Loss of life estimation in flood risk assessment

Theory and applications

Proefschrift

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Quantitative risk analysis is generally used to quantify the risks associated with accidents in a technical system. The resulting risk estimates, expressing the combination of probabilities and consequences of a set of possible accidents, provide the input for risk evaluation and decision-making. One of the most important types of consequences of accidents concerns the loss of human life. In general, there is limited insight in the magnitude of loss of life caused by accidents, and no general methodology that can be used to estimate loss of life for different event types is available. In particular in the field of flood risk assessment, limited insight exists in the number of fatalities that can result from the flooding of low-lying areas protected by flood defences. In the first part of this thesis a general approach for loss of life estimation and risk quantification is proposed. The second part focuses on the estimation of loss of life caused by floods.

Part one: A general approach for loss of life estimation and risk quantification
A general method has been proposed for the estimation of loss of life. It is generally applicable to 'small probability – large consequence' accidents within the engineering domain, such as floods, earthquakes and chemical accidents. An estimate of the loss of life caused by an event can be obtained based on three elements: 1) the intensity of physical effects (e.g. toxic gasses or water) and the extent of the exposed area; 2) the number of people exposed (sometimes reduced by evacuation, shelter and rescue) and 3) the mortality amongst the people exposed. Mortality (i.e. the number of fatalities divided by the number of people exposed) is usually determined with a so-called dose response function or mortality function. This gives the relationship between the intensity of physical effects and the mortality in the exposed population.

General analytical formulations have been developed for the quantification of individual risk[1] and societal risk[2] based on reliability theory. The formulations give insight in the properties of the FN curve, the individual risk contours and their mutual relationship. These insights can be used to verify the consistency of individual and societal risk calculations obtained from numerical models. The foundation of consequence and risk quantification has been improved with the developed general approach. It enhances the possibilities to assess the risks and the effects of risk reducing measures for various fields of application.

In section four of this thesis the effects of uncertainties in loss of life estimates on the outcomes of risk quantification have been investigated. It has been shown how uncertainties affect the distribution of the number of fatalities given an accident. Two types of uncertainty influence this distribution. Firstly, uncertainty arises in the consequences of the exposure of a group of people to physical effects due to the variation in individual responses

1 Individual risk: The probability (per year) of being killed at a certain location assuming permanent presence of the population.
2 Societal risk: The probability of exceedance (per year) of an accident with a certain number of fatalities. Societal risk is often shown by means of an FN curve. It displays the probability per year of accidents with N or more fatalities.

to exposure. The resulting probability distribution of the number of fatalities is determined by dependencies between individual failures. Secondly, model uncertainty can exist in the dose response function. These uncertainties do not have an effect on the expected number of fatalities, but they affect the value of the standard deviation of the number of fatalities. Thereby the uncertainties can affect compliance to risk averse risk limits, for example the limit line for risk acceptance with a quadratic steepness in the FN curve.

Part two: Loss of life estimation and flood risk assessment
The scarcely available information regarding loss of life in historical floods has been evaluated. Analysis of global data on natural disasters shows that the impacts of floods on a global scale are enormous. Coastal and river floods that affect low-lying areas protected by flood defences can cause many fatalities. Especially in the Netherlands, where large parts of the country are below sea level or the high water levels in the rivers, floods can have disastrous consequences. Based on available event statistics it has been shown that a first order estimate of loss of life due to coastal flood events can be obtained by assuming that 1% of the exposed population will not survive the event. This rule of thumb gives a good approximation of the overall number of fatalities for some historical events, e.g. the floods in the Netherlands in 1953 and the flooding of New Orleans after hurricane Katrina in 2005.

By analysing historical flood events, the insight in the factors that influence the loss of life caused by floods of low-lying areas protected by flood defences has been improved. The number of fatalities caused by a flood event is determined by the characteristics of the flood (water, depth, velocity, rise rate), the possibilities for warning, evacuation and shelter, and the loss of shelter due to the collapse of buildings. Mortality rates are the highest near breaches and in areas with a large water depth, a high rise rate and a large number of buildings collapsed.

The existing models for loss of life estimation used in different regions and for different types of floods (e.g. for dam breaks, coastal floods, tsunamis) have been reviewed. This showed that the existing models do not take into account all of the most relevant factors (see above) and that they are often to a limited extent based on empirical data of historical flood events.

In section 7 of this thesis, a new method has been proposed for the estimation of loss of life caused by the flooding of low-lying areas protected by flood defences. An estimate of the loss of life due to a flood event can be given based on: 1) information regarding the flood characteristics; 2) an analysis of the exposed population and evacuation and 3) an estimate of the mortality amongst the exposed population. By analysing empirical information from historical floods, such as the floods in the Netherlands in 1953, mortality functions have been developed. These relate the mortality amongst the exposed population to the flood characteristics for different zones in the flooded area. Comparison of the outcomes of the proposed method with information from historical flood events shows that it gives an accurate approximation of the number of observed fatalities during these events. The outcomes of the proposed method are sensitive to the chosen flood scenario (especially to the number of breaches and the size of the flooded area) and the rise rate of the floodwater.

Consequently a preliminary analysis of the loss of life caused by the flooding of New Orleans after hurricane Katrina in the year 2005 has been presented. The hurricane caused more than 1100 fatalities in the state of Louisiana in the United States. The majority of these fatalities was elderly. A preliminary dataset that gives information on the recovery locations for 771 fatalities has been analysed. One third of the analysed fatalities occurred outside the flooded areas or in hospitals and shelters in the flooded area. These fatalities were due to the adverse public health situation that developed after the floods. Two thirds of the analysed fatalities were most likely associated with the direct physical impacts of the flood and mostly caused by drowning. Similar to historical flood events, the mortality rates were the highest in areas near severe breaches and in areas with large water depths. The total number of fatalities that is predicted for the New Orleans flood with the method proposed in section 7 of this thesis is within a factor 2 with the (preliminary) number of observed recoveries in the flooded area. Based on the available data for New Orleans, a relationship has been derived between the water depth and mortality. One difference with earlier findings is that the data for New Orleans do not show an influence of the rise rate on mortality. The available data for New Orleans do not support the claim that mortality during a contemporary flood event is lower than during historical events. The overall mortality amongst the exposed population for this event was approximately 1%, which is similar to the mortality for historical flood events. The presented results and analyses for New Orleans are preliminary: the analysed mortality dataset is incomplete and several assumptions have been made in the analysis of mortality. Despite these limitations, the reported results confirm earlier findings regarding the main determinants of loss of life and they give important insights in the relationship between mortality and flood characteristics.

