j=1}^{10} P_{7,j,l} \left(N_\tau \sum_{i=1}^{3} P_{5,i}(x_1, \ldots, x_6) \right) \quad (10)$$

$$I_\tau = \sum_{j=1}^{10} P_{8,j,m} \left(N_\tau \sum_{i=1}^{3} P_{5,i}(x_1, \ldots, x_6) \right) \quad (11)$$

5. CASE STUDY: MASS EVACUATION FOR THE NETHERLANDS

5.1. Introduction to Flood Risk Management in the Netherlands

People in the Netherlands live in a delta that is mostly below sea level. The Netherlands has a long history in flood protection that began in the Middle Ages.[59] In this article, we focus on flooding in the Netherlands from rivers caused by extreme discharges and sea floods caused by storm surge and tide. Risk analyses for the Netherlands in 2008[60] and 2009[61] showed flooding to be the disaster type with the most extreme, catastrophic consequences, although the probability is "highly unlikely" because of the relatively high safety standards as defined in the Water Act (Fig. 5).

People in The Netherlands have a low perception for flood risk and no incentive to prepare mitigating measures.[62] An evaluation of flood risk policy in 2004 showed that more attention had to be paid to flood protection and emergency management. Loss of life due to flooding was far more than all combined disasters related to external safety policy.[63] Since 2004 and since Katrina, more attention has been given to emergency planning (examples are national[64,65] and regional planning,[66,67] development of flooding scenarios and expert-teams,[68] such as a national commission of flooding and national operational staff).

A flood event is low frequency event for the Netherlands. The frequency of evacuations is higher than the frequency of floods but still remains uncommon and probably has a frequency of less than a lifetime.[69] Emergency planning for floods is activated about once every five to ten years.[65] Therefore, preparation for flooding also means preparation for false alarms and for situations when no measures are taken despite a threat. Forecasting models and early warnings are used to alert crisis organizations and citizens and to implement measures. The probability for the window of time for preventive evacuation for the Netherlands is defined by experts for different areas (Table III). This window of time is based on available forecasting models, early warning procedures, and the expected willingness to call for evacuation. The uncertainties give more information than the expected window of time because also the possibility of less or more time is shown. For all flood scenarios it is shown that at least 10% of all events

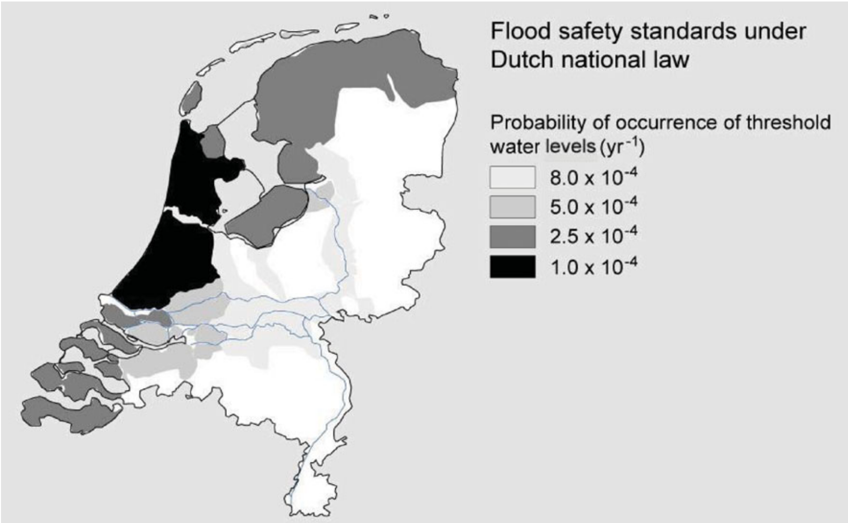

Fig. 5. Safety standards (Dutch Water Act).

Table III. Probability Distribution of Available Time for Evacuation Based on Hydrological Forecasts and Decision Making[48]

Time	River Rhine	River Meuse	Low Tidal River Area	Northern Coast	South West Coast	Western Coast	Lake IIssel Area
No time	0.1	0.1	0.3	0.1	0.1	0.1	0.2
1 day	0.2	0.4	0.5	0.15	0.4	0.45	0.4
2 days	0.5	0.5	0.2	0.5	0.5	0.3	0.4
3 days	0.2	0.0	0.0	0.2	0.0	0.1	0.0
4 days	0.0	0.0	0.0	0.05	0.0	0.05	0.0

happen unexpectedly. Also is taken into account that decisions for evacuation are not made more early than necessary. In the Netherlands the lead time for coastal areas is longer than for river areas but models shows less certain information.

The possibility of preventive evacuation increases as the available time increases. Although, for some areas, it is still—far from—impossible to evacuate completely out of the area before the dike is breached, as illustrated by the expected value for the success of preventive evacuation in the Netherlands (e.g., for the most critical dike ring, it is expected that approximately 15% of the inhabitants can leave the area preventively[48]).

5.2. Implementation of EvacuAid

5.2.1. Evacuation Model

The Evacuation Calculator[18] was used to develop evacuation scenarios. This model is most suitable because it already contains road network N, determines the required time for evacuation and offers flexibility to vary parameters $(x_1, \ldots, x_6)$ and the calculation time is limited. The Evacuation Calculator module is a standard for evacuation planning and risk analyses in the Netherlands and was developed for scenarios in large-scale areas.[18] Therefore, many scenarios are already available.[70,49,71] Evacuees evacuate to safe places or shelters outside the traffic network. Although shelter locations can be defined it is known that most people take care of themselves. Therefore, they first have to leave the exit points of the model.

The Evacuation Calculator also contains possible optimistic and pessimistic scenarios for evacuation. Although the traffic models can be validated for normal conditions this is almost not possible for low frequency events such as mass evacuation. These scenarios therefore describe the range of possible events and show the impact of management of roads of crowds.[18] The scenarios are:

1. Reference: inhabitants are assumed to be free in choice regarding their route for evacuation.
2. Nearest exit: evacuees are assumed to evacuate by heading to the nearest exit, regardless of capacity and use of this exit.

(3) Advanced traffic management: evacuees are optimally divided over the available exit points, taking the capacity of these exit points into account.

The results of the runs of the model for these scenarios result in the hierarchy of optimistic, medium, and pessimistic scenarios. "Advanced traffic management" is in most cases the most optimistic scenario. Depending on the characteristics of an area "nearest exit" or "reference" is the pessimistic or medium strategy.

Because the Netherlands lacks experience with mass evacuation, these scenarios cannot be validated. In reality, all of them could occur, and the scenario that evacuates the most people is considered as the optimistic scenario $x_{6,1}$; the second as the pessimistic scenario $x_{6,2}$; and the last as the expected scenario $x_{6,3}$. The results of the scenarios are defined for 1, 2, 3, and 4 days after the start of the evacuation.

