Delft Cluster

Title:	Consequences of floods: the development of a method to estimate the loss of life

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Abstract

Large parts of the Netherlands lie below sea-level, and the hazard of large scale floods leading to extensive damage and loss of life is always present. In this paper a framework for the estimation of loss of life caused by floods in the Netherlands is proposed. The method takes into account the effect of evacuation during the flood and various mechanisms which lead to fatalities during a flood. The relationships between flood characteristics and number of fatalities are based on data from the 1953 disaster, during which the south-western part of the Netherlands was flooded, and that caused 1836 fatalities. The method is applied in two case studies to give a first estimate of the number of fatalities caused by a river dike breach near Rotterdam and failure of the coastal defence near Katwijk, both leading to a flood of the Central Holland area.

PROJECT NAME:	**Flood consequences**	PROJECT CODE:	**02.03.03**
BASEPROJECT NAME:	**Flood consequences and acceptability**	BASEPROJECT CODE:	**02.03**
THEME NAME:	**Risk of flooding**	THEME CODE:	**02**

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1 Introduction

The Delft Cluster project “Consequences of floods” aimed at assessing a large number of possible flood impacts ranging from damage to infrastructure and housing, economic loss, environmental risks, and casualties. This paper focuses on the last subject, i.e. loss of life.

Every year floods cause enormous damage all over the world. In the last decade of the 20th century floods accounted for about 12% of all deaths from natural disasters, claiming about 93,000 fatalities (derived from the OFDA / CRED International Disaster Database, www.cred.be). Floods may also lead to other health effects, and can have various physical as well as psychological impacts (Ohl, 2000; WHO, 2002; Hajat, 2003). These health effects may also result in indirect delayed loss of life due to stress and illnesses. Increased levels of mortality in the year after a flood are for example reported by Bennet (1970). Little research has been carried out on estimation of loss of life caused by floods. An overview of the available methods is given by Jonkman et al. (2002).

This paper describes the advances in the research on this topic made in the Delft Cluster project “Consequences of floods”. The aim of this part of the project was to develop a method to estimate the number of fatalities during floods in the Netherlands, taking into account the characteristics of the flood and the effect of an evacuation before or during the flood. To fulfil this aim, the following activities were carried out:

- Assessment of the relation between loss of life and different flooding characteristics, such as maximum water depth, maximum flow velocities, and rate of rise (section 2);
- Estimation of the time needed for evacuation (section 3);
- Development of a loss of life model in a GIS, using the knowledge on loss of life and evacuation (section 4);
- Application of the GIS-based model to two case study areas in Central Holland (section 5).

Although an attempt has been made to assess both direct loss of life caused by drowning and indirect loss of life due to diseases, this paper mainly focuses on the direct loss of life by drowning, i.e. during the flood period.

2 Development of a flood-mortality function

2.1 Introduction

Loss of life during a flood can occur in many ways. For instance, people can be swept in the water and buildings can collapse. Also indirect causes, such as flood induced heart attacks, shocks and electrocution during the clean up phase can contribute to the death toll. Floods can even result in higher mortality levels in the years afterwards, due to an increase of stress and illnesses, see for example (Bennet, 1970). More insight in the death causes of floods and the related circumstances is necessary to gain understanding and to improve the prevention of fatalities. This investigation focuses mainly on direct deaths during the flood, amongst those who are unable to escape from the flooded area. For a better understanding of loss of life caused by floods more insight is required in the relation between the causes of death and the flood and area characteristics. This type of study requires extensive (quantitative) information from historical floods. The availability of this type of data is in general very limited.

In this study a more simplified approach is chosen. In a so-called flood mortality function the probability of drowning is statistically related to the hydraulic circumstances, such as maximum water depth, maximum flow velocities, and rate of rise of the water. The exact causes are not accounted for. Flood mortality relationships should be preferably based on reliable data, derived from historical floods. Therefore an investigation of available information from historical floods was carried out. So far, detailed data on drowning persons for the 1953 floods in the Netherlands have been retrieved from Waarts (1992).

2.2 Development of a flood mortality function based on the 1953 flood disaster in the Netherlands

During this flood a storm surge from the North Sea inundated large parts of the southwest of the Netherlands. This event caused enormous damage and shock, moreover 1836 persons were killed due to this disaster. Based on the available information on fatalities it was investigated whether a relation between hydraulic flood characteristics and flood mortality could be found. In this case the effects of evacuation are neglected: the disaster struck unexpectedly at night, no evacuation could be carried out. The loss of life can thus be directly related to the presence of persons at different locations and the flooding circumstances.

Based on the collected data from the 1953 flood the following approach is proposed to relate flood mortality (i.e. the fraction of inhabitants in an area that lose their life in the flood) to hydraulic characteristics of the flood. Three categories of flood deaths are distinguished:

- Drowning persons due to rapidly rising water
- Drowning persons due to high flow velocities
- Deaths due to other causes, such as hypothermia, heart attacks, shock, failed rescue, etc.

In the analysed data (Waarts, 1992) it has been recorded to which of these causes the fatalities per location can be attributed. The distribution of the numbers of flood deaths is shown in Table 2.1.

Cause	Number of deaths	Percentage
Rapidly rising water	1054	61%
High flow velocities	254	15%
Other causes	427	25%

Table 2.1 Distribution of flood deaths of the 1953 flood in the Netherlands over the categories for 1726 of the 1835 recorded flood deaths (based on Waarts, 1992)

The table shows that rapidly rising water levels were the main cause of death during the unexpected 1953 flood. This information on drowning categories is used to propose criteria for each of these three categories to estimate the contribution to total loss of life.

2.3 Fatalities due to rapidly rising water levels

When the water rises rapidly, dangerous situations may occur. People will not be able to reach high grounds or even to reach the higher floors of buildings. It is expected that especially the combination of water depth and rate of rising causes the danger, since dangerous situations will especially occur in larger water depths. The fatalities caused by rapid increase in water depth during the 1953 flood are shown in Figure 2.1. From this figure it can be seen that mortality increases with water level. The following function is derived:

$$f(h)_{rise} = 9.18 \cdot 10^{-4} \cdot e^{1.52 \cdot h} \qquad f(h)_{rise} \leq 1 \qquad (1)$$

with f(h)rise is the fraction of inhabitants killed by rapidly rising water levels and h is the water depth.

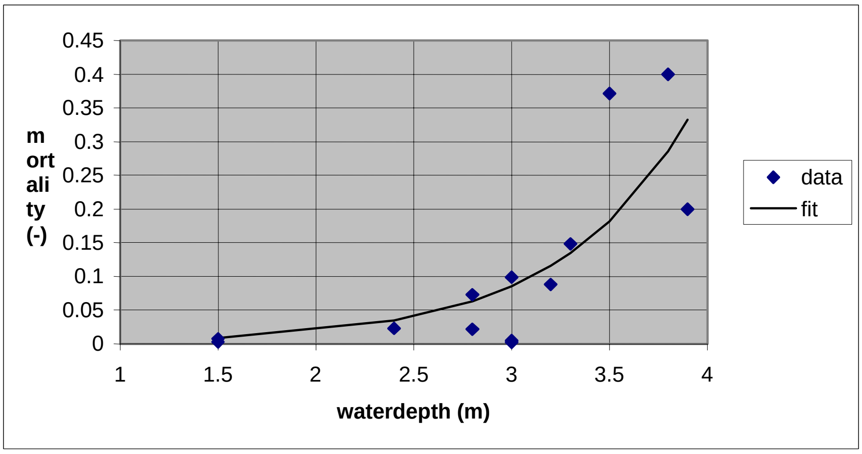


Figure 2.1 Proposed function for estimation of flood mortality for rapidly rising water

Based on the known values of the rate of water level rise it is assumed that this function should be applied if the water rises with 1 m/hr or more. A specific problem is the extrapolation of this function for larger water depths. No data is available for water depths of more than 3.9 m. As the proposed function is very steep at the upper end, extrapolation may result in unrealistic numbers of deaths. For instance, at about a water depth of about 5.3 m, the maximum fraction of 100% deaths is reached. In further research the elapse of this function for larger water depth is to be assessed. Now it is assumed that the 100% value applies to all water depths of 5.3 m or more.