The risks due to flooding of the dike ring area 'South Holland' in the Netherlands have been analysed in a case study. The method developed in section 7 of this thesis has been used to estimate the loss of life for different flood scenarios. Results indicate that a flood event in this area can expose large and densely populated areas and result in hundreds or even thousands of fatalities. Evacuation of South Holland before a coastal flood will be difficult due to the large amount of time required for evacuation and the limited time available. By combination with available information regarding the probability of occurrence of different flood scenarios, the flood risks have been quantified. The probability of death for a person in South Holland due to flooding, the so-called individual risk, is small. The probability of a flood disaster with many fatalities, the so-called societal risk, is relatively large. The societal risk of flooding for South Holland is high in comparison with the societal risks for other sectors in the Netherlands, such as the chemical sector and aviation. The societal risk of flooding appears to be unacceptable according to some of the existing risk limits that have been proposed in literature. These results indicate the necessity of a further societal discussion on the acceptable level of flood risk in the Netherlands. The decision has to be made whether the current risks are acceptable or whether additional risk reducing measures are necessary. The methods and results presented in this thesis provide the input information to make these decisions.

S.N. Jonkman, April 2007

Samenvatting

Inschatting van het aantal slachtoffers en de analyse van overstromingsrisico's – Theorie en toepassingen

Een kwantitatieve risico analyse wordt vaak gebruikt om de risico's van technische systemen te bepalen. Door middel van risico schattingen worden de kansen en gevolgen van mogelijke ongevallen gekwantificeerd. Deze informatie vormt de basis voor de evaluatie van het risico en de besluitvorming over de aanvaardbaarheid van het risico. Eén van de belangrijkste gevolgen van ongevallen betreft het verlies van mensenlevens. Over het algemeen is er weinig inzicht in het aantal slachtoffers dat door ongevallen veroorzaakt kan worden. Er is dan ook geen algemene methodologie beschikbaar om een schatting te maken van het aantal slachtoffers bij verschillende ongevalstypen. In het bijzonder voor grootschalige overstromingen van laaggelegen gebieden is er weinig inzicht in het aantal slachtoffers dat door een dergelijke ramp kan worden veroorzaakt. In het eerste deel van dit proefschrift is een algemene methode uitgewerkt waarmee het aantal slachtoffers bij ongevallen en de daarmee samenhangende risico's kunnen worden bepaald. Het tweede deel richt zich op de analyse van slachtoffers ten gevolge van grootschalige overstromingen.

Deel 1: Een algemene methode voor de inschatting van het aantal slachtoffers en de kwantificering van risico's

Allereerst is een voorstel gedaan voor een algemene methode voor de inschatting van het aantal slachtoffers ten gevolge van ongevallen. De methode is ontwikkeld voor zogenaamde 'kleine kans – groot gevolg' ongevallen in het technische domein en is toepasbaar voor bijvoorbeeld overstromingen, aardbevingen en chemische ongevallen. Een schatting van het aantal slachtoffers kan worden verkregen op basis van drie elementen: 1) de intensiteit van fysische effecten (bv. water of toxische stoffen) en de omvang van het getroffen gebied; 2) het aantal getroffen personen (dit kan mogelijk gereduceerd worden door evacuatie, opvang van mensen in het getroffen gebied en reddingsacties) en 3) De sterfte in de getroffen bevolking. De sterfte (het aantal slachtoffers gedeeld door het aantal blootgestelde personen) wordt over het algemeen bepaald met een zogenaamde dosis-respons functie, die ook wel slachtofferfunctie wordt genoemd. Een dergelijke functie geeft het verband tussen de intensiteit van fysische effecten en de sterfte onder de getroffen bevolking.

In hoofdstuk 3 zijn algemene analytische vergelijkingen ontwikkeld voor de kwantificering van het individueel risico[1] en maatschappelijk risico[2]. Deze formuleringen geven inzicht in eigenschappen van de groepsrisico- (of FN-) curve en de individuele risicocontouren en hun onderlinge relatie. Door middel van de voorgestelde methode is de basis voor gevolg en risico schattingen verbeterd. Dit biedt mogelijkheden voor een betere analyse van risico's en risico reducerende maatregelen voor verschillende toepassingsgebieden.

1 Het individueel risico geeft de kans per jaar dat een persoon die zich permanent op een bepaalde plaats bevindt, dodelijk wordt getroffen door een ongeval.

2 Het maatschappelijk risico betreft de overschrijdingskans per jaar van een ongeval met een zeker aantal slachtoffers. Het maatschappelijk risico wordt vaak uitgedrukt met een zogenaamde groepsrisico- of FN-curve. Deze toont de kans per jaar op ongevallen met N of meer slachtoffers.

In hoofdstuk 4 zijn de effecten van de onzekerheid in slachtofferschattingen op de uitkomsten van risico kwantificering onderzocht. Er is aangetoond hoe onzekerheden de kansverdeling van het aantal slachtoffers gegeven een ongeval beïnvloeden. Twee typen onzekerheid hebben invloed op deze verdeling. Ten eerste is er onzekerheid in de gevolgen van blootstelling van een groep mensen aan fysische effecten door variatie in de individuele responsen. De resulterende kansverdeling van het aantal slachtoffers wordt bepaald door afhankelijkheden tussen individuele sterfgevallen. Ten tweede kan er sprake zijn van modelonzekerheid in de dosis-respons functie. Beide typen onzekerheden hebben geen invloed op de verwachtingswaarde van het aantal slachtoffers gegeven een ongeval, maar wel op de standaard deviatie van het aantal slachtoffers. Daarom kunnen deze onzekerheden invloed hebben op het voldoen van een situatie aan risico averse risiconormen, zoals de normlijn voor risico acceptatie in FN-curve met een kwadratische steilheid.

Deel 2: Inschatting van het aantal slachtoffers en de analyse van overstromingsrisico's

In het tweede deel van dit proefschrift is de beschikbare informatie met betrekking tot slachtoffers bij overstromingen onderzocht. Analyse van wereldwijde gegevens van natuurrampen laat zien dat de gevolgen van overstromingen op wereldwijde schaal enorm zijn. Vooral grootschalige overstromingen van laaggelegen gebieden die beschermd zijn door waterkeringen veroorzaken veel slachtoffers. Met name in Nederland, waar grote delen van het land onder de zeespiegel of de hoogwaterstanden in de rivieren liggen, kunnen grootschalige overstromingen vanuit deze wateren tot catastrofale gevolgen leiden. Op basis van de beschikbare gegevens is geconcludeerd dat een eerste orde schatting van de sterfte door grootschalige overstromingen vanuit de kust te geven is door aan te nemen dat 1% van de getroffen bevolking om het leven zal komen. Deze vuistregel geeft een goede benadering van het totaal aantal slachtoffers voor enkele historische rampen, zoals de Watersnoodramp in 1953 en de overstroming van New Orleans door orkaan Katrina in het jaar 2005.