5.2.2. *Reference Scenario*

The model and scenarios were developed for the Dutch national capability analyses by the Ministry of Interior. These models were also used in the risk analyses for optimal safety levels for the prevention of flooding[72] and actual flood risk[52] was used as the reference (the most likely) situation. These scenarios all focus on the entire threatened area instead of a selected part such as a dike-ring area and are, therefore, most realistic.

The most likely scenario, and other scenarios, takes noncooperative behavior into account, which assumes that 20% of the people will not adhere to the desired strategy as announced by the government. The remaining 80% of the population will follow the instructions of the government's evacuation strategy. This 20% estimate is based on an enquiry by "TNS NIPO" in the Netherlands and on what has been learned from experience during hurricane-induced evacuation in New Orleans.[73] These reference scenarios are described in detail in other research.[19,1]

5.2.3. *Probabilities and Expert Opinion*

Each scenario contributes to the expected success of the evacuation. No literature or data are available regarding this contribution. Therefore, the values of $P_{6,j,k}$, $P_{7,j,l}$, and $P_{8,j,m}$ and $W_{1,k}$, $W_{2,l}$, and $W_{3,m}$ are estimated by 15 experts with at least three years of experience in the field of forecasting, flood risk analyses, evacuation management, citizen response, and emergency management. Therefore, the standard Delphi method is applied as a forecasting procedure because this method structures group processes so that the process is effective in allowing a group of individuals, as a whole, to deal with complex problems.[74] Each expert made a first blind estimation of the probabilities. These estimations were discussed among the experts and after discussion each expert could make a new estimation using new arguments. This resulted in estimation in mean values of the probabilities (mean scores of all participants) as presented in Tables A2 and A3. This method is further described and analyzed by Rowe and Wright.[75]

The results were validated during interviews with Dutch practitioners and researchers, and with the latest information on the expected loss of life in case of flooding as determined in the study of Flood Risk Analyses of the Ministry of Public Works and Water Management.

The probability $P_{4,1}$ for the expected time available for evacuation and decision making until the moment of dike breach t_1 was estimated to be 0.7. The probability $P_{4,2}$ and $P_{4,3}$ for a time period of 1 day more (t_3) or less (t_2) were both estimated to be 0.15.

5.2.4. *Different Location of Vertical Evacuation*

No previous literature or Dutch experience provides the numbers for people who will evacuate to a certain destination (e.g., public shelter, shelter in place) and how well they will be prepared. Although literature describes that noncooperative behavior exists and that the system will not be optimal with regards to shelters,[76,77] forecasts of future responses are unknown. On the basis of expert opinion, it is estimated that 50% of those who evacuate vertically will move to a public shelter; 40% will shelter in place and take precautions; and 10% will shelter in place without these measures.

5.2.5. *Mortality Rates*

The loss of life in the event of large-scale flooding is related to the number of people in an area during the onset of a flood and can be calculated by accounting for the local characteristics and the location of people.[3,78] This research uses the total number of people who are exposed during the onset of a flood and relates that to the water depth and water velocity. Literature about loss of life in case of flood shows that a first estimation of mortality rates for coastal or river flooding is about 0.1–1% of the total affected population,[78,3,79] where the 0.1% is for a situation with multiple emergency measures. Other literature has shown that the probability of loss of life is also related to the local situation and age of persons[54–56] and the circumstances when people get hit.[54,57,20,80,81]

To compare the loss of life for different evacuation strategies, different locations are defined and a mortality rate must be defined for each. No detailed functions exist or are known that relate loss of life to a specific type of location.

On the basis of the literature above and expert opinion mortality rates are estimated for the Dutch situation. These mortality rates have been applied to the number of people who live in each dike ring area taking into account the consequences of evacuation. These results for the most critical dike ring are (dike ring 14) area have been compared with results of a fully probabilistic flood risk assessment for the current situation, which showed similar numbers for loss of life.[52] The expected loss of life for dike ring area 14 is within the same range. Therefore, it is concluded to be adequate for this purpose, the rates are:

(1) 0.001% mortality rate for those who leave the area preventively (e.g., car accidents). This rate will be applied to H_τ .
(2) 0.3% mortality rate for those who shelter in place and take precautionary measures: V_1.
(3) 0.7% mortality rate for those who shelter in place and do not take precautionary measures: V_2.
(4) 0.1% mortality rate for those who evacuate vertically to a public shelter or safe haven: V_3.
(5) 1% mortality rate for those who are not in the above locations (e.g., in a car when they get hit): R_t.

These mortality rates estimate the total number of people who lose their life due to a flood event, (these include the rescue operation). More research about these mortality rates is recommended; when the method is applied in other areas the mortality rates must be reconsidered for the local situation.

5.3. Results of EvacuAid

EvacuAid was applied for three dike ring areas in the Netherlands:

(1) South Holland, dike ring area 14 along the Western Coast: One of the largest dike ring areas along the coast with the highest economic value in the Netherlands. The impossibility of a preventive evacuation is often addressed in literature.[3,4]
(2) Friesland and Groningen, dike ring area 6 along the Northern Coast: Large dike ring area along the coast in the Netherlands, but less populated than South Holland.
(3) Rivierenland, dike ring area 43 along the River Rhine: Large dike ring area in a river area.

Table A4 presents the expected loss of life in case of preventive evacuation for $\tau = 1, \tau = 2$, and $\tau = 3$ days and for different values of k, l, or m. Table A5 presents the results for vertical evacuation in the same manner. A value for k, l, or m higher than 3 is a more pessimistic situation then the expected situation for the parameters C, A, and I. A value less than 3 is an optimistic situation. These insights can be used to prioritize the use of means.

The results in Fig. 6 show the consequences of a better or worse performance of citizen response, response of authorities, and the use of infrastructure (C, A, and I) as a function of τ from one to three days (equal to the length of the used evacuation scenarios in the database). The results also show that the available time τ influences loss of life more than C, A, and I. Theoretically, when τ is long enough, a preventive evacuation will finally result in less fatalities then a vertical evacuation in all situations. This is because the mortality rate for those who leave the area preventively is less than the mortality rate of all other locations. However, the value of τ is not infinite because forecasts are not available and no decision are made about evacuation because of the consequences (see Table III). When τ is very limited, a vertical evacuation might result in less loss of life than preventive evacuation. The moment when a preventive evacuation results in the same loss of life as a vertical evacuation is called the "Evacuation Dilemma Point." The moment when this Evacuation Dilemma Point occurs depends strongly on the characteristics of the local area (e.g., the number of people, available roads) and the performance of the citizen response, the authority response, and the use of infrastructure.