2.4 Fatalities due to high flow velocities

Due to high flow velocities people can lose their stability, fall into the water and drown. Also, buildings can collapse. Especially dangerous situations will occur near the breach (where high flow velocities occur). Therefore it was proposed by Waarts (1992) to assume that everyone present within an area with a radius of twice the breach width will drown. This criterion can be worked out in more detail using the knowledge obtained on the strength of buildings and the stability of persons in fast flowing waters.

Tests on the stability of humans in flows have been carried out by Abt et al. (1989). In this Delft Cluster project, a method was set up to analyse the collapse of buildings during floods (Roos, 2003). The mechanism of collapse of walls is considered for four types of housing: traditional buildings (types 1 and 2: TB 1 & TB 2), Cast concrete (CC) and prefabrication (PF). The combinations of water depth and flow velocity for which a wall of a certain building type will collapse with 100% probability, are shown in Figure 2.2.

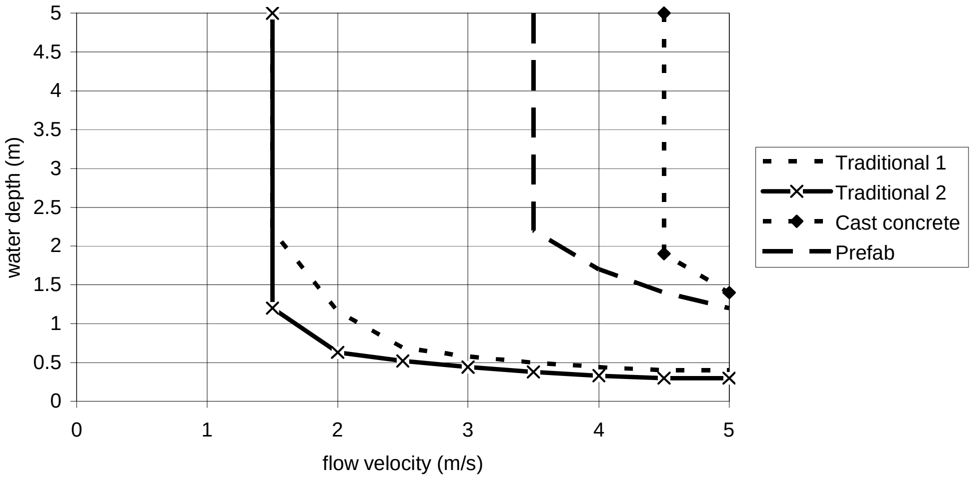


Figure 2.3 Combination of flow velocity and water depth for which a wall of a certain type of building stock will collapse with 100% probability, based on Roos et al (2003)

In the model developed by TNO the probability of collapse of a wall can be determined as a function of water depth and flow velocity. In this study a simplified approach is chosen in which only the boundaries for 100% collapse are considered for further analysis. Based Figure 2.3 loss of life due to collapse of buildings can be estimated as follows. A constant distribution of building stock over the different types is assumed for the different locations (TB1: 19%, TB2: 55%, CC: 20%, PF: 1%, others: 6%). Consequently it is assumed that this distribution equals the distribution of persons over the building types. Now it should be considered that these figures represent the collapse of one wall, it is assumed that in 70% of these cases the total building will collapse. It is also assumed that the collapse of a building in fastly flowing water will result in the death of all those present in the building.

Consider as an example local flood conditions at a certain location of 1,5m water depth and 3 m/s flow velocity. From the figure it can be derived that walls of traditional building stock types 1 and 2 will collapse. 70% of these buildings will totally collapse. Now (0,7*(0.55+0.19)=0.52) of the total amount of buildings collapse, and 52% of the persons can be assumed to have drowned.

A more simple criterion for the damage to buildings in flow conditions is proposed in the Rescdam project (Rescdam, 2000). Total damage to masonry, concrete and brick houses will occur if the product of water depth and flow velocity exceeds the following criterion:

$$h \cdot v \geq 7m^2/s \qquad and \quad v \geq 2m/s \qquad (2)$$

with v is the flow velocity (m/s) and h is the water depth (m).

Under the assumption that most persons remain indoor during the flood and that persons will drown when the building collapses, a criterion for building strength is proposed to estimate the contribution of deaths due to high flow velocities. In the case study the simple analysis of the Rescdam project is applied. The procedure based on the model of TNO can be implemented in further case studies.

2.5 Deaths due to other causes

If fatalities are not caused by rapidly rising water levels or high flow velocities, other causes may also result in fatalities. These causes can be for example hypothermia or fatigue of persons, collapse of building after a long period of hydraulic load. Also, indirect causes of death, such as heart attacks and electrocution, can be relevant. For the 1953 flood the reported mortalities for other causes are shown in Figure 2.3.

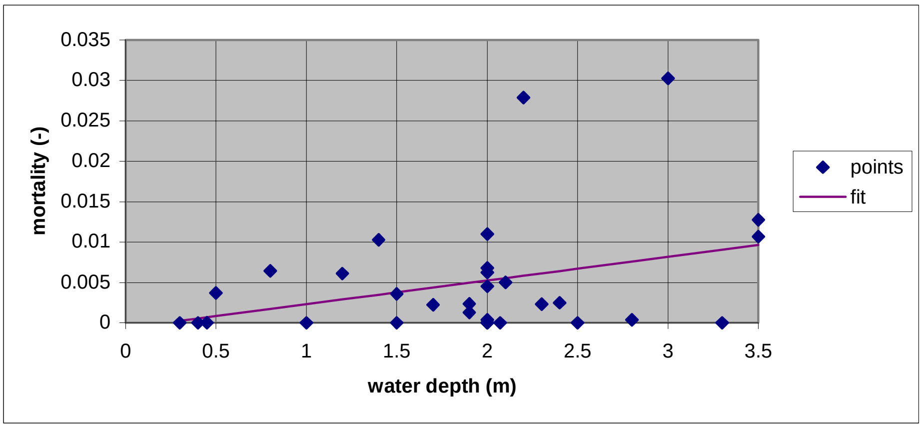


Figure 2.3 Proposed function for flood mortality estimation due to other causes

The following function has been derived:

$$f(h)_{other} = 1.41 \cdot 10^{-3} \cdot e^{0.59 \cdot h} \qquad f(h)_{other} \leq 1 \qquad (3)$$

As these causes of death also occur in slowly increasing water depths, this function is used to estimate the number of casualties in areas with an increase in water depth of less than 1 m/hr.

3 Estimation of the time needed for evacuation

Application of the above described relations between flooding characteristics and number of fatalities is likely to result in an overestimation of the number of fatalities as possibilities for evacuation or escape are not accounted for. For instance, when flow velocities and water depths are large, a large number of inhabitants is expected to die. However, in reality the number of fatalities will differ depending on whether these large depths and strong flows occur immediately after failure of the dike, or several hours or days later. To estimate the percentage of the population that is able to evacuate or escape before the flood water reaches their houses, information is needed about the time required time for an evacuation or unorganised escape.

Evacuation has been studied in great detail in the Poldevac project (e.g. Van der Meulen and Leenders, 2002). In this project, a detailed transport model was developed and applied to simulate evacuation. Delays and risk for traffic jams due to the presence of cross roads and traffic lights were accounted for. Ideally such a transport model should be available for the entire country. Only with this type of model it is possible to produce accurate estimates of requested evacuation times and of the time needed for people living in different locations to reach a safe place. Unfortunately this model is not available for the case study area. Also, this type of model requires an extensive amount of input data and is therefore not suitable for a more generic use for other flood prone areas.

Barendregt et al. (2002) developed a more simple conceptual method to simulate an evacuation of a flood prone area in the Netherlands. This model mainly considers preventive evacuation before the beginning of the flood. A preventive evacuation consists of three stages: the decision making, initiation of the evacuation, and the evacuation itself. The time needed for each phase depends on the availability of an evacuation plan (how well are inhabitants and local authorities prepared), the number of people to be evacuated and the available infrastructure. An example of an evacuation function is shown in Figure 3.1.