Door middel van een analyse van beschikbare gegevens van historische overstromingen is het inzicht in de factoren die het aantal slachtoffers beïnvloeden verbeterd. Het aantal slachtoffers hangt met name af van de kenmerken van de overstroming (diepte, stroomsnelheid, stijgsnelheid), de mogelijkheden voor waarschuwing en evacuatie van de bevolking, de beschikbaarheid van vluchtplaatsen en het instorten van gebouwen. Bij historische overstromingen was de sterfte met name hoog nabij bressen in de waterkering en in gebieden met een grote waterdiepte, een hoge stijgsnelheid en een groot aantal ingestorte gebouwen.

Er is een overzicht gegeven van bestaande slachtoffermodellen die in verschillende landen en voor verschillende typen overstromingen (bv. voor stuwdam breuken, overstromingen vanuit zee, tsunamis) worden gebruikt. In de bestaande modellen zijn niet alle relevante factoren meegenomen. Daarnaast zijn de bestaande modellen over het algemeen slechts in beperkte mate gebaseerd op empirische gegevens van historische overstromingen.

In hoofdstuk 7 van dit proefschrift is een nieuwe methode voorgesteld voor de inschatting van het aantal slachtoffers ten gevolge van overstromingen van laaggelegen gebieden die worden beschermd door waterkeringen. Een inschatting van het aantal slachtoffers kan worden gegeven op basis van: 1) informatie met betrekking tot de kenmerken van de overstroming; 2) een analyse van evacuatie en de omvang van de door de overstroming getroffen bevolking; 3) de bepaling van de sterfte onder de getroffen bevolking. Op basis van empirische gegevens van historische overstromingen, zoals de Watersnoodramp in 1953, zijn zogenaamde slachtofferfuncties ontwikkeld. Hiermee is de sterfte te relateren aan de kenmerken van de overstroming voor verschillende zones in het overstroomde gebied. Vergelijking van de resultaten van de methode met gegevens van historische overstromingen laat zien dat de voorgestelde methode een goede benadering geeft van het aantal geobserveerde slachtoffers bij deze overstromingen. De uitkomsten van de methode zijn gevoelig voor het gekozen overstromingsscenario (vooral het aantal bressen en de omvang van het overstroomde gebied) en de stijgsnelheid van het water.

Vervolgens is een eerste analyse van het aantal slachtoffers door de overstroming van New Orleans door de orkaan Katrina in 2005 uitgevoerd. Deze orkaan veroorzaakte meer dan 1100 doden in de staat Louisiana in de Verenigde Staten. Het merendeel van deze slachtoffers waren ouderen. Een voorlopige dataset die informatie geeft over de bergingslocaties van 771 slachtoffers is geanalyseerd. Eén derde deel van de geanalyseerde groep slachtoffers werd geborgen buiten het overstroomde gebied of in ziekenhuizen en opvangplaatsen (shelters) in het overstroomde gebied. Deze slachtoffers zijn gevallen door de verslechterende omstandigheden en het gebrek aan gezondheidszorg vlak na de overstromingen. Twee derde van de geanalyseerde groep slachtoffers is direct gerelateerd aan de effecten van de overstroming. Het merendeel van deze slachtoffers is verdronken. Net als bij historische overstromingen was het sterftepercentage in New Orleans het grootst nabij bressen en in gebieden met grote waterdieptes. Het aantal slachtoffers is achteraf voorspeld met de methode die is voorgesteld in hoofdstuk 7 van dit proefschrift. Het voorspelde aantal slachtoffers wijkt minder dan een factor twee af ten opzichte van het voorlopig aantal geborgen slachtoffers. Daarnaast is op basis van de beschikbare gegevens voor New Orleans een relatie afgeleid tussen de waterdiepte en de sterfte in het overstroomde gebied. Een verschil met de eerdere analyse is dat er voor New Orleans geen invloed van de stijgsnelheid op de sterfte is gevonden. Uit de beschikbare gegevens voor New Orleans blijkt niet dat de sterfte bij een overstroming in de huidige tijd kleiner is dan bij overstromingen in het verleden. Bij de overstroming van New Orleans kwam ongeveer 1% van de getroffen personen om het leven. Deze waarde ligt in dezelfde orde van grootte als de sterfte bij historische overstromingen. De gerapporteerde analyses van de ramp in New Orleans hebben een voorlopig karakter. De informatie met betrekking tot slachtoffers is nog incompleet en bij de analyses zijn verschillende aannames gedaan. Ondanks deze beperkingen bevestigen de resultaten de eerdere bevindingen met betrekking tot de factoren die het aantal slachtoffers beïnvloeden. Daarbij geven ze ook belangrijk inzicht in de relatie tussen overstromingskenmerken en sterfte.

Tot slot zijn de overstromingsrisico's voor dijkringgebied Zuid Holland geanalyseerd. De in hoofdstuk 7 ontwikkelde methode is gebruikt om het aantal slachtoffers voor verschillende overstromingsscenario's te bepalen. Hieruit blijkt dat een overstroming van Zuid Holland kan leiden tot honderden of zelfs duizenden slachtoffers. Een volledige evacuatie van dit gebied bij een dreigende overstroming vanuit de kust is onhaalbaar (door de lange benodigde tijd en de korte beschikbare tijd voor evacuatie). De overstromingsrisico's zijn bepaald door de gevolgschattingen te combineren met de beschikbare informatie over de kans van optreden van de verschillende overstromingsscenario's. De kans voor een persoon in Zuid Holland om door een overstroming om het leven te komen, het zogenaamde individueel risico, is klein. Echter, de kans op een overstromingsramp met veel slachtoffers, het zogenaamde groepsrisico, is relatief groot. Het groepsrisico voor overstroming van Zuid Holland is namelijk groter dan de groepsrisico's voor andere sectoren in Nederland, zoals de luchtvaart en de chemische industrie. Het groepsrisico blijkt onacceptabel volgens een bestaande norm die in de literatuur is voorgesteld. De resultaten geven aan dat een verdere maatschappelijke discussie over de aanvaardbaarheid van overstromingsrisico's in Nederland noodzakelijk is. In deze discussie moet besloten worden of de huidige risico's aanvaardbaar zijn of dat aanvullende maatregelen noodzakelijk zijn. De methoden en resultaten die zijn beschreven in dit proefschrift leveren de informatie aan om deze besluiten te nemen.