For dike ring 14, only in a few of all possible events a preventive evacuation will result in less loss of life then vertical evacuation. Fig. 6 shows that only when τ is three or more days, and when k, l, or m all

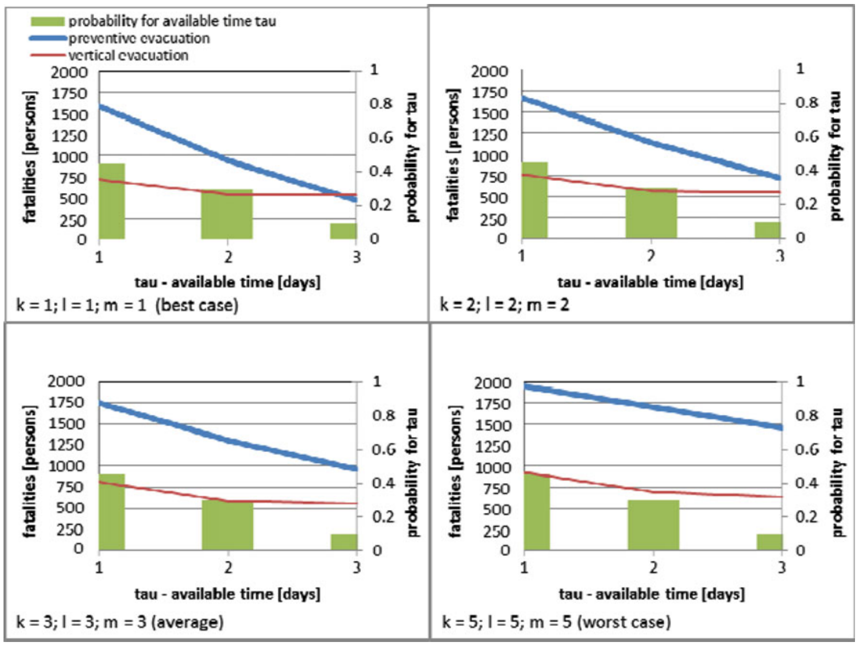

Fig. 6. Expected loss of life in dike ring 14 for vertical and preventive evacuation when τ is 1–3 days for different circumstances (best case when (k, l, or m have value 1, a worst case, an optimistic and average situation) related to the probability distribution of the available time for evacuation.

have the value of 1, which is the most optimistic situation, a preventive evacuation (470 fatalities) results in less loss of life then vertical evacuation (530 fatalities). Only in 15% of all possible events τ is three days or more as also shown in Table III.

For all other circumstances that have been examined in dike ring 14, a vertical evacuation will result in less loss of life even when τ is three days. Because of extreme weather conditions some time might not be available for evacuation;[(48)] this time will reduce the available time for evacuation. When, for example, T_2 is 24 hours as used for a worst credible flood, for dike ring area 14 the decision for evacuation has to be made four days before the possible dike breach if τ has to be three days.[(1)] In that case a preventive evacuation only results in less loss of life than vertical evacuation in 5% of all possible events. A vertical evacuation is therefore the preferred strategy for dike ring 14, although this strategy still contains a preventive evacuation of 20% of the population.

Other areas show different outcomes with respect to the best evacuation strategy (vertical or preventive) and the Dilemma Point. For dike ring 6 (Fig. 7), the Dilemma Point in an average situation occurs after an approximate τ of two days, and the probability of this window of time for evacuation is 50%. Preparation for evacuation should therefore take preventive evacuation as well as vertical evacuation into account. In case of a real event, decisionmakers have to select the best strategy based on the actual circumstances (with actual values for τ and k, l, or m.) For dike ring 43 (Fig. 7) the Dilemma Point for an average situation is after about one day, thus a preventive evacuation seems more attractive for most events.

The figures also show that the success of a preventive evacuation is more sensitive for changes in τ, C, A, and I than vertical evacuation. This sensitivity occurs because preventive evacuation focuses on the removal of people in the threatened area. People who are hit by a flood during the evacuation are most vulnerable. The figures also show that an increase in time for evacuation τ is more effective than an increase in the quality C, A, and I. In addition, loss of life is never reduced to zero because 20% of the people will use vertical evacuation in the case of a preventive evacuation and because of loss of life during transportation. The sensitivity for vertical evacuation for τ, C, A, and I is caused by the group of people (20% of the population) who still use preventive evacuation in these scenarios.

6. DISCUSSION

6.1. From Deterministic Planning to Adaptive Planning Using a Probabilistic Approach

A preventive evacuation will result in less loss of life in cases of enough time; a vertical evacuation

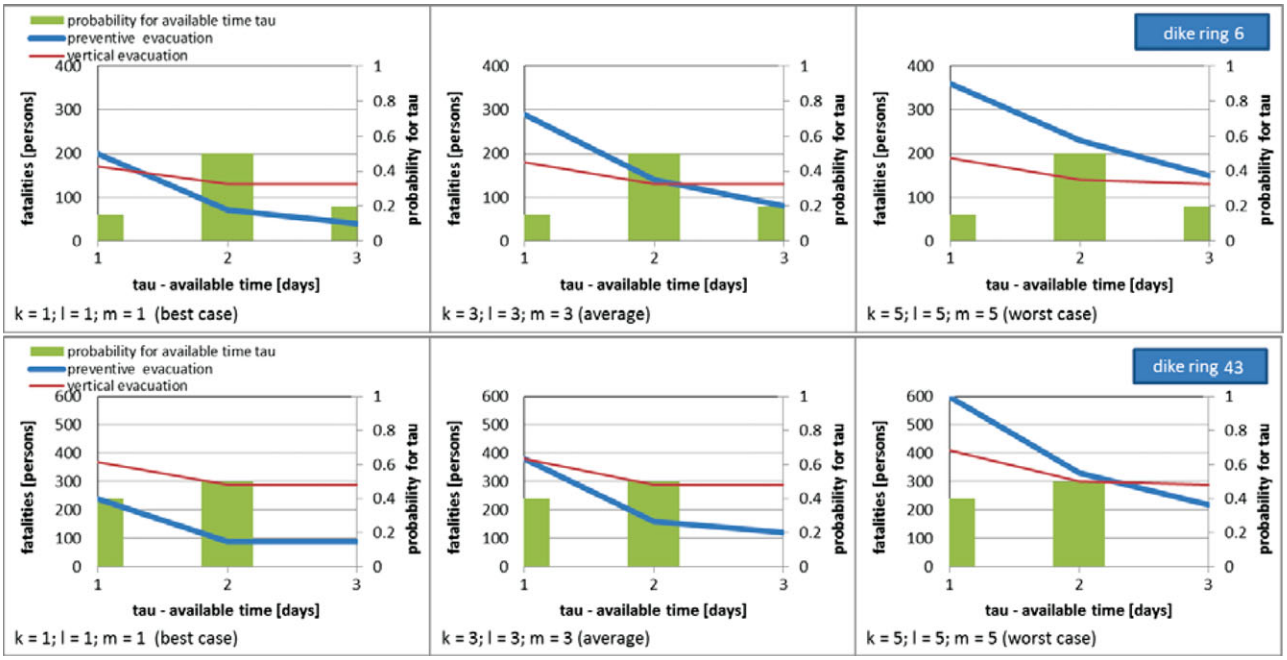

Fig. 7. Expected loss of life in dike ring 6 (above) and 43 (below) for vertical and preventive evacuation when τ is 1–3 days for different circumstances (best case when (k, l, or m have value 1, a worst case, an optimistic and average situation) related to the probability distribution of the available time for evacuation.

might result in less loss of life when time is limited. The moment when preventive evacuation becomes more attractive depends on the area and the adaptive use of infrastructure, citizen response, and response of authorities.