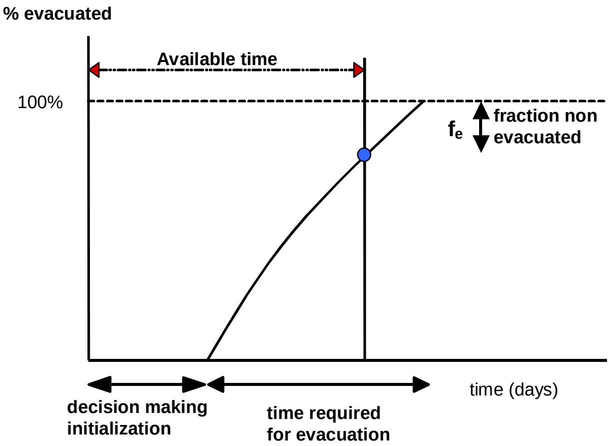


Figure 3.1 Evacuation curve after Barendregt et al. (2002)

The available time for evacuation depends on the predictability of the water levels at sea or in the river and the failure mechanism. While extreme river discharges in the Netherlands can be predicted up to several days ahead, extreme sea water levels have a much shorter prediction time (6 – 10 hours). Failure of a dike is relatively easy to predict in case of overtopping, but is much more difficult to foresee in case of the failure mechanism piping. In case of evacuation or escape after failure of the dike, the available time only depends on the travel time of the flood wave to a certain location within the flooded area. The time needed for decision making and initialization in that case equals the time needed to warn people and for the people to prepare themselves for departure. The time required for evacuation depends on the capacity of the infrastructure. In the case of evacuation after failure of the river dike this will mainly be the capacity of the roads as the railway system is expected to be dysfunctional. Depending on the available time and the requested time, a certain percentage of the inhabitants will be able to escape in time. The percentage that is not able to escape is indicated by fe in Figure 3.1. These persons will be exposed to the flooding conditions and run a risk of drowning. Since high rise buildings provide shelter places during a flood, it is assumed that persons present in high rise buildings are safe and can be considered as ‘evacuated’.

4 Development of a loss of life model in a GIS

To estimate the number of fatalities caused by a flood event, the relationships between flood characteristics and fatalities and the knowledge on evacuation times need to be integrated into a so-called loss of life model. As most information with respect to the flooding characteristics, locations of houses and number of inhabitants varies spatially, it is preferred to develop such a model in a Geographic Information System (GIS).

Figure 4.1 shows the overall framework of the loss of life model. Information on the number of inhabitants, the capacity of the available infrastructure and the time of inundation are combined in the evacuation model to estimate the number of people that are unable to escape. This, together with information about the water depth and flow velocities is used as input for the flood mortality functions (section 2). The outcome consists of a map showing the number of fatalities at different locations within the flooded area. GIS maps indicating the number of inhabitants were derived from the damage and loss of life model developed by Rijkswaterstaat, DWW (Vrisou van Eck et al., 2000. Characteristics of the flood, such as time of inundation, water depth and flow velocities are based on hydraulic computations with the SOBEK model (Asselman and Heynert, 2003). The model was developed in the GIS-package PCRaster (Van Deursen, 1995).

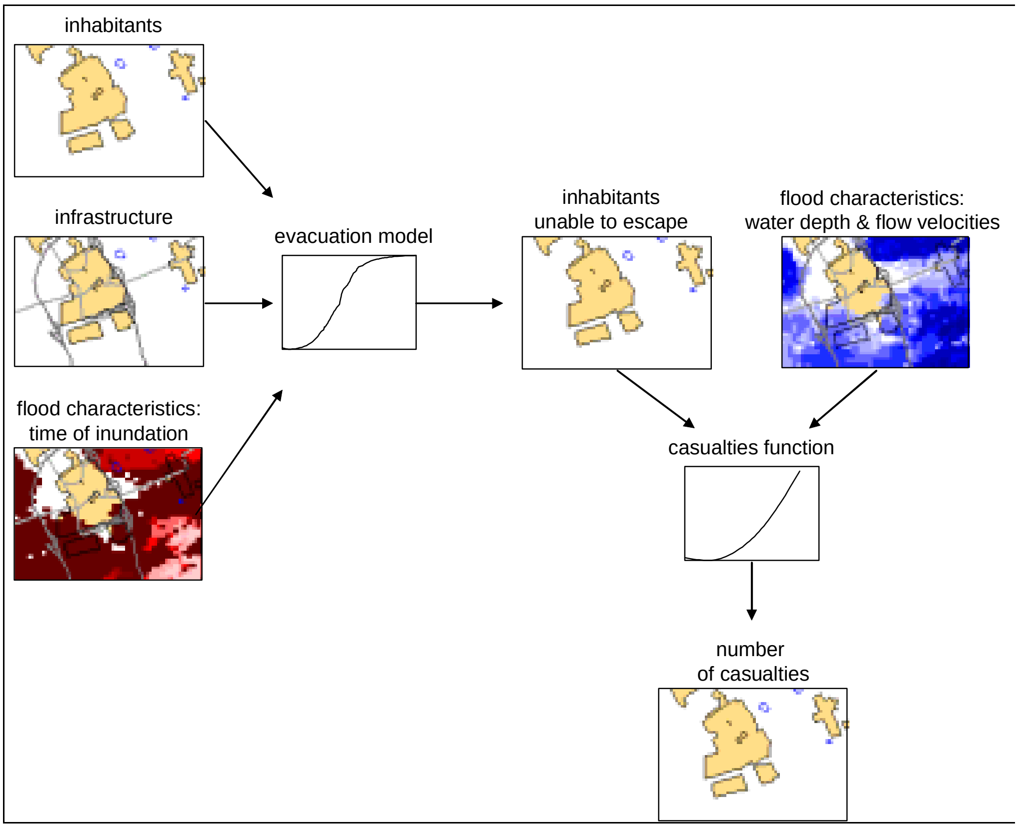


Figure 4.1 Flow chart of the loss of life model in GIS

5 Application of the GIS-based model to the case study area in Central Holland

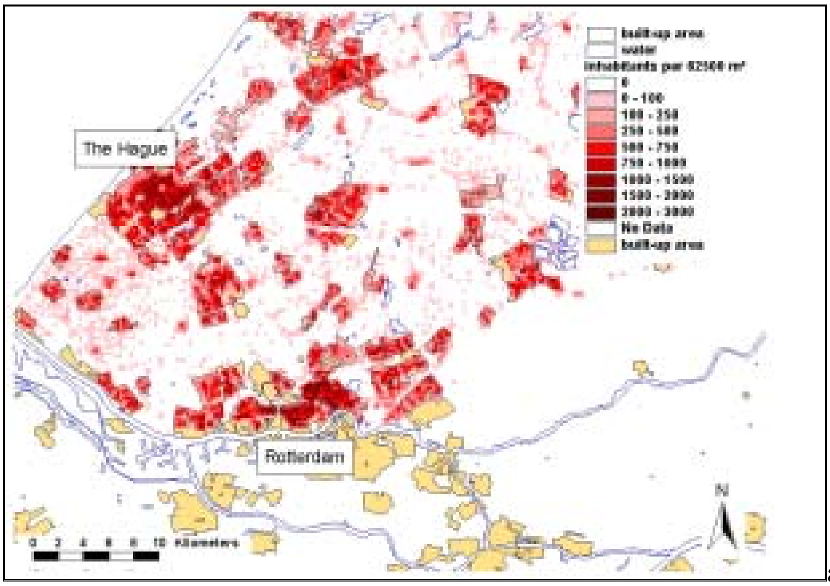
5.1 Introduction

The loss of life model was applied to the case study area ‘dijkring 14’, i.e. Central Holland. The model approach described previously is explained here in more detail using model input and output maps of the case study area for illustration. Section 5.2 describes the results in case of a breach in the river dike near Rotterdam. The number of casualties caused by failure of the coastal defence system near Katwijk is shown in Section 5.3. A more detailed analysis on the evacuation model and importance of the evacuation route is given in Section 5.4.