S.N. Jonkman, April 2007

1 Introduction

To indicate the general background of this thesis the historical development of risk management (section 1.1), the interpretation of risk and uncertainty (section 1.2) and the risk assessment process (section 1.3) are outlined. Section 1.4 gives a description of the objectives of this thesis.

1.1 Historical development of risk management

Human existence involves exposure to many hazards. Since the beginning of civilization natural disasters ('acts of God'), such as floods and earthquakes, have threatened humanity. With technological progress new technologies and corresponding hazards were introduced. Since the industrial revolution, technical hazards, such as industrial accidents, train derailments, tunnel fires and airplane crashes also disrupt society on a regular basis. As a background to this study a brief historical overview of mans ways of dealing with risk and safety is outlined, based on work by Bernstein (1997), Covello and Mumpower (1985) and Ale (2003, 2005).

Early history: natural disasters and belief
Our prehistoric ancestors were mainly threatened by natural hazards originating from wild fires, floods and wild animals. Long ago, people tried to protect themselves with relatively simple and mainly intuitive methods, for example by building their houses on high grounds to protect them against floods. Various forms of belief and religion played an important role in the attempts to avert harm. In the 5th century BC Chinese government officials required the yearly sacrifice of a maiden virgin to propitiate the Yellow River Gods in order to prevent flooding. The ancient Greek consulted the Pythia, the oracle of Delphi, to advise them in important and difficult decisions.

Also more rational forms of risk management can be found in the earlier history in relation to man-made hazards. The concept of liability is recognized in the building code of Hammurabi, which was issued around 1780 BC. It stated: "If a builder builds a house for a man and does not make its construction firm and the house which he has built collapses and causes the death of the owner of the house, that builder shall be put to death" (Corotis, 2003). The concept of insurance of ships and cargoes was known in Babylonian and Greek civilizations.

Development of risk management and regulation
Since ancient times, government authorities have directly intervened to reduce, mitigate or control the risks associated with natural disasters, epidemic diseases, pollution and food contamination. Early civilizations developed instruments to deal with man-made hazards, such as fires and transportation accidents. Examples are the traffic safety regulations introduced in ancient Rome, and the already mentioned building code of Hammurabi. However, the level of development of risk management techniques differed between civilizations and corresponding geographical areas. In North Western Europe man mainly adapted to natural hazards until the Middle Ages. For example, until the 13th century protection against flooding in the Netherlands was mainly example achieved by living on dwelling mounds (in Dutch: terpen) or on higher grounds. In the 13th century a more

active approach was taken in this field. The first flood defences (dikes) were constructed and the organisational structures to maintain these dikes, the so-called water boards, were introduced.

Throughout time, the introduction of new technologies and the occurrence of the accompanying disasters led to the development of protection systems and regulation in a kind of longer-term trial and error process. Ale (2003) describes two examples of such situations in the Netherlands. In 1654 an explosion of the gunpowder tower demolished a large part of the city centre of Delft, see figure 1-1. About 1500 people were killed. After this disaster, the storage of gunpowder was removed outside the city boundaries.

Figure 1-1: The explosion in Delft in 1654

In 1807 a similar explosion destroyed a part of the city centre of Leiden. The event caused 150 fatalities, including 50 children whose school was demolished by the blast. The explosion led to an imperial decree issued by emperor Napoleon, in which a distinction was made between 1) industries forbidden in the city, 2) industries allowed to be located in the city centre if proven safe enough, and 3) industries always allowed inside the city centre. Despite the introduction of these regulations in the 19th century, another explosion of a fireworks storage inside the city of Enschede caused 12 fatalities in the year 2000.

The developments in the industrial revolution in the 19th century led to new regulations. Many people moved to the city to work in the factories. They lived and worked in very unhealthy circumstances. These conditions, especially for the child labourers, eventually led to the introduction of legislation on occupational safety and the recognition of employer's responsibility. Historically, the occurrence of disasters also triggered the improvement of protection systems. For example, the flood defence system in the Netherlands has mainly been shaped by flood disasters. The 30km long closure dam in the Zuiderzee (currently IJsselmeer) was constructed after the floods in that area in 1916. The storm surge disaster of 1953 flooded large parts of the southwest of the country and caused more than 1800 fatalities. As a reaction to this disaster, the Delta works were constructed to protect this region against flooding.

The quantitative understanding of risk

The development of algebra began in ancient Egypt and Babylon around 3000 BC. It was further developed in the Indian, Greek and Islamic world. The Hindu-Arabic numbering system reached Europe seven to eight hundred years ago and laid the foundation for the development of mathematics. These mathematical methods later provided the tools for the quantitative understanding of risk. It was not until the Renaissance that scientists gained understanding of the concepts of probability and chance. Although their knowledge mainly originated from the desire to understand gambling problems, it later provided the tools for quantitative risk analyses. Preceded by investigations of mainly Italian scientists, the Frenchmen Pascal and Fermat introduced the probability theory around 1660. The late 17th and the 18th century showed a rapid development of probability theory and its applications, with contributions from, for example, Arbuthnot, Halley and Bernoulli. In the 18th century the calculation of life expectancy tables (introduced in the Netherlands by Johan de Witt) was a common practice and a flourishing marine insurance industry developed in London. Another important milestone was the work of reverend Bayes in the second half of the 18th century. He showed how to update or revise beliefs based on new information. In 1792 Laplace analysed life expectancy with and without smallpox vaccination, providing a first prototype of comparative risk analysis (Simon, 1951). However, it was not until the late 20th century that these newly developed techniques were systematically applied in safety assessment and regulation.

The 20th century

In the early 20th century the probability theory was related to physical sciences for the first time. Einstein and others discussed how the mechanical behaviour of particles, such as atoms, could be given a statistical interpretation. One example is the so-called Brownian motion of gas particles, which is described as a stochastic or random process. In that period the probability theory was developed further, for example with the probability axioms of Kolmogorov and the philosophical and mathematical underpinnings of probability theory published by the economist J.M. Keynes. Von Neumann and Morgenstern (1943) proposed the theoretical foundations for decision-making regarding situations that involve uncertainty and risk. The early 20th century was also marked by disasters associated with the failure of large engineering systems, such as the sinking of the Titanic in 1912 and the disastrous loss of the Hindenburg zeppelin in 1937.