Combining the results of EvacuAid with the lead time due to forecasts shows the need to prepare for vertical or preventive evacuation in an area or for both strategies. Preparation with a strong focus on preventive evacuation limits a possible reduction of loss of life as can be achieved for other strategies. In addition the focus on preventive evacuation and the assumption of enough lead time results in fantasy documents.[34] Fantasy documents are only used to show that organizations are prepared but are useless in case of a real event. In this case the real circumstances will not meet the circumstances as assumed in planning as enough lead time.

Preparation for vertical evacuation could be used as a basic strategy for evacuation planning. For all areas in the case study a vertical evacuation will result in less loss of time when the lead time is limited; after time a preventive evacuation becomes more effective. Preparing for preventive evacuation in addition to vertical evacuation provides the opportunity for adaptive planning. First, preparations are made for a plan A (preventive evacuation), when time is limited, or in case of unforeseen events, plan B (vertical evacuation) could be used.

6.2. Communication as Strategic Asset

Adaptive planning could facilitate citizen response and therefore has great implication for risk communication. During the transition phase, authorities create the best conditions for evacuation such as the concept of traffic management in the Netherlands[22] or the contra flow system in New Orleans.[15] Infrastructure and available means can be used to increase possibilities for evacuation.

Communication to the public is also a strategic asset to improve behavior or reduce the impact of shadow evacuation. In addition, information about the actual event, strategy, and a fall-back scenario can be communicated to the public and local first responders. All stakeholders can take their own measures from which the authorities anticipated the best way possible.

6.3. Cost Benefit Approaches for Evacuation Planning

A cost-benefit analyses supports the optimal investment strategy for flood risk management. On the basis of a cost-benefit approach, the need to invest in multiple layers as prevention or evacuation management can be defined related to their contribution to the risk, and the costs of measures. The evacuation fraction described the fraction of people who can evacuate. The loss of life prevented by the investment is the benefit of evacuation planning. This can be defined by a combination of the time available for evacuation based on lead time and time needed for decision making and the effectiveness of evacuation over time using EvacuAid.

Also in case of a crisis insight in costs and benefits can support top strategic decision making. EvacuAid shows the number of prevented loss of life for different strategies. Decisionmakers can combine this with knowledge of the probability of the event (and occurrence of false alarms) and the costs of evacuation itself. An early choice for a preventive evacuation will cause more economical costs for the economy than a later choice for a less time consuming vertical evacuation. Insight into the consequences of evacuation offers rational risk-based information that can be used by decisionmakers.

6.4. Decision Making Based on Actual Forecasted Conditions

The risk analyses in the case studies shows the characteristics of an area strongly influence the effectiveness of evacuation in terms of loss of life. A risk-based approach gives insight into the relevance of planning for vertical or preventive evacuation in an area. Also insight is given into the effectiveness of measures based on a reference situation. Therefore, decisionmakers can focus on the most effective measures when resource, time, and budget are limited.

The level of preparation of the authorities and the perception of the public changes over time. For authorities it is known that it is a struggle to keep attention for the consequences of flood.[82] Therefore, attention will rise and decline over time. Also public awareness is not fixed, which can be illustrated by some evacuation in the United States. The public perception, and also the willingness to evacuate, during Hurricane Gustav in 2008 was far more than during Katrina in New Orleans in 2005.[83]

6.5. Impact of the Dilemma Point

The Dilemma Point describes the moment when a preventive evacuation results in the same loss of life as a vertical evacuation. When more time is available for evacuation a preventive evacuation will result in less loss of life; when less time is available a vertical evacuation will result in less loss of life. Using forecasts and the knowledge about the actual circumstances and implemented measures, in a real event the strategy can be chosen for an area that minimizes loss of life.

When planning for mass evacuation this (expected) Dilemma Point can be defined and related to statistics of lead time. The need to plan for vertical and preventive evacuation becomes clear. When the lead time is always more than the moment when the Dilemma Point occurs preparation can focus on preventive evacuation. The Dutch case, however, shows that the lead time for an area could be more or less than the Dilemma Point. For these areas planning for both strategies for evacuation is relevant. For some areas, such as dike ring area 14, even very optimistic lead time is almost equal to the Dilemma Point. For these areas it can be questioned if planning for preventive evacuation is relevant becomes a vertical evacuation seems to be the strategy that minimizes loss of life in almost all cases.

6.6. Relevance of EvacuAid: Up to a Normative Approach

The EvacuAid method has been developed to compare different evacuation strategies and to relate the possible success of evacuation to other parameters (e.g., the probability of the flood event, the economic consequences). EvacuAid supports decisionmakers during the situation when a mass evacuation must start before a flood event and also applies for emergency planning. This period of decision making is called top strategic decision making.[31] The final decision will create the boundary conditions to execute an evacuation and multiparty, decentralized decision making. The method applies for evacuation in which the time needed for transportation is significant (compared to the time needed to prepare for evacuation).

The current probabilities, weights, and mortality rates are estimated by experts using a Delphi approach. The results of the method are validated during interviews of experts and scientists. This requirement of experts is also the weakness of the method. For a location such as the Netherlands where a flood is a low frequency event, mass evacuation for flooding is a unique event. Even in other areas that face a mass evacuation more frequently there is a lack of data and statistics for mass evacuation and after each event the system will be updated after implementation of improvements. An example is New Orleans where measures were taken after several hurricanes such as Ivan and Katrina. Scenarios and their probabilities must be reconsidered over time after an evacuation experience or new knowledge.

To improve the relevance for emergency planning and decision making, a common understanding and level of acceptance is required. For successful implementation, an agreed upon standard is recommended for how to use the scenarios and how to use the measures that contribute to the success of the evacuation. A standard approach creates the conditions for connected (and realistic) emergency planning. The planning of multiple organizations can be connected in an overall plan based on decision trees.

7. CONCLUSIONS AND RECOMMENDATIONS

The potential benefits, such as a reduction in loss of life and damage to movable goods, a strategy for evacuation must depend on a combination of the use of the physical environment, citizen response, response of authorities, and the circumstances of a threat, including the available time. When the mortality rate is related to the location where evacuees are exposed, different strategies can be developed to optimize the reduction in loss of life.