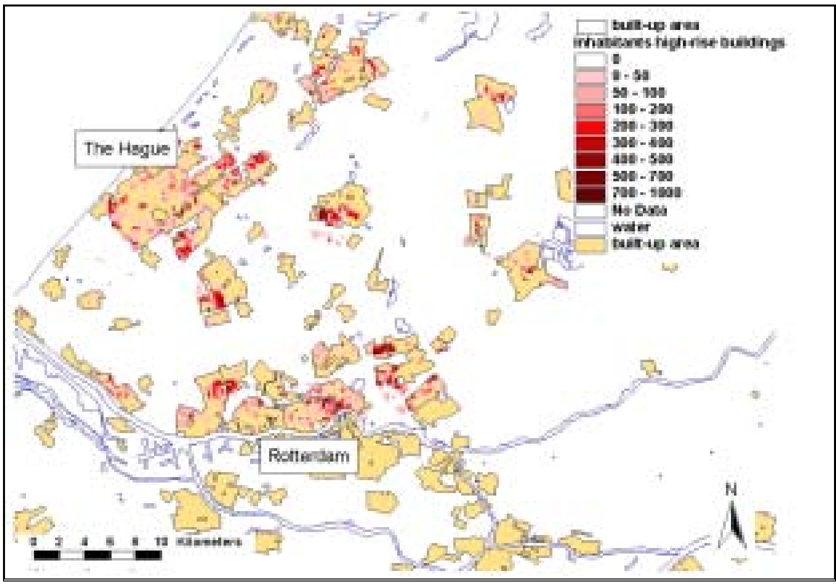
5.2 Loss of life estimation for failure of the river dike near Rotterdam

Inhabitants

As the case study area includes large cities such as Rotterdam, Amsterdam and The Hague, the total number of people living here equals 3.6 million. Figure 5.1 shows the spatial distribution of the inhabitants. Figure 5.1a indicates the total number of inhabitants per grid cell of 250 x 250 m², whereas Figure 5.1b shows the number of people living in high-rise buildings. This differentiation was made as it determines whether or not the occupants are able to find a safe place in their homes as the water level rises.



a

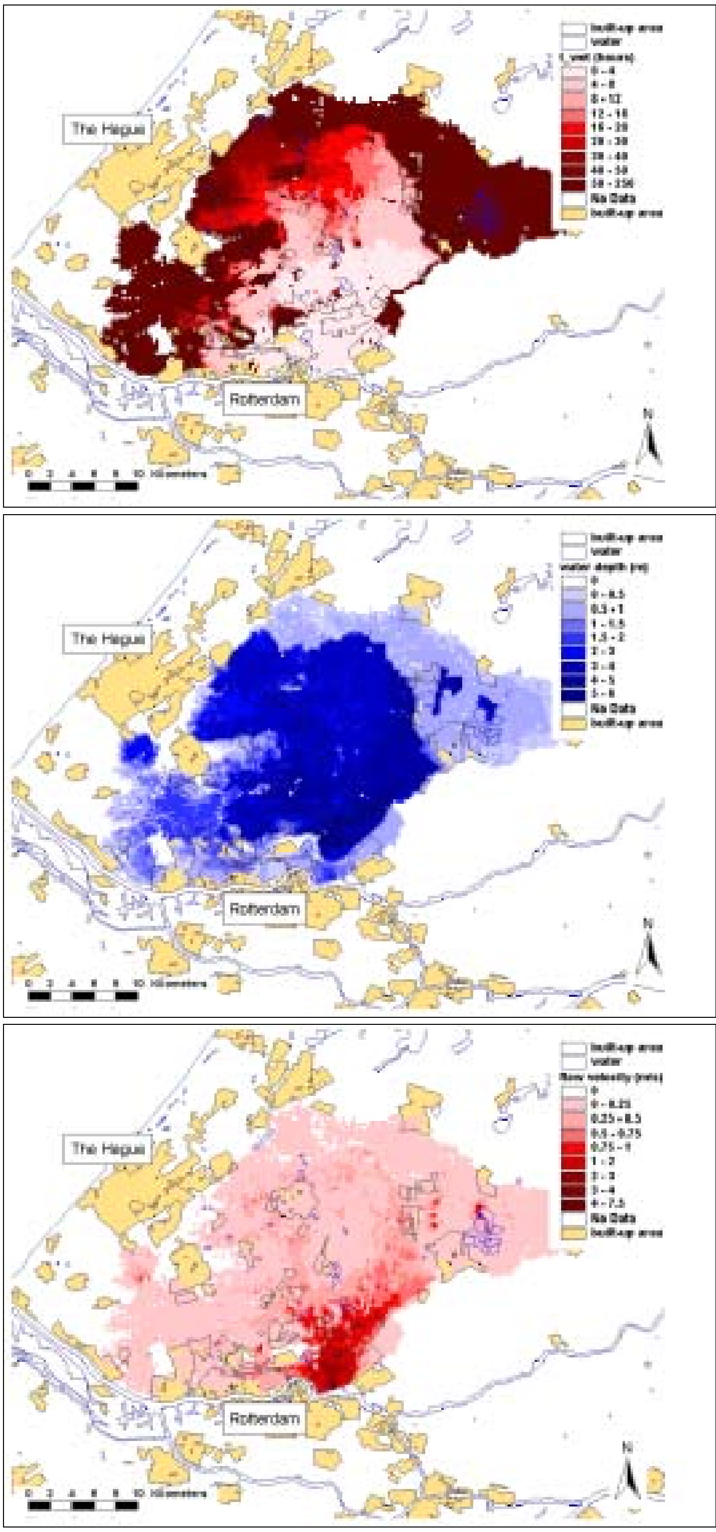


b

Figure 5.1 Number of inhabitants per 250x250 m² grid cell: (a) total, (b) in high-rise buildings

Flood characteristics

Flooding simulations were carried out using the 2D hydraulic SOBEK model. The simulations are described in more detail by Asselman and Heynert (2003). The most important results of the simulation for the Rotterdam-case are shown in Figure 5.2. Figure 5.2a shows the time of inundation in hours after failure of the dike. The south-east part is flooded within 5 hours. It takes about 5 days or more before places near the boundary of the flooded area are inundated. Water depths decrease from 6 m in the central part to less than 1 m at the boundary of the flooded area (Figure 5.2b). Maximum flow velocities follow a similar distribution with very high values of up to 7 m/s near the dike breach, decreasing to about 0.1 m/s at the boundaries of the inundated area (Figure 5.2c).



a b c

Figure 5.2 Flood characteristics computed with the 2D hydraulic model: (a) time of inundation (hours after failure of the river dike), (b) maximum water depth (m), (c) maximum flow velocity (m/s)

Possibilities for evacuation and escape

In this example a worst case scenario is considered. It assumed that the dike breaches unexpectedly, without the possibility of pre-flood evacuation. Although in practice a forecast of extreme river discharges is likely, the considered unexpected scenario is possible and realistic, however with small probability. As no traffic or transport model was available for the area used in the case study, it was assumed that the conceptual function developed by Barendregt et al. (2002) for non-organised evacuation in a theoretical polder area is also valid in the case study area. The total time needed for non-organised evacuation was taken as 50 hours. The time needed for decision making and initialization was assumed to take about 4 hours. In the case study this time covers the time needed for warning and getting ready for departure of the people that have to be evacuated. As this function was not based on a traffic model for the case study area, the estimated time required for evacuation is very uncertain. Therefore, different functions were used to assess the sensitivity of the model results for uncertainties in requested evacuation time. In total 3 functions were applied. All functions have an initiation time of 4 hours. The total time needed for evacuation or escape, however, varies from 25 to 100 hours.