Corotis (2003) states that the first introduction of safety through probability was made in a publication by the American National Bureau of Standards in 1945. Important theoretical developments were made in the field of structural safety in the 1940's and 1950's, for example in the papers by Freudenthal. In this field probabilistic methods have been used in design codes since the 1970's.

The principles of risk management were also applied to other areas. After the storm surge in the Netherlands in 1953 (see above), the optimal protection level that the new Delta Works should provide, was determined in an econometric analysis. The costs of investments in dike safety were weighed against the benefits associated with risk reduction (van Dantzig, 1956). This approach resulted in an optimal level of safety with a corresponding failure probability of the dikes. Probabilistic techniques were used to design the Eastern Scheldt storm surge barrier, which is a part of the Delta Works.

Bedford and Cooke (2002) describe the first applications of probabilistic risk analysis in other sectors. Basic probabilistic methods were developed in the aerospace sector in the 1960's. Risk analysis was fully applied for the first time by the United States Nuclear Regulatory Commission (NRC, 1975). In this well-known Reactor Safety Study nuclear accident probabilities and consequences were assessed. In both fields of application, aerospace and nuclear engineering, the outcomes of quantitative risk analyses were heavily criticized and often rejected by decision makers. However, (near-) accidents, such as the incident with the Three Mile Island nuclear reactor in 1979 and the accident with the Challenger space shuttle in 1986, stimulated the further development and application of risk analysis.

The chemical sector has a similar history. A first full-scale risk analysis was undertaken in the United Kingdom in the Canvey Island study (HSE, 1978). Several accidents in 1970's, such as the Seveso accident in 1976, and the accident in Bhopal in India in 1984 triggered the further development of quantitative risk assessment and risk regulation in the chemical industry. Quantitative criteria for judging the tolerability of risks were proposed in the 1970' s and they were implemented in regulation in the Netherlands and the United Kingdom. At the end of the 20th century risk management techniques became more widespread in other engineering systems, such as flood defence, energy supply and information technology.

Parallel with the technical development of the quantitative approach of risk in engineering, other disciplines, such as psychology and economy, have also explored the concept of risk. In the late 1970's social scientists started to get involved in acceptable risk debates, which were until then mainly the domain of the physical scientists and engineering community. Psychologists have explored the perception of risk and the associated factors (see also section 1.2.2). Risk management techniques are also widespread in economic applications. In 1952 Harry Markowitz performed important work for the application of risk analysis in economics. He demonstrated mathematically that the diversification of a portfolio of stocks was a better and more profitable strategy than putting all your eggs in one basket. Risk management is now widely applied to corporate finance and investment decisions and it forms an essential part of almost every larger company's policy.

Since September 11 2001 a new challenge to risk analysts has emerged in the form of terrorism. Although the prediction of (the probability) of terrorist acts is difficult, probabilistic techniques can provide useful information for protection of vulnerable parts of society (Wilson, 2005).

Some important concluding remarks

Safety can be considered a basic need for societal and economic development[1]. Situations that are insufficiently safe require repeated and exceedingly high investments in reparation and compensation of damage. Thereby such situations limit possibilities for societal and economic development. Throughout history it can be seen that scarce resources are allocated first to reduce the risks from basic threats such as famine and disease, which have a large influence on public health and life expectancy. With societal development life expectancy will increase and more attention will be given to small probability- large consequences

1 Safety is also an important need for personal development. In the hierarchy of needs of psychologist Maslow the need for safety follows after the basic physiological needs, such as air, water and food.

accidents. Although those types of accidents, such as chemical and nuclear disasters, have a marginal contribution to overall life expectancy they can cause large damages and societal disruption.

Risk management decisions in the early history were based primarily on common sense, ordinary knowledge, trial and error, or non-scientific knowledge and beliefs. The concept of risk analysis originates from the urge to understand gambling problems, but important scientific progress was made in the 18th and 19th century. In the second half of the 20th century the introduction of new techniques, such as chemical and nuclear engineering also implied a shift from natural risks to more technological ones. In these emerging fields risk analysis provided useful in attempts to provide systematic and consistent criteria for the design and management of these systems. As a result, quantitative risk assessment techniques became widely applied in different sectors in the late 20th century.

Note that in modern societies an absolute division between technological or man-made hazards ('acts of God') and natural hazards ('acts of nature') is less appropriate. Although natural disasters may be triggered by natural causes, the magnitude of natural risks will depend on human (man-made) decisions and actions. For example, the decision to live near a volcano or to build dikes along a river, will affect the magnitude of these 'natural' risks.

History also shows that the applications of risk analysis techniques, risk regulation and the development of protection systems have been driven by accidents. In the aftermath of accidents society often demands new and improved defence systems, and more strict risk regulation. Based on risk analyses, protection systems can be designed that offer sufficient protection to societal values. The application of risk management techniques could thereby contribute to a more pro-active approach than reacting after disasters only.

1.2 Risk: definition, perception and uncertainty

This section discusses the interpretation of risk and related issues. In section 1.2.1 existing meanings attributed to risk are explored and a working definition is proposed. Consequently, risk perception (1.2.2), uncertainty (1.2.3) and the treatment of uncertainty in risk analysis (1.2.4) are discussed.

1.2.1 The definition of risk

Existing definitions

Risk is often associated with the occurrence of disasters. In general the word disaster refers to an event that significantly interferes with human and societal activity. More specific medical definitions exist that define disasters in terms of the magnitude of adverse consequences resulting from the exposure and the efforts required to correct these consequences (Combs *et al.*, 1999; de Boer, 1990). In general terms, risk refers to the dangers associated with processes with uncertain outcomes (Reid, 1992), but "risk definition depends on who defines" (Kelman, 2003a). Below, some interpretations of risk in different sectors are discussed.

In economics, different main meanings are attributed to risk. Firstly, risk is generally associated with a deviation from an expected value (of return). In the second definition (based on the work of the Basel Committee) it is defined as: risk is the quantifiable likelihood of loss or less than expected return. Within the insurance sector risk is treated as expected loss, which is similar to definition used in some other sectors (see below).

The risk concept adapted by social scientists considers risk as a contextual notion and a social construct. Therefore the perceived risk (and the adopted definition) will depend on several underlying determinants of perception (see section 1.2.2). Vlek (1996) has summarized 11 formal definitions used in social sciences, see table 1-1. Examples of other, more informal risk definitions used in psychology are “the lack of perceived controllability”, “set of possible negative consequences” and “fear of loss” (Vlek, 1996).