The EvacuAid method can be applied for realistic emergency planning as well as for top strategic decision making in case of a crisis during the transition phase. The method gives insight into the loss of life for different strategies as preventive evacuation or vertical evacuation. The method is applicable for evacuation management when the phase of decision making and transportation is a significant part related to the phase of early warning and sense making. Decisionmakers can combine the insights with the probability of an event and the costs of evacuation and use this as a rational basis for decision making. Also, estimations can be made about the effectiveness of measures to influence citizen response and adapt infrastructure or decision making based on the actual circumstances in case of a threat. For emergency planning the expected number of people who can evacuate can be defined using the lead time and the effectiveness of evacuation. This evacuation fraction can be used for flood risk analyses and cost-benefit analyses that take loss of life into account.

The EvacuAid method shows that the result of an evacuation is strongly influenced by uncertainties. Therefore, evacuation planning must account for these uncertainties. The benefits compared to a deterministic approach of a better preparedness can be assessed by the method.

In the case study for the Netherlands, it is shown that the combination of available time for evacuation and required time related to a strategy are most important. For the Netherlands, in the case of flood risk, preparation for an evacuation should focus on a vertical evacuation in addition to a preventive evacuation. When time is limited, a vertical evacuation is expected to result in less loss of life. Depending on the characteristics of an area, such as the number of people, infrastructure, expected response of citizens and authorities, and the possible lead time, the need for complete preventive evacuation can be examined. The moment when a preventive evacuation is expected to result in the same loss of life as a vertical evacuation is called the “Dilemma Point.” When there is less time, a vertical evacuation could result in less loss of life. When more time is available, a preventive evacuation will be more successful. For the area of South Holland, a strategy of complete preventive evacuation will only result in less loss of life than a vertical evacuation in a best-case situation. For other areas, both strategies are equally relevant.

Emergency planning for mass evacuation requires adaptive planning based on uncertainties and a probabilistic approach because the next flood event and benefits of evacuation cannot be defined in advance. For the Netherlands, basic strategies can be used for adaptive planning to minimize loss of life: a preventive evacuation and vertical evacuation as prepared for each local area. The actual strategy in case of an event can be developed based on the actual conditions and forecasts to minimize loss of life, which means minimizing the possibility that people are hit by a flood during an evacuation in combination with the safest location related to the impact and actual circumstances.

The method EvacuAid can be further improved to make better prediction when more insight is develop into the probability of several possible scenarios for evacuation and the costs and benefits of measures. Because the traffic models are not validated for mass evacuation in low frequency events these strongly depend on expert judgment (as also deterministic scenarios do). However the probabilistic approach gives insight in the effectiveness of several measures (planning, risk communication, traffic management, forecasting, etc.) and therefore can be used to give direction to further improvements based on the local characteristics of an area. Because of lack of experience the probabilities have to be evaluated over time to take changes in the environment, planning, or risk perception into account as well as to implement lessons learnt of evacuation elsewhere. In general more research is needed for the mortality rates at different locations inside the flood zone. When the method is applied outside Dutch dike rings new estimations have to be made about the mortality rates based on the local situation. More research is also needed to the consequences of a better risk perception and use of shelters with regard to loss of life. It is also recommended that the estimated probabilities and scenarios are reassessed over time to keep them up to date; this can be combined with inspection intervals of levees, for example.

APPENDIX

Table AI. List of Parameters

Parameter	Unit	Description
D_τ	Persons	Number of people who can move within the available timeframe for evacuation τ to the desired location
τ	Days	Available timeframe for evacuation
H_τ	Persons	Number of people who can leave the area within τ
V_1	Persons	Number of people who stay at home and take no extra precautions
V_2	Persons	Number of people who stay at home and take precautions
V_3	Persons	Number of people in a public shelter
T_1	Days	Period needed for decision making
T_2	Days	Period that extreme weather conditions limit evacuation
T_3	Days	Period between the expected moment of impact and the moment of detection of the threat
N_τ	–	Road network
$x_1, \ldots, x_6$	–	Deterministic description of state variables for road network N_τ
j	–	Scenario based on combination of $x_1, \ldots, x_6$
P	%	Probability
C_τ	Persons	Subset of H_τ influenced by measures of citizens
A_τ	Persons	Subset of H_τ influenced by measures of authorities
I_τ	Persons	Subset of H_τ influenced by efficiency of the use of physical environment
k,l,m	–	Actual condition for C, A, I on an ordinal scale of 1–5 (1 = extreme positive, 3 = average, 5 = extreme negative)
W	–	Performance of C (or A, I) given actual condition of k or l, m
L	Persons	Loss of life
n_i	%	Mortality rate for location i
R_t	Persons	Number of people who did not reach the desired location

Table A2. $P_{6,j,k}$, $P_{7,j,l}$, and $P_{8,j,m}$: The Probability of Each Scenario j Related to C, A, and I and k,l, and m in the Application of EvacuAid in the Netherlands

		Citizen Response (C)					Response of Authorities (A)					Environment and Infrastructure (I)				
	k,l, and m	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
Reference		0.25	0.36	0.48	0.39	0.30	0.25	0.39	0.53	0.41	0.30	0.20	0.33	0.45	0.33	0.20
Departure curve	Departure in 8 hours	0.15	0.11	0.08	0.09	0.10	0.15	0.11	0.08	0.14	0.20					
Average load of traffic	3 persons/car	0.25	0.16	0.08	0.04	0.00	0.25	0.18	0.10	0.05	0.00					
	1 person/car	0.00	0.04	0.08	0.14	0.20	0.00	0.05	0.10	0.18	0.25					
Average travel speed	40 km/hour	0.25	0.16	0.08	0.04	0.00						0.35	0.23	0.10	0.05	0.00
	2 km/hour	0.00	0.04	0.08	0.14	0.20						0.00	0.05	0.10	0.20	0.30
Capacity of outflow of an area	Factor 0.3 (+ 50%)						0.35	0.23	0.10	0.05	0.00	0.25	0.18	0.10	0.05	0.00
	Factor 0.1 (–50%)						0.00	0.05	0.10	0.18	0.25	0.00	0.05	0.10	0.15	0.20
Average road capacity	Breakdown of a highway	0.05	0.06	0.08	0.09	0.10						0.10	0.09	0.08	0.11	0.15
	Breakdown of a regional way	0.05	0.06	0.08	0.09	0.10						0.10	0.09	0.08	0.11	0.15

Table A3. $W_{1,k}$, $W_{2,l}$, and $W_{3,m}$ in the Application of EvacuAid in the Netherlands