The percentage of the inhabitants that are able to evacuate or escape before the flood reaches their houses is shown in Figure 5.3. As is to be expected, the pattern in Figure 5.3 closely resembles that of the time of inundation (Figure 5.2a). In the south-east part hardly anybody is able to escape, whereas closer to the boundaries of the inundated area the percentage of inhabitants that is able to evacuate increases to 100%.

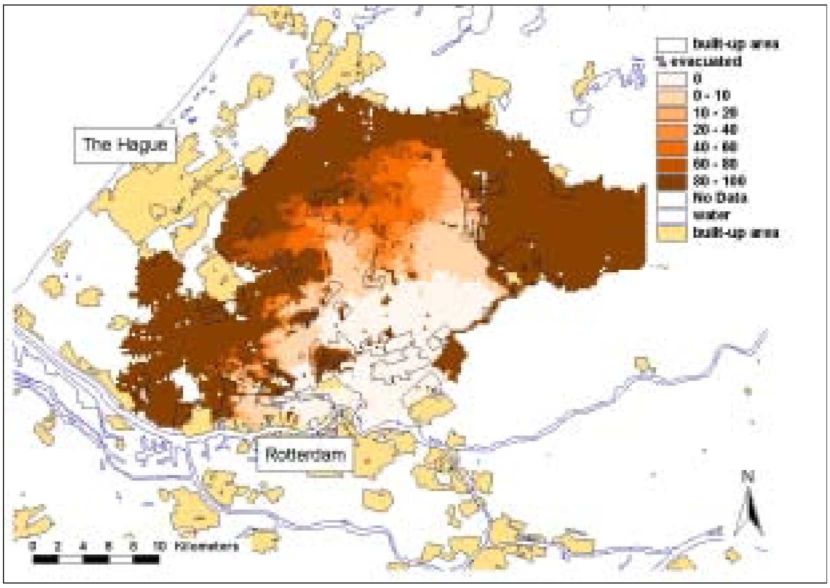


Figure 5.3 Percentage of inhabitants that can evacuate or escape when the total time required for evacuation equals 50 hours

Fatalities

The number of fatalities within the flooded area is estimated using the relationships (as described in section 2) between fatalities and:

- water depth in areas with slow rising water levels (i.e. increase in water depth less than 1 m per hour);
- water depth in areas with rapidly rising water levels (i.e. more than 1 m per hour);
- flow velocity (collapse of buildings).

It is assumed that people living in high-rise buildings are safe, regardless of the water depth that occurs.

The estimated number of fatalities caused by either large water depths or high flow velocities is shown in Figure 5.4. The results are described in more detail in Table 5.1 and 5.2.

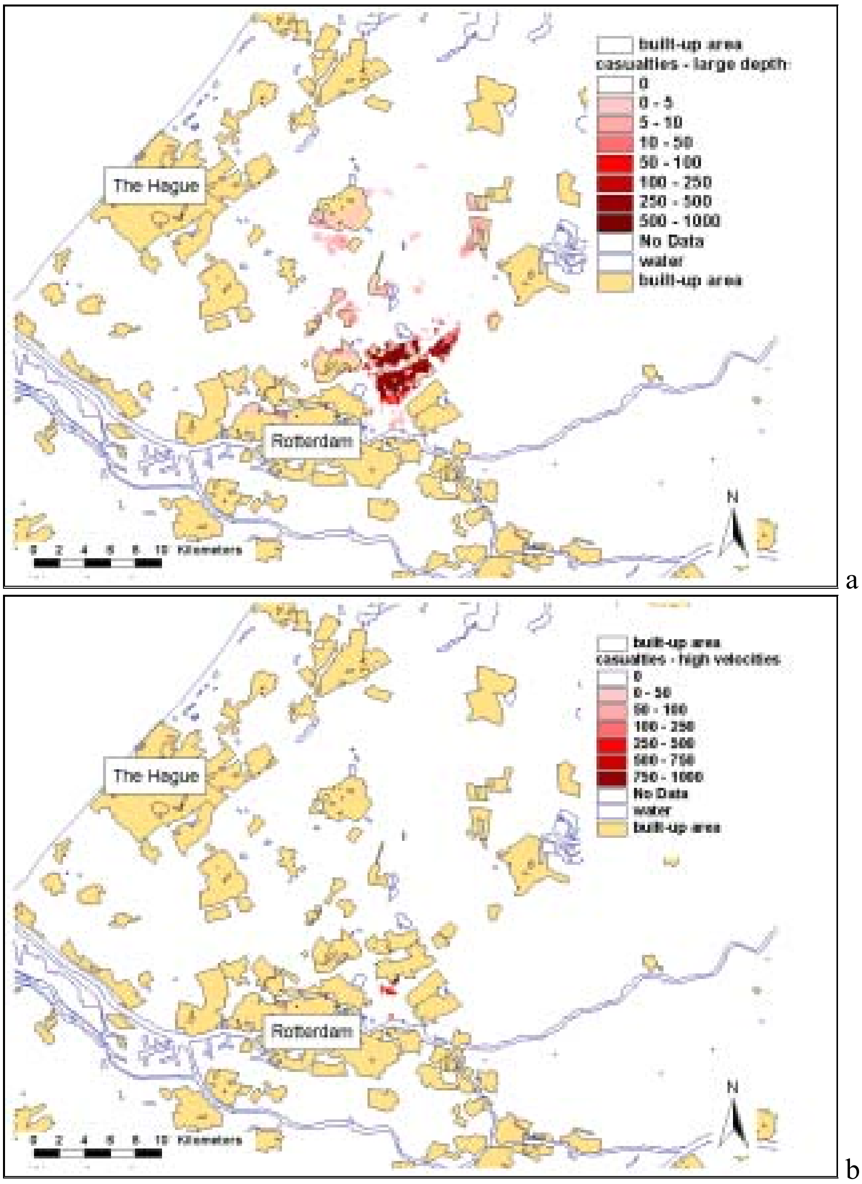


Figure 5.4 Estimated number of fatalities per grid cell of 250x250 m² when the required time for evacuation is 50 hours: (a) fatalities caused by large water depths, (b) fatalities caused by high flow velocities

Nr. of inhabitants	Estimated value
nr of inhabitants dike ring area	3.60E+06
nr of inhabitants inundated area	942334
nr of inhabitants unable to escape	485795
nr of inhabitants unable to escape, living in high-rise buildings	40354
fatalities due to high flow velocities	5035
fatalities due to large water depths, rapid rise	66453
fatalities due to large water depths, slow rise	2154
total nr of fatalities	71800
% of inhabitants killed	7.6

Table 5.1 Estimated number of fatalities using the evacuation function based on a required time of 50 hours

	required time for evacuation or escape (hours)			
	25	50	100	no evacuation
total nr of fatalities	71169	71800	72154	84608
% of inhabitants killed	7.6	7.6	7.7	9.0

Table 5.2 Estimated number of fatalities using different evacuation functions

It can be concluded that the criterion of high flow velocities in combination with large water depths, strong enough for the destruction of buildings only causes deaths near the dike breach (Figure 5.4b). The number of deaths caused by large water depths is much larger. Also the area in which people are killed due to large water depths is larger (Figure 5.4a). It is likely however that the number of fatalities caused by large water depths in areas with rapidly rising water levels is overestimated, because of extrapolation of the established relationship between water depth and percentage of people killed (section 2). No people get killed near the boundaries of the flooded area. This is because almost everybody is able to escape, but also because water depths and flow velocities are low.

The results in Table 5.2 also indicate that evacuation during the flood does not significantly reduce the number of fatalities in this case study area. This is because the area where most lives are lost is inundated within a few hours. Escape during the flood is therefore impossible. Only evacuation beforehand may help to reduce the number of fatalities in this area.

5.3 Loss of life estimation for failure of the coastal defence near Katwijk

Inhabitants
The total number of people living in the study area equals 3.6 million. Figure 5.1 shows the spatial distribution of the inhabitants within the area and the number of people living in high-rise buildings.