Table 1-1: Formal definitions of risk used in social sciences (Vlek, 1996) [2]

1	Probability of undesired consequence
2	Seriousness of (maximum) possible undesired consequence
3	Multi-attribute weighted sum of components of possible undesired consequences
4	Probability x seriousness of undesired consequence (‘expected loss’)
5	Probability-weighted sum of all possible undesired consequences (‘average expected loss’)
6	Fitted function through graph of points relating probability to extent of undesired consequences
7	Semi variance of possible undesired consequences about their average
8	Variance of all possible consequences about mean expected consequence
9	Weighted sum of expected value and variance of all possible consequences
10	Weighted combination of various parameters of the probability distribution of all possible consequences
11	Weight of possible undesired consequences (‘loss’) relative to comparable possible desired consequences

The definitions applied in the research on natural hazards, often define risk in terms of hazard and vulnerability. Hazard refers to a source of danger or alternatively to something that can cause risk. The difference between the hazard and risk concepts is that most risk definitions explicitly include the probability or likelihood of an undesired event. Vulnerability relates to potential consequences in case of an event.

In the view adopted in physical sciences and engineering risk is determined by measurement and calculation. A widely used definition considers risk as the product of the probability of an event and its consequences, i.e. as expected loss. However narrowing risk to this fixed product excludes the possibility to model risk as a distribution of outcomes. Probabilities and consequences of an event are quantified and combined in a risk number or graph, which forms the basis for decision-making. Kaplan and Garrick (1981) define risk as a set of scenarios (s_i), each of which has a probability (p_i) and a consequence (x_i).

An ongoing debate between social and physical scientists, sometimes indicated as subjectivists and objectivists, focuses on the interpretation of risk. Many “subjectivists” claim that “there is no such thing as real risk or objective risk” (Slovic, 2000). Some argue that risk quantification is a subjective activity, which can lead to misleading results. However, in this thesis the quantitative approach of risk is adopted, which is used in the domain of physical sciences and engineering. It offers the possibility to quantify (estimates of) observable characteristics of the risk, e.g. the frequency of occurrence of accidents with certain conse-

2 Note that definitions 1 and 4 characterize risk for one single undesired event, while the other definitions concern a set of multiple undesired events. Of course one single event is a specific case of a set of events. Therefore definition 4 can be considered a special case of definition 5; and definition 1 as a special case of 6.

quences[3]. The approach also has the benefit that outcomes are verifiable based on rules and assumptions laid down beforehand. As such, the objective approach is believed to give the best for a rational quantification and presentation of (characteristics of) the risk. Aspects related to risk perception can be taken into account in the evaluation and decision-making regarding the risk (see further discussion in section 1.3).

Proposed definition in this study and risk measurement
It is not the objective, nor pretension of this study to establish a uniformly accepted definition of risk. Nevertheless, the following working definition is used:

"Risk is a function of the probabilities and consequences of a set of undesired events."

Within quantitative risk assessment risks are often expressed with a so-called (quantitative) **risk measure**: "an expression or graph which quantifies or depicts risk as a mathematical function of the probabilities and consequences of a set of undesired events". Synonyms include measure of risk and risk indicator. The risk measure plays an important role in communicating the risk analysis, and it constitutes the basis for evaluation of risks and decision-making (see section 1.3).

The above definitions allow the inclusion of several existing risk concepts / definitions[4], such as risk as the product of an independent probability and a consequence magnitude (i.e. expected loss). Also the so-called risk curve, which graphically shows the probability of exceedance of a certain level of consequences, fits within the definition. A well-known example of such a risk curve is the FN curve, see figure 1-2. It displays the probability of exceedance of N fatalities and is mostly shown on a double logarithmic scale. The FN curve was originally introduced for the assessment of the risks in the nuclear industry (Farmer, 1967; Kendall *et al.*, 1977) and is now used to display and limit risks in various countries and sectors.

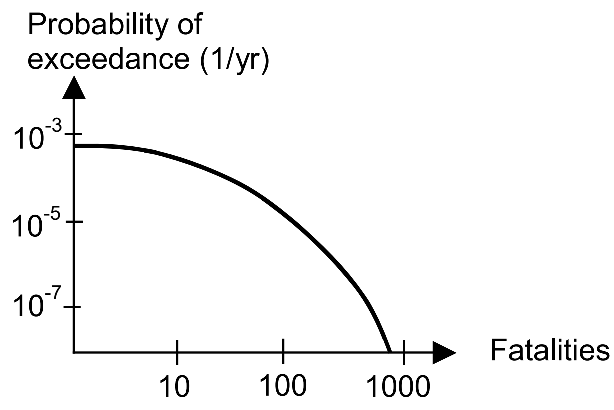

Figure 1-2: FN curve

3 This is also how insurance premiums are calculated for events that occur relatively frequently. Based on observed accident statistics, the expected losses are assessed.
4 The proposed general definition also encompasses the majority of psychological risk definitions from table 1-1 (see also Suddle and Waarts, 2003). Most of these definitions can be directly derived from the probability density function of consequences It is noted that definitions in which zero weight is assigned to probability or consequence (e.g. definition 2 in table 1-1), are not considered valid risk definitions, because they do not differ from the expression of probability or consequence.

Probability and consequences

The proposed definition of risk requires further discussion of the elements probability and consequences. In general the probability of an event can be defined as the (observer's judgment of the) likelihood of that event occurring (French, 1998). Two main interpretations of probability exist: the frequentist and Bayesian, see e.g. Bedford and Cooke (2002) for further discussion. In the frequentist (or objective) approach probability is considered an observable or countable entity to be obtained from experiments or historical events. In the Bayesian (or subjective) meaning probability is used to express a 'degree of belief' or a 'state of confidence'. In this study a Bayesian interpretation is adopted, in which the reported probability is an estimate of the actual probability of an event. This estimate can be based on both objective and subjective elements. For example, an estimated probability of failure of a certain system can be based on a limited number of observations on historical failures combined with expert judgments related to system-specific failure mechanisms, see also (Apostolakis, 1990). The benefit of the Bayesian probability interpretation is that it can also be used when the available amount of statistical data is limited, which is the case in most practical situations (e.g. in a design of a structure). In the context of quantitative risk analysis probability is generally expressed as probability of occurrence per unit time[5], generally per year.