Parameter			Conditional Probability			Parameter			Conditional Probability			Parameter			Conditional Probability		
Citizens' Response	Response of Authorities	Environment and Infrastructure	Citizens' Response	Response of Authorities	Environment and Infrastructure	Citizens' Response	Response of Authorities	Environment and Infrastructure	Citizens' Response	Response of Authorities	Environment and Infrastructure	Citizens' Response	Response of Authorities	Environment and Infrastructure	Citizens' Response	Response of Authorities	Environment and Infrastructure
Max	Max	Max	0.5	0.25	0.25	Ave	Max	Max	0.3	0.4	0.3	Min	Max	Max	0.5	0.25	0.25
Max	Max	Ave	0.4	0.2	0.4	Ave	Max	Ave	0.3	0.4	0.3	Min	Max	Ave	0.4	0.3	0.3
Max	Max	Min	0.4	0.2	0.4	Ave	Max	Min	0.3	0.4	0.3	Min	Max	Min	0.4	0.3	0.3
Max	Ave	Max	0.4	0.2	0.4	Ave	Ave	Max	0.3	0.2	0.5	Min	Ave	Max	0.4	0.3	0.3
Max	Ave	Ave	0.6	0.2	0.2	Ave	Ave	Ave	0.33	0.33	0.33	Min	Ave	Ave	0.6	0.2	0.2
Max	Ave	Min	0.4	0.3	0.3	Ave	Ave	Min	0.3	0.2	0.5	Min	Ave	Min	0.4	0.2	0.4
Max	Min	Max	0.4	0.3	0.3	Ave	Min	Max	0.3	0.4	0.3	Min	Min	Max	0.4	0.2	0.4
Max	Min	Ave	0.4	0.3	0.3	Ave	Min	Ave	0.3	0.4	0.3	Min	Min	Ave	0.4	0.2	0.4
Max	Min	Min	0.5	0.25	0.25	Ave	Min	Min	0.3	0.4	0.3	Min	Min	Min	0.5	0.25	0.25

Table A4. Loss of Life (Rounded to Tens) in Case of Preventive Evacuation

		Number Dike Ring Area											
		Only the value for citizen response (C), response of authorities (A), or environment and infrastructure (I) has been changed based on the average situation (k, l, and $m = 3$).									C, A, and I all have the same value for k, l, and m		
		Dike Ring Area 14			Dike Ring Area 6			Dike Ring Area 43					
	k, l, m	C	A	I	C	A	I	C	A	I	14	6	43
τ ° 3 days	1	680	730	730	60	60	60	100	110	100	470	40	90
	2	890	870	890	70	70	70	110	110	110	720	60	100
	3	960	960	960	80	80	80	120	120	120	960	80	120
	4	1,040	1,060	1,040	90	90	90	130	140	130	1,220	110	160
	5	1,240	1,190	1,200	120	110	110	170	170	160	1,460	150	220
τ ° 2 days	1	1,120	1,110	1,140	100	110	100	120	130	130	940	70	90
	2	1,260	1,230	1,250	130	120	130	150	150	150	1,130	100	120
	3	1,310	1,310	1,310	140	140	140	160	160	160	1,310	140	160
	4	1,370	1,390	1,370	150	160	150	180	190	180	1,520	190	240
	5	1,530	1,490	1,500	190	180	180	250	250	230	1,700	230	330
τ ° 1 days	1	1,660	1,650	1,670	240	240	250	300	330	300	1,580	200	240
	2	1,730	1,710	1,720	280	270	270	360	360	350	1,660	250	310
	3	1,750	1,750	1,750	290	290	290	380	380	380	1,750	290	380
	4	1,780	1,790	1,790	300	300	300	420	430	410	1,860	320	500
	5	1,860	1,840	1,850	320	320	320	510	480	490	1,950	360	600

Table A5. Loss of Life (Rounded to Tens) in Case of Vertical Evacuation

		Number Dike Ring Area											
		Only the value for citizen response (C), response of authorities (A), or environment and infrastructure (I) has been changed based on the average situation (k, l, and $m = 3$).									C, A, and I all have the same value for k, l, and m		
		Dike Ring Area 14			Dike Ring Area 6			Dike Ring Area 43					
	k, l, m	C	A	I	C	A	I	C	A	I	14	6	43
τ ° 3 days	1	540	550	540	130	130	130	290	290	290	530	130	290
	2	550	550	550	130	130	130	290	290	290	540	130	290
	3	560	560	560	130	130	130	290	290	290	560	130	290
	4	570	570	570	130	130	130	290	290	290	600	130	290
	5	600	600	570	130	130	130	290	290	290	640	130	290
τ ° 2 days	1	560	570	560	130	130	130	290	290	290	540	130	290
	2	580	580	580	130	130	130	290	290	290	560	130	290
	3	590	590	590	130	130	130	290	290	290	590	130	290
	4	610	610	610	130	130	130	290	290	290	650	130	290
	5	650	640	650	140	130	140	300	290	300	700	140	300
τ ° 1 days	1	750	770	760	170	170	170	380	380	380	710	170	370
	2	800	800	800	170	170	170	380	380	380	760	170	380
	3	820	820	820	180	180	180	380	380	380	820	180	380
	4	830	840	840	180	180	180	380	380	390	870	180	390
	5	880	860	870	180	180	180	400	390	400	930	190	410