Flood characteristics
Similar as for the dike breach near Rotterdam, flooding simulations were carried out using the 2D hydraulic SOBEK model (see Asselman and Heynert, 2003). The most important results of this simulation are shown in Figure 5.5. Figure 5.5a shows the time of inundation in hours after failure of the dike. The area closest to Katwijk is flooded within 4 hours. It takes more than 2 days before places near the boundary of the flooded area are inundated. Large water depths of more than 3 m only occur in the “Grote Polder” north east of The Hague and some polders north east of Leiden. In the main part of the area water depths vary between a few decimetre and about 2 (Figure 5.5b). Maximum flow velocities of about 1 to more than 3 m/s occur near the location of failure of the coastal defence. In the main part of the flooded area maximum flow velocities are less than 0.5 m/s (Figure 5.5c).

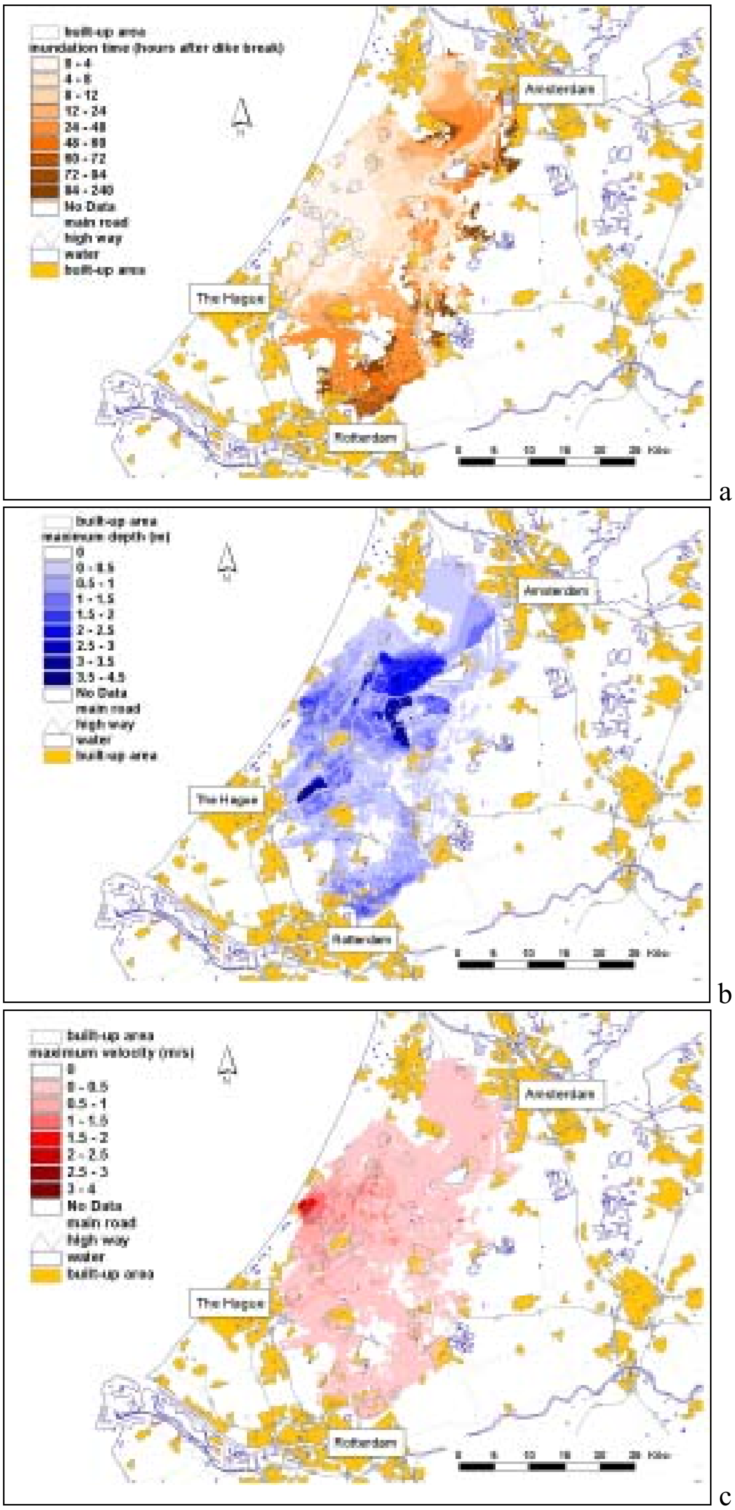


Figure 5.5 Flood characteristics computed with the 2D hydraulic model: (a) time of inundation (hours after failure of the river dike), (b) maximum water depth (m), (c) maximum flow velocity (m/s)

Possibilities for evacuation and escape

Again, an unexpectedly occurring flood is considered, without any possibilities for pre-flood evacuation. This assumption is considered more realistic for a coastal flood, since the time available for the prediction of storm surges is limited, in the order of magnitude of a few hours. Similar as for the Rotterdam-case described in section 5.2, the total time needed for non-organised evacuation was taken as 50 hours. A sensitivity analysis was carried out with different time periods needed for evacuation or escape, varying from 25 to 100 hours.

The percentage of the inhabitants that are able to evacuate or escape before the flood reaches their houses is shown in Figure 5.6. As is to be expected, the pattern in Figure 5.6 closely resembles that of the time of inundation (Figure 5.5a). Near Katwijk and Leiden hardly anybody is able to escape, whereas closer to the boundaries of the inundated area the percentage of inhabitants that is able to evacuate increases to 100%.

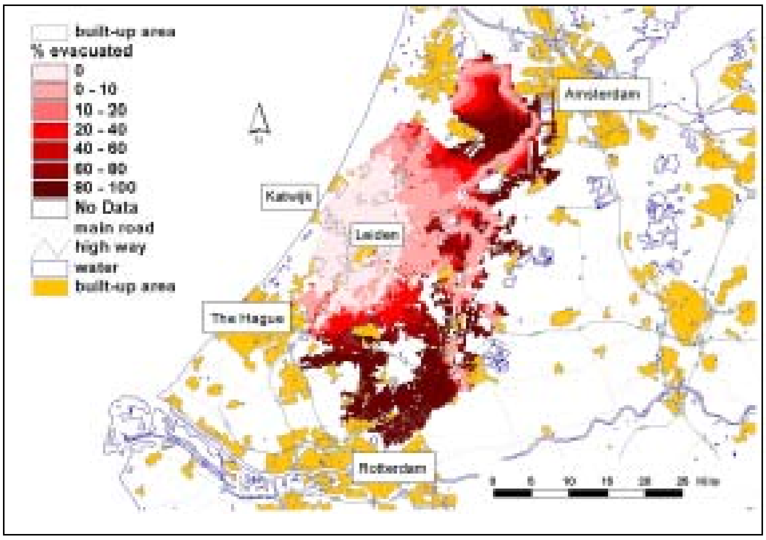


Figure 5.6 Percentage of inhabitants that can evacuate or escape when the total time required for evacuation equals 50 hours

Fatalities

The number of fatalities within the flooded area is estimated using the relationships between fatalities and:

- water depth in areas with slow rising water levels (i.e. increase in water depth less than 1 m per hour);
- water depth in areas with rapidly rising water levels (i.e. more than 1 m per hour);
- flow velocity (collapse of buildings).

It is assumed that people living in high-rise buildings are safe, regardless of the water depth that occurs.

The estimated number of fatalities caused by large water depths is shown in Figure 5.7. As flow velocities in combination with water depths are low (i.e. maximum values of about 5 m²/s), no fatalities occur due to collapse of buildings. The results are described in more detail in Table 5.3 and 5.4. In these tables, the figures for Rotterdam are given for comparison.