The **consequences** of an undesired event can include the loss of human life and the loss of economical, ecological and societal values. These consequences can be considered the different dimensions of the risk, see also (Kaplan and Garrick, 1981) and section 1.4.1 for further discussion.

1.2.2 Risk perception

The concept of perception can be characterised as "a subjective, personal, representation of some concrete and agreed reality or stimulus" (Pidgeon, 1992). The basic dimensions underlying risk perception (or perceived riskiness) have been investigated by various authors (Slovic, 1987; Vlek, 1996) and are shown in table 1-2.

Table 1-2: Basic dimensions of risk perception (Vlek, 1996)

1	Potential degree of harm or fatality
2	Physical extent of damage (area affected)
3	Social extent of damage (number of people involved)
4	Time distribution of damage (immediate and/or delayed effects)
5	Probability of undesired consequence
6	Controllability (by self or trusted expert) of consequences
7	Experience with, familiarity, imaginability of consequences
8	Voluntariness of exposure (freedom of choice)
9	Clarity, importance of expected benefits
10	Social distribution of risks and benefits
11	Harmful intentionality

Dimensions 1 to 4 are related to the consequences of undesired events, and dimension 5 concerns the probability. It is argued here that dimensions 7 to 11 describe the nature of the (risky) activity, rather than the risk itself. Especially those factors clarify the interpretation of risk as a contextual notion. Several attempts have been undertaken to cluster the

5 Note that probability (P) still differs from frequency (f) as: $0 \leq P \leq 1$ and $0 \leq f \leq \infty$. For values of P and f that are much smaller than one probability and frequency can be used interchangeably.

above factors. According to Slovic (1987) risk attitudes depend on two factors, indicated as dread risk (including factors such as perceived lack of control, dread, catastrophic potential, fatal consequences and the inequitable distribution of risks and benefits) and unknown risk (characterized by unobservable, unknown, new, delayed hazards).

Risk aversion is related to the perception of risk. It concerns the aversion against accidents with multiple fatalities[6], because these cause large societal disruption[7]. In general, risk aversion refers to a situation where one accident with 100 fatalities is perceived as more dreadful (and less acceptable) than 100 accidents with one fatality. In some countries[8] the quantitative limits for acceptable risk reflect this risk aversion, as they allow these large accidents with a more than (linearly) proportional smaller probability. Apart from aversion to large numbers of fatalities, there could also be an aversion towards large consequences in general, e.g. towards large economic damage. For example the loss of 1000 Euros in one bet will be valued worse than 1000 losses of 1 Euro in 1000 separate bets. Faber and Maes (2004) give a somewhat different interpretation of risk aversion. They relate it to the follow-up consequences triggered by extreme events.

1.2.3 Uncertainty

Uncertainty concerns something that it is not known definitely, such as the outcome of a throw with a dice. In general two main types of uncertainty are distinguished: inherent and knowledge uncertainty.

Inherent or aleatory uncertainty arises through the (natural) variability or randomness in the states of a system. The (theoretical) probability of each outcome (1,2…6) when throwing a dice is 1/6 per throw, but the exact outcome of one throw is never certain. Similarly, tossing a coin can result in a head or tail and the maximum river discharge differs from year to year. In theory, this probability can be observed frequentistically if the amount of observations is infinite. **Knowledge** or epistemic uncertainty arises from a lack of knowledge. Estimated probabilities may be based on limited data, or models of not fully understood processes and thus they are uncertain. Knowledge uncertainties can be reduced or even eliminated with measurements, as certainty in a scientific meaning is achieved through observation (Bedford and Cooke, 2002). Inherent uncertainties represent the randomness of nature and they cannot be reduced.

Vrouwenvelder and Vrijling (2000) show that the above subdivision between the two main types of uncertainty applies to different sectors, although different words may be used for these types of uncertainty. Van Gelder (2000) proposes a further categorisation of uncertainties, see also (Apostolakis, 1990). Inherent uncertainties exist both in time and space. Knowledge uncertainties are subdivided into model and statistical uncertainty. The model uncertainty represents the fact that processes and phenomena may not be completely known and understood. Statistical uncertainty arises from the uncertainty whether the chosen statistical function gives an adequate description of the phenomenon. In this respect the statistical uncertainty can be subdivided in uncertainty in the distribution type

6 Other interpretations of the concept of risk aversion exist. For example, Bedford (2005) considers the type of aversion described above as disaster aversion, and refers to risk aversion as the aversion against knowledge uncertainties in the rates of different accident types.
7 Faber and Maes (2004) relate the risk aversion to the follow-up consequences triggered by extreme events.
8 For example in the Netherlands the FN limit line has a quadratic steepness.

and in the parameters of this distribution. The described uncertainties are summarized in figure 1-3. It is noted that the boundaries between the subcategories of uncertainty are not totally distinct. For example, "Inherent" natural variations in soil characteristics can be reduced with measurements. Nevertheless, the proposed classification of uncertainties is found to be a useful framework for a structured identification of uncertainties and their treatment in risk management (see also next section).

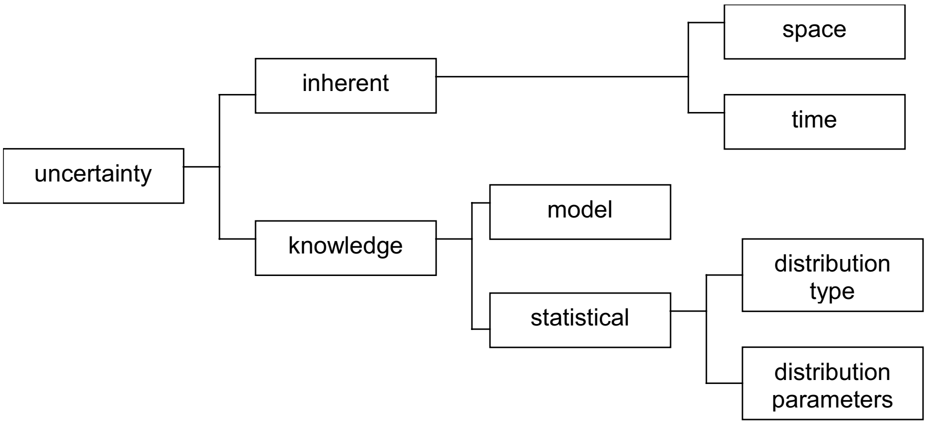

Figure 1-3: Overview of classification of uncertainties, based on van Gelder (2000)

1.2.4 Treatment of uncertainties in risk analysis

Different levels of treatment of uncertainty can be identified in the context of risk analysis, see also (Benjamin and Cornell, 1970; Ditlevsen and Madsen, 1996). Based on (Kaplan and Garrick, 1981; Paté Cornell, 1996) three approaches are distinguished:

1. Assessment of inherent uncertainties only
2. Separated assessment of inherent and knowledge uncertainties
3. Integrated assessment of inherent and knowledge uncertainties

1. Assessment of inherent uncertainties only

Inherent uncertainty is expressed by means of a probability of occurrence of a certain event or outcome. In this approach it is assumed that the value of the probability of a certain outcome is exactly known and knowledge uncertainty is neglected. A probability distribution and a corresponding single risk curve can be used to express and display the probabilities over a range of different outcomes (see the left part of figure 1-4).