REFERENCES

1. Kolen B, Helsloot I. Time needed to evacuate the Netherlands in the event of large-scale flooding: Strategies and consequences. Disasters: Journal of Disaster Studies, Policy & Management, 2012; 36(4):700–722.
2. Bourque LB, Siegel JM, Kano M, Wood MM. Weathering the storm: impact of hurricanes on physical and mental health. Annals of the American Academy of Political and Social Science, 2006; 604:121–159.
3. Jonkman SN. Loss of life estimation in flood risk assessment. Theory and applications. PhD Thesis. Delft University of Technology, 2007.
4. Barendregt A, van Noortwijk JM, van der Doef M, Holterman SR. 2005. Determining the time available for evacuation of a dike-ring area by expert judgement. In Vrijling JK, Ruijgh E, Stalenberg B, Van Gelder PHAJM, Verlaan M, Zijderveld A, Waarts P (eds). Internation Symposium on Stochastic Hydraulics 23 and 24 May 2005, at Nijmegen, 2005.
5. Urbina E, Wolshon B. National review of hurricane evacuation plans and policies: A comparison and contrast of state practices. Transportation Practices Part A, 2003; 37:257–275.
6. Vrijling JK. The lesson of New Orleans. Pp. 57–69 in Kallen MJ, Kuniewski SP (trans and eds). Risk and Decision Analysis in Maintenance Optimization and Flood Management. Amsterdam: IOS Press, 2009.
7. Wolshon B, Urbina E, Wilmot C, Levitan M. Review of policies and practices for hurricane evacuation, I: Transportation planning, preparedness, and responses. Natural Hazards Review, 2005; 6:129–142.
8. Dow K, Cutter CL. Public orders and personal opinions: Household strategies for hurricane risk assessment. Environmental Hazards, 2000; 2:143–155.
9. Gruntfest EC, Carsell K. The Warning Process: Toward an Understanding of False Alarms. Colorado Springs: University of Colorado at Colorado Springs, 2000.
10. Kolen B, Holterman S, van Zuilekom KM, Friso K. If Things Do Go Wrong: Influence of Road Capacity on Possibility for Different Strategies for Evacuation on a National Scale in Case of Potential Flooding (in Dutch). Lelystad: HKV Lijn in water, University of Twente and Goudappel Coffeng, 2008.
11. Helsloot I, Bankoff G, Groenendaal J. Dealing with citizen response and evacuation during large scale flooding in industrial societies. In Bierens J (trans and ed). Handbook on Drowning (version 2, in press). Springer Verlag, 2012.
12. VNK2. De methode van VNK2 nader verklaard, de technische achtergronden. 011.
13. Pel AJ. Transportation modelling for regional evacuations. PhD Thesis. Delft University of Technology, Delft, 2011.
14. Haynes K, Coates L, Leigh R, Handmer J, Whittaker J, Gissing A, McAneney J, Opper S. Shelter-in-place versus evacuation in flash floods. Environmental Hazards, 2009; 8(4):291–303.
15. Wolshon B. Evacuation planning and engineering for Hurricane Katrina. The evacuation of New Orleans had some unprecedented successes and glaring failures. Bridge National Academy of Engineering, 2006; 36(1):27–34.
16. CNN. New Orleans disaster plan: Get out of town. CNN 2006 Monday, August 29, 2005.
17. (TMO) Taskforce Management Flooding. First Impression Exercise Waterproef. The Hague, 2009.
18. van Zuilekom KM, van Maarseveen MFAM, van der Doef MR. A decision support system for preventive evacuation of people. Pp. 229–253 in Van Oosterom PZ, Fendel S, EM (trans and eds). Geo-Information for Disaster Management: Springer Berlin Heidelberg, 2005.
19. Friso K, Zuilekom van KM, Kolen B. Evaluation of the national concept traffic management for mass evacuation in the Netherlands. In Proceedings of the International Conference: IEEE ICNSC. Delft, 2011.
20. Haynes K, Coates L, Leigh R, Gissing A, McAneney J, Handmer J, Opper S. Shelter-in-place versus Evacuation in Flash Flood Environments. In Proceedings of the NSW & Victorian Flood Management Conference. Albury, Australia, 2009.
21. LA-DOTD Metropolitan New Orleans Contraflow Plan, 2009.
22. Wegh E. National Concept Traffic Management for Exercise Waterproef (in Dutch). Utrecht: Ministry of Transport, Public Works and Water Management, 2008.
23. Helsloot I, Ruitenberg A. Citizen response to disaster; a review of literature and some applications. Journal on Contingency and Crisis Management, 2004; 12(3):98–111.
24. Quarantelli EL. The Sociology of Panic. Delaware: Disaster Research Centre, University of Delaware, 1999.
25. Perry RW, Lindell MK. Understanding citizens response to disasters with implications for terrorism. Journal of Contingencies and Crisis Management, 2003; 11(2):51–52.
26. Mileti DS, Drabek TE, Haas E. Human systems in extreme environments: A sociological perspective. University of Colorado, 1975.
27. Mitchell JT, Cutter SL, Edmonds AS. Improving shadow evacuation management: Case study of the Graniteville, South Carolina chlorine spill. Journal of Emergency Management, 2007; 5(1):28–34.
28. DHS US Department of Homeland Security. Lessons learned, mass evacuation: Developing a contraflow plan, 2006.
29. Rasmussen J, Brehmer B, Leplat J. Distributed Decision Making. Cognitive Models for Cooperative Work. Chichester: John Wiley & Sons, 1991.
30. Schneeweiss C. Distributed decision making—A unified approach. European Journal of Operational Research, 2003; 150:237–252.
31. Kolen B, Helsloot I. The impact of the process of decision making to evacuation planning illustrated for flooding in the Netherlands. Journal of Disaster Studies, Policy & Management, 2012, in press.
32. Gwynne S, Galea ER, Owen M, Lawrence PJ. An investigation of the aspects of occupant behavior required for evacuation modeling. Vol II in DeCicco PR (ed). Evacuation from Fires. Amityville, NY: Baywood Publishing Company.
33. Stijnen JW. Bergen met onzekerheden (in Dutch). Stromingen, 2007; 13(2):11–22.
34. Clarke L. Mission Improbable, Using Fantasy Documents to Tame Disaster. Chicago: University of Chicago Press, 1999.
35. Petruccelli U. Urban evacuation in seismic emergency conditions. ITE Journal, 2003; 73(8):25–30.
36. Mens MJP, van der Vat M, Lumbroso D. A comparison of evacuation models for flood event management: Application on the Schelde and Thames estuaries. In Samules P. Huntington S, Allsop W, Harrop J (trans and eds). Flood Risk Management: Research and Practice. London: Taylor & Francis Group, 2008.
37. Bellamy LJ. Review of evacuation data, report no. C768/LJB. London: Technica, 1986.
38. CF04. Hurricane evacuation route Galveston County, Final report, Delft, 2003. Available at: http://www.ct.tudelft.nl/ogbouw/projects/houston3/finalreport_houston2003.pdf, Accessed October 24, 2012.
39. Barendregt A, van Noortwijk JM, van Maarseveen MFAM, Tutert SIA, Zuidgeest MHP, Van Zuilekom KM. Evacuatie Bij dreigende overstromingen (in Dutch). Lelystad: Universiteit Twente & HKV Lijn in water, 2002.
40. Kolen B, Thonus B. Landelijke Evacuatie Module. Lelystad: HKV Lijn in water, 2010.