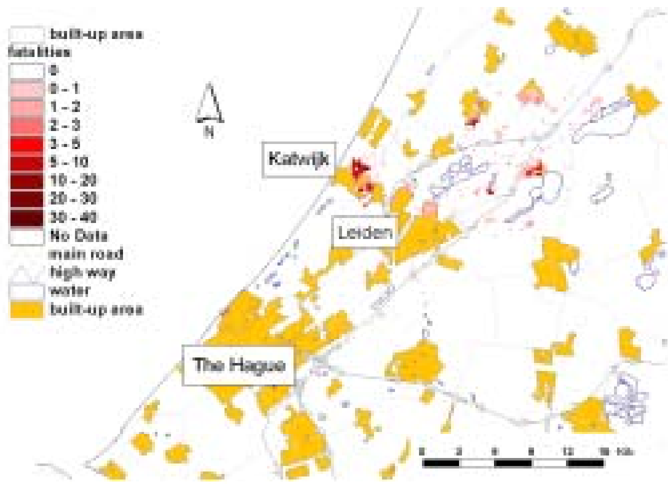


Figure 5.7 Estimated number of fatalities per grid cell of 250x250 m² when the required time for evacuation is 50 hours. All fatalities are cause by large water depths.

Nr. of inhabitants	Estimated value	
	Katwijk	Rotterdam
nr of inhabitants dike ring area	3.60E+06	3.60E+06
nr of inhabitants inundated area	833720	942334
nr of inhabitants unable to escape	511156	485795
nr of inhabitants unable to escape, living in high-rise buildings	22875	40354
fatalities due to high flow velocities	0	5035
fatalities due to large water depths, rapid rise	181	66453
fatalities due to large water depths, slow rise	386	2154
total nr of fatalities	567	71800
% of inhabitants killed	0.06	7.6

Table 5.3 Estimated number of fatalities using the evacuation function based on a required time of 50 hours

	required time for evacuation or escape (hours)			
	25	50	100	no evacuation
total nr of fatalities Katwijk	512	567	592	731
total nr of fatalities Rotterdam	71169	71800	72154	84608

Table 5.4 Estimated number of fatalities using different evacuation functions

The most striking feature from Table 5.3 is the large difference in estimated number of fatalities caused by a dike break near Rotterdam and failure of the coastal defence near Katwijk. Although the total number of inhabitants affected by the flood and the number of inhabitants that can not be evacuated in time are almost equal in both cases, the total number of deaths varies significantly. This difference is caused by differences in hydraulic conditions. In the Rotterdam most fatalities are due to the combination of high water depths and rise rates. The main reason for the limited numbers of fatalities for the coastal flood is the fact that almost nowhere rapidly rising water occurs. While the difference in water level at the river and the surface elevation of the polders near Rotterdam was about 9 m, the difference in sea water level and ground elevation near Katwijk is only about 4 m. Also flow velocities are lower in case of failure of the coastal defence near Katwijk because water level slope is much less. Furthermore, the duration of the inflow is shorter in the Katwijk-case because water levels at the North Sea decrease due to the tides and the relatively short duration of the storm (i.e. several hours) in comparison with the duration of the flood wave at the Rhine (i.e. several weeks). This results in a smaller total volume of stored water, a slower rise of the water level in the inundated areas and lower water depths. Especially in the more densely populated areas such as Leiden and many cities and villages around Leiden, water depths and rise rates are low. Consequently, the number of fatalities that are to be expected in these cities and villages is low as well.

The results in Table 5.4 indicate that evacuation during the flood reduces the number of fatalities in this case study area and that the effect of the total time needed for evacuation has a stronger impact on the number of fatalities in the Katwijk-case than in the Rotterdam-case. However, according to table 5.4 the influence of total time available for evacuation is limited, since most fatalities will occur near the breach (where no evacuation during the flood is possible). In both cases it is assumed that evacuation starts after initiation of the flood. It is expected that a pre-flood evacuation will strongly influence the number of fatalities, since in this case also inhabitants near (potential) breach location can be removed. Therefore it is recommended to analyse the effects of an evacuation hours of days before initiation of the flood in further studies.

5.4 Evacuation route

In the current model, a simple relation is assumed between the time available for evacuation and the percentage of inhabitants that is able to escape. However, in assessing loss of life also the choice of evacuation route and the duration of the evacuation process will be important factors. When the flood wave washes away a traffic jam of cars with persons trying to escape, the death toll will be very high, since persons will have no possibility to reach a safe place. The assessment of safe evacuation routes therefore is an important aspect in disaster management planning. The problem is illustrated with the following example taken from the Rotterdam-case:
According to the evacuation model, people living in Rotterdam-Hilligersberg can be evacuated as more than 90 hours are available before the flood reaches this district. However, when the area around Hilligersberg is analysed (Figure 5.8), it appears hat escape is impossible as Hilligersberg is cut off from the safer areas within a few hours after failure of the dike. This is explained in more detail in Tables 5.5 and 5.6.

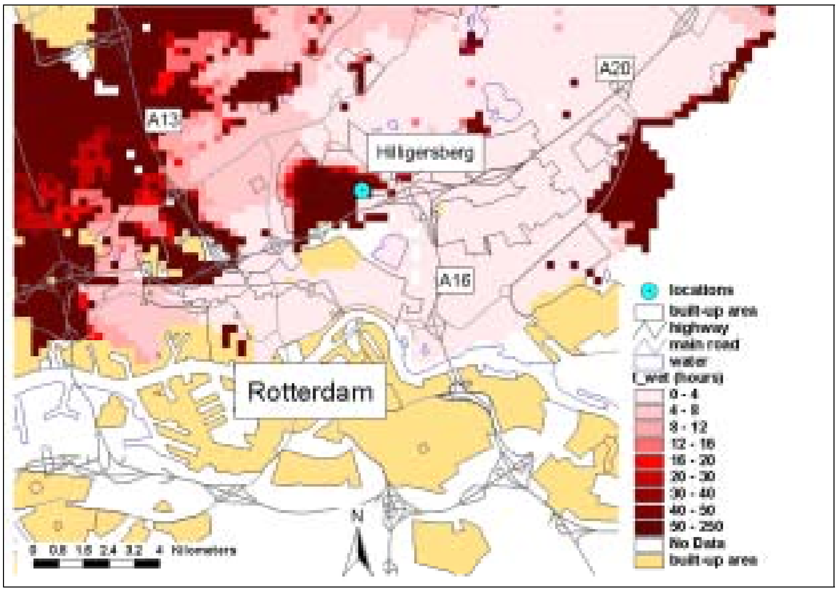


Figure 5.8 Detailed map of time of inundation near Rotterdam Hilligersberg

City	Rotterdam-Hilligersberg
available time (hours)	60
Route	A20 Gouda
distance (km)	27
driving speed (km/h)	20
driving time needed (hours)	1.5
time before departure (hours)	4
total time (hours)	5.5
risk ?	very low

Table 5.5 Determination of the risk for drowning for inhabitants of the eastern part of Rotterdam Hilligersberg based on the time of inundation

According to the modelling results, the inhabitants of Rotterdam Hilligersberg have 60 hours or more before the flood reaches their houses. If we assume that people living in this area try to take the A20, a large highway, towards Gouda, they need to travel 27 km. If we assume that the speed at the highway is limited because of traffic jams, the total time needed to reach Gouda is about 1.5 hours. Even if we assume that it takes 4 hours to warn the inhabitants in Rotterdam-Hilligersberg there would b plenty of time to reach Gouda. In other words: the model results indicate a very low risk for drowning for people living in this part of Rotterdam (Table 5.5).

However, if the time of inundation of the escape route is taken into account, a different risk estimate is obtained (Table 5.6). The nearest bottleneck at the escape route is the road that leads to the highway as well as the highway itself. The distance to the bottleneck is 1.5 km and last for about 20 km. The available time to get passed this bottleneck is only 1 hour. Even if the inhabitants of Rotterdam-Hilligersberg can be warned within a very short period after failure of the river dike, it is very unlikely that they will be able to reach Gouda in time. In other words: if they try to escape they run a very high risk for drowning.

City	Rotterdam-Hilligersberg
Bottleneck	road to highway, highway
Available time (hours)	1
distance to bottleneck (km)	1.5
total time needed (hours)	> 1
risk ?	very large !

Table 5.6 Determination of the risk for drowning for inhabitants of the eastern part of Rotterdam Hilligersberg based on the time of inundation of the escape route

From this example it can be concluded that a more detailed evacuation or traffic model is needed to determine whether inhabitants are really able to escape. Also, insight is needed into the way people react to the risk for flooding. In the case of Hilligersberg it would be better to stay indoor and find a place at the attic instead of trying to escape by car. Good instructions to the people living in areas that have a flood risk may significantly reduce the number of casualties. Timing of evacuation, but also instructions on the safest roads to take are important aspects in evacuation plans.

6 Discussion & conclusions

In this paper a framework for the estimation of loss of life caused by floods in the Netherlands is proposed. The method takes into account the effect of evacuation during the flood and various mechanisms which lead to fatalities during a flood. The method is based on data from the 1953 disaster, which flooded the South Western Part of the Netherlands, and caused 1835 fatalities. In a case study the method is applied to give a first estimate of the number fatalities caused by a dike breach near Rotterdam, leading to a flood of the Central Holland area. The applied method is a first proposal based on limited data. Hence, several aspects should be further investigated to improve the estimate of the model.

Loss of life model
The estimation of the number of fatalities is based on relations obtained from a single event, i.e. the 1953 flood. The model should be improved and updated with more recent information from international floods. However, systematic data on health effects and mortality from flood events are rare. Therefore centralized and systematic reporting of deaths and injuries from floods using standardized methodology is strongly recommended (Hajat, 2003). Special attention should be given to the function that is used for the estimation of casualties in fast rising waters. This function results in very high mortality fractions for water depths of more than 4 m, because the elapse of the function at larger depths is not based on observations from past floods, but on mere extrapolation of data. Rapidly flowing waters near the breach can lead to destruction of buildings and severe loss of life. A relatively simple criterion for this drowning mechanism was used. Implementation of more detailed relations derived from the investigation of the collapse of buildings (Roos, 2003) is recommended.

Evacuation and warning
The evacuation model needs to be improved in two ways. First, the estimated time required for evacuation should be based on a more realistic transport or traffic model taking into account the capacity of the roads and possible bottlenecks in the infrastructure that may cause serious delays. Second, the evacuation model should be able to indicate where people that try to escape are at a certain moment during the flood.

Case studies: Coastal versus river floods
It is often believed that coastal floods are more severe than river floods as the supply of water is unlimited. The inflow through dike breaches along rivers is limited by the discharge through these rivers. This is not the case along coasts. However, this study shows that river floods can be much more disastrous than coastal floods. The main causes for this remarkable outcome are the duration of the inflow period and the water level slope (i.e. difference between sea or river water level and elevation of the flooded land near the gap). In the Katwijk-case the relatively high elevation of the land behind the gap, the effect of the tide and the relatively short duration of the storm all limit the inflow. In the Rotterdam-case inflow can continue for weeks due to the longer duration of river floods when compared with storm surges and the extremely low elevation of the polders behind the breach. The extreme hydraulic conditions in the Rotterdam-case result in a very large number of fatalities. River floods at other locations along the rivers Rhine and Meuse are probably much less disastrous as the difference in elevation between river water levels and the height of the flooded land is less. Also, the duration during which inflow of water takes place will be shorter as after several days the river water levels will drop below the elevation of the floodplain. Near Rotterdam floodplains are absent so that inflow can continue for a much longer period of time.
It also has to be noted that in both cases an unexpectedly occurring flood, without an opportunity for pre-flood evacuation, is considered. This may be a more or less realistic assumption for the coastal flood, where the prediction and thus warning time are small. However, prediction of a flood and initiation of evacuation will often be possible in the case of high river discharges. The analysed river flood case, without pre-flood evacuation, can thus be considered as a “worst case” flood. Therefore it is recommended to analyse the effects of evacuation hours of days before initiation of the river flood in further studies. In the further interpretation of results also the probability of occurrence of a certain flood should be taken into account.

Conclusion
The newly developed method that accounts for possibilities for escape will produce more realistic estimates for casualties than the methods that are presently being used and that do not take evacuation and escape into account. Regardless of the improvements that can be made to this method it is believed that the developed methodology is of practical relevance. Decision makers can benefit from the evacuation model as a tool in their disaster management planning. Also, the methods developed

within the loss of life and evacuation research provide information on the effectiveness of various measures on reducing the risk of fatalities.

7 References

Abt, S.R., R.J. Wittler, and A. Taylor,
Predicting human instability in flood flows,
in: *Hydraulic Engineering – proceedings of the 1989 National Conference on Hydraulic Engineering;* Ports, M.A. (ed.); American society of civil engineers, 1989.

Asselman, N.E.M. and K.V. Heynert,
Consequences of floods: 2D hydraulic simulations for the case study area in Central Holland,
Delft: Delft Cluster paper, 2003.

Barendregt, A., J.M. van Noortwijk, M.F.A.M. van Maarseveen, S.I.A. Tutert, M.H.P. Zuidgeest and K.M. van Zuilekom,
Evacuatie bij dreigende overstromingen,
Report PR 546, Universiteit Twente and HKVlijn in water (in Dutch), 2002.

Bennet, G.,
Bristol floods 1968 – Controlled survey of effects on health of local community disaster,
British Medical Journal, 3, 454-458, 1970.

Hajat, S., K. Ebi., S. Kovats, B. Menne, S. Edwards and A. Haines,
The human health consequences of flooding in Europe and the implications for public health: a review of the evidence,
To be published in: *Journal Applied Environmental Science and Public Health*, submitted in 2003.

Jonkman S.N., P.H.A.J.M. van Gelder and J.K. Vrijling,
An overview of loss of life models for sea and river floods,
in: *Proc. Flood Defence '2002*, Wu et al. (eds). Science Press, New York Ltd., ISBN 7-03-008310-5, 2002.

Ohl, C.A., S. Tapsell,
Flooding and human health,
British Medical Journal, 321, 1167-1168, 2002.

Roos, W., P. Waarts and A. Vrouwenvelder,
Damage to buildings,
Delft: Delft Cluster paper, 2003.

Van der Meulen G.G. and Leenders, P.H.J.A.,
PoldEvac: Polder Inundation & Evacuation, a step towards the development of an integrated and cross-bordering disaster management approach.
See: http://www.compuplan.nl/english/pe-indexe.htm, 2002.

Van Deursen, W.P.A.,
Geographical Information Systems and Dynamic Models: development and application of a prototype spatial modelling language.
PhD thesis, Utrecht University, NGS 190, 1995.

Vrisou van Eck, N., M. Kok, A.C.W.M. Vrouwenvelder,
Standard method for predicting damage and casualties as a result of floods (2000).

WHO Regional office for Europe,

Floods: Climate change and adaptation strategies for human health,
report on a WHO meeting, London, UK, 30 June – 2 July 2002

Rescdam,
The use of physical models in dam-break flood analysis.
Helsinki University of Technolgy, 2002.

Waarts, P.H.,
Methode voor de bepaling van het aantal doden als gevolg van inundatie (Method for determining loss of life caused by inundation, in Dutch).
Report Delft: TNO, 1992.

General Appendix: Delft Cluster Research Programme Information

This publication is a result of the Delft Cluster research-program 1999-2002 (ICES-KIS-II), that consists of 7 research themes:
►Soil and structures, ►Risks due to flooding, ►Coast and river , ►Urban infrastructure, ►Subsurface management, ►Integrated water resources management, ►Knowledge management.

This publication is part of:

Research Theme	:	Risk of Flooding		
Baseproject name	:	Measuring, Monitoring and Exploration		
Project name	:	Monitoringsfilosofie Hermes		
Projectleader/Institute		Prof. A.C.W.M. Vrouwenvelder	TNO	
Project number	:	01.01.07		
Projectduration	:	01-04-2002	-	1-07-2003
Financial sponsor(s)	:	Delft Cluster		
		Ministry of Public Works, Road and Water Management		
Projectparticipants	:	GeoDelft		
		WL|Delft Hydraulics		
		TNO		
		Delft University of Technology		
		Twente University		
		Alterra		
		CSO		
		Delphiro		
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Number of involved PhD-students	:	2		
Number of involved PostDocs	:	0		

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Other Involved personnel

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