41. Feinberg WE, Johnson NR. Firescap: Simulation of evacuation response to a fire alarm. Journal of Mathematical Sociology, 1997; 20(2–3):247–269.
42. Bliemer MCJ. Indy 2.0: Model specification. University of Delft. 2005.
43. Kolen B, Thonus B, Zuilekom KM, Romph E. Serious gaming for the preparation of mass evacuation. In IEEE ICNSC 2011, Series Serious Gaming for the Preparation of Mass Evacuation. Delft, 2011.
44. Kolen B. From Threat Until Evacuation—Learning to Evacuate (in Dutch). Delft: HKV Lijn in water, 2009.
45. Windhouwer CJ, Sanders CJ, Kluder GA. Decision Support System Emergency Planning, Creating Evacuation Strategies in the Event of Flooding. Deventer: Oranjewoud, 2004.
46. Pel AJ, Bliemer MCJ, Hoogendoorn SP. EVAQ: A new analytical model for voluntary and mandatory evacuation strategies on time-varying networks. In Proceedings of the 11th International IEEE Conference on Intelligent Transportation Systems. China, 2008.
47. Hydro BC. BC Hydro Life Safety Modelling Environment V2.0 Beta User Manual, 2006.
48. Maaskant B, Kolen B, Jongejan R, Jonkman SN, Kok M. Fractions of Preventive Evacuation in Case of Flooding in the Netherlands (in Dutch). Lelystad: HKV consultants, 2009.
49. Kolen B, Holterman S, Zuilekom KM, van Friso K. If Things Do Go Wrong: Influence of Road Capacity on Possibility for Different Strategies for Evacuation on a National Scale in Case of Potential Flooding (in Dutch). Lelystad: HKV Lijn in water, University of Twente and Goudappel Coffeng, 2008.
50. Ministry of the Interior and Kingdom Relations Ministry of Transport Public Works and Water Management. Capacity analysis for the task large-scale evacuation. Report National Security (in Dutch). The Hague, 2008.
51. AGS. Risicobeleid en rampenbestrijding. Op weg naar meer samenhang. Adviesraad Gevaarlijke Stoffen. Den Haag, 2008.
52. Jongejan R, Stefess H, Roode N, Horst W ter, Maaskant B. The VNK2 project: A detailed, large scale quantative flood risk analysis for the Netherlands. In ICFM5. Tokyo, Japan, 2011.
53. De Bruijn K, Beckers J, Van Der Most H. Casualty risks in the discussion on new flood protection standards in the Netherlands. Pp. 73–83 in de Wrachien D, Proverbs D, Brebbia CA, Mambretti S (eds). Second International Conference on Flood Recovery, Innovation and Response. Ashurst, UK: Wessex Institute of Technology, 2010.
54. Jonkman SN, Maaskant B, Boyd E, Levitan ML. Loss of life caused by the flooding of New Orleans after Hurricane Katrina: Analysis of the relationship between flood characteristics and mortality. Risk Analysis, 2009; 29 (5):676–698.
55. Kok M, Vermeij-Braak E, Kanning W, Kolen B, Thonus B, Adams-Tonk A. Two Years After Katrina (in Dutch). Lelystad: HKV Lijn in water, University of Delft, 2007.
56. Drobota SD, Benight C, Gruntfest EC. Risk factors for driving into flooded roads. Environmental Hazards (2007), doi:10.1016/j.envhaz.2007.07.003.
57. Jonkman SN, Kelman I. An analysis of the causes and circumstances of flood disaster deaths. Disasters: Journal of Disaster Studies, Policy & Management, 2005; 29(1):75–97.
58. Baker EJ. Hurricane evacuation behavior. International Journal of Mass Emergencies and Disasters, 1991; 9(2):287–310.
59. van de Ven GP. Man-made lowlands, history of water management and land reclamation in the Netherlands. International Commission on Irrigation and Drainage (ICID). Utrecht, The Netherlands, 2004.
60. (BZK) Ministry of the Interior and Kingdom relations. National Security, National Risk Assessment 2008 (in Dutch). Den Haag: Ministry of the Interior and Kingdom relations, 2008.
61. (BZK) Ministry of the Interior and Kingdom Relations. National Security, National Risk Assessment 2009 (in Dutch). The Hague: Ministry of the Interior and Kingdom Relations, 2009.
62. Terpstra T. Flood Preparedness; Thoughts, Feelings and Intentions of the Dutch Public. Enschede: University of Twente, 2009.
63. ten Brinke WBM, Bannink BA, Ligtvoet W. The evaluation of flood risk policy in the Netherlands. Journal on Watermanagement, 2008; 151(4):181–188.
64. (BZK) Ministry of the Interior and Kingdom Relations. National Crisis Plan Extreme Water Levels and Flooding, Communication Strategy (in Dutch). The Hague, 2008.
65. Ven W. National Plan for Extreme Water Levels and Flooding (in Dutch). Lelystad: RWS Waterdienst, 2010.
66. Haaglanden Hulpverleningsregio. Coordinatieplan Overstromingen Haaglanden, versie 1.3 (24 april 2008) (in Dutch), 2008.
67. Brabant Veiligheidsregio Midden- en West-. Regionaal basisplan overstromingen, Samen voorbereiden op overstromingen, versie 1.0 juni 2008 (in Dutch), 2008.
68. Crisisbeheersing Landelijk Beraad. Basisvereisten crisismanagement, De decentrale normen benoemd, 2006.
69. HKV. Figures for evacuation for cost benefit analyses. Memorandum PR1919–10 (in Dutch). Lelystad, 2010.
70. Friso K, Banninga J, van Zuilekom KM. FLORIS—Modelling and Analyses of Evacuation (in Dutch). Deventer: Goudappel Coffeng, University of Twente, 2008.
71. Jonkman SN, Cappendijk P. Veiligheid Nederland in Kaart—Inschatting van het aantal slachtoffers ten gevolge van overstroming; Dijkringen 7, 14 en 36 (in Dutch), 2006.
72. BZK, Ven W. Capaciteitenanalyse voor grootschalige evacuaties. Den Haag, 2008.
73. NIPO. Risk Perception of Flooding Related to Willingness to Evacuate (in Dutch). Amsterdam, 2006.
74. Linstone HA, Turoff M (eds). The Dephi Method: Techniques and Applications Reading. MA: Addison-Wesly Publishing Company, 1975.
75. Rowe G, Wright G. The delphi technique as a forecasting tool: Issues and analysis. International Journal of Forecasting, 1999; 15:353–375.
76. Chiu WT, Arnold J, Shih YT, Hsiung KH, Chi HY, Chiu CH, Tsai WC, Huang WC. A survey of international urban search-and-rescue teams following the Ji Ji earthquake. Disasters: Journal of Disaster Studies, Policy & Management, 2002; 26:85–94.
77. Ng M, Park J, Waller ST. A hybrid bilevel model for the optimal shelter assignment in emergency evacuations. Computer-Aided Civil and Infrastructure Engineering, 2010; 25(8):547–556.
78. Jonkman SN Vrijling JK. Loss of life due to floods. Journal of Flood Risk Management, 2008; 1:43–56.
79. Boyd E. New Orleans was prepared but it was overwhelmed (correspondence). Nature, 2006:442:244.
80. Slager K. De ramp, reconstructie van de overstroming van 1953, 2003.
81. Kolen B, Helsloot I, Maaskant B, Thonus B. EvacuAid: A probabilistic evacuation model to determine the expected loss of life for different mass evacuation strategies. In Albores P (ed). INTERCEPT 2010. Birmingham, 2010.
82. ten Brinke WBM, Saeijs GEM, Helsloot I, Van Alphen J. Safety chain approach in flood risk management. Municipal Engineer, 2008; 161(4):181–188.
83. Cole J. Hurricane Gustav—Testing the lessons learned from Katrina. Emergency Management, Editor, HSR Monitor, 2008.