2. Separated assessment of inherent and knowledge uncertainties

In this second approach the knowledge uncertainties in probability and consequence estimates are explicitly addressed. These uncertainties may be associated with limitations in the model or the number of observations. Knowledge uncertainty in an outcome is expressed by means of a conditional distribution[9]. The conditional distribution expresses the knowledge uncertainty in the estimate of the inherent uncertainty (therefore they are indicated here as being treated separately). These knowledge uncertainties can be displayed with a family of risk curves (see right part of figure 1-4), where each curve represents a confidence level. For example for the 5% curve, we estimate with 5% confidence that in reality the combined probability and damage level will be below this curve. This approach

9 The probability of a certain outcome (i.e. inherent uncertainty) is generally expressed with a frequency. Knowledge uncertainty is generally expressed by means of a probability without units. Therefore Kaplan and Garrick (1981) indicate this concept as 'probability of frequency'.

also implies that for each loss level a conditional distribution of the corresponding probability of exceedance can be depicted.

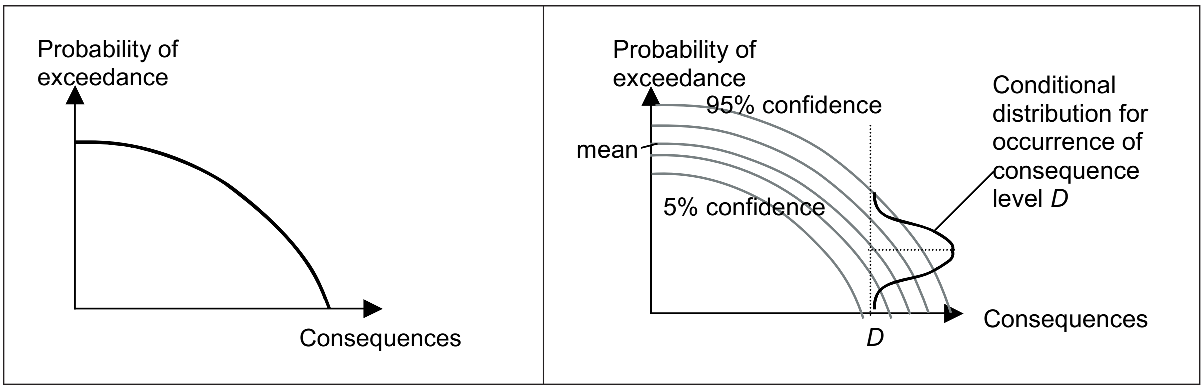

Figure 1-4: left: Single risk curve to display inherent uncertainty; right: family of risk curves to show the effects of epistemic uncertainty (based on Kaplan and Garrick, 1981; Paté Cornell, 1996)

3. Integrated assessment of inherent and knowledge uncertainties
In the third approach both types of uncertainty are integrated into one numerical estimate of the probability of an outcome by means of Bayesian probability theory, see also (van Gelder, 2000) for further background. The resulting probability represents an estimate of the actual or inherent uncertainty, with the effects of knowledge uncertainty added to it.

Discussion
It is important to realize that failure probabilities and the uncertainties are elements in decision problems. The probabilistic analysis gives insight in the factors that determine the eventual probability and risk estimate. In this context it is less desirable to fully neglect knowledge uncertainties. This is done in the first approach which only involves inherent uncertainties. The second approach (separated assessment of inherent and knowledge uncertainties) gives insight in the extent of knowledge uncertainties. Several policy studies (e.g. Chauhan and Bowles, 2003; Paté Cornell, 2002; RIVM, 2004) have shown the application of these ideas. A possible disadvantage is that the median (50%) risk curve is often considered the actual risk curve. An advantage[10] of the third approach (integrated assessment of inherent and knowledge uncertainties) is that the effects of uncertainty are explicitly included in the determination of failure probabilities and risk levels. This inclusion generally results in an increase of the probability value and thus a conservative estimate[11]. Reduction of knowledge uncertainties will lead to a reduction of probability and risk estimates. This implies that the effectiveness of reduction of knowledge uncertainty, e.g. due to field measurements or improvement of the model, can be compared with physical measures (that reduce the inherent probability). This concept is insightful for decision makers, as it gives guidance on the effectiveness of different risk reduction options.

Overall, it is recommended to include the knowledge uncertainty in the risk analysis. Depending on the available information and the level of detail of risk assessment the second (separated assessment) or third approach (integrated assessment) can be chosen (see

10 A possible disadvantage of integrating knowledge uncertainties in a reliability analysis is that their influence on the final outcome cannot be directly observed. Therefore it is suggested to carry out two analyses: one that includes knowledge uncertainties; one hypothetical situation without knowledge uncertainties, so with assumed average values. The difference between the outcomes of these two calculations shows the influence of knowledge uncertainty on the system reliability or risk.
11 van Gelder (2000; pp. 33-37) shows how knowledge uncertainties will lead to an increase of the probability value.

also Paté Cornell, 1996). It is noted that uncertainties may be treated differently in risk analyses in different sectors, which can lead to problems in the comparison of risk levels between sectors.

Apart from the influence of uncertainties, other factors can also influence estimates of the failure probability. Probability estimates could deviate from the inherent (or actual) failure probability due to inaccurate schematisations. For example, certain failure mechanisms that contribute to failure could be omitted in the analysis[12] or wrong (average) input values could be used. Due to such issues the estimated failure probability can vary over time. Seife (2003) discusses in an illustrative example how the initial estimate of the space shuttle failure probability ranged from 1 in 100 flights to 1 in 100.000 flights in the 1980's. Following the loss of the Challenger (1986) and Columbia vessels (2002) the official estimate moved to 1 in 250 flights, while the actual space shuttle failure record amounts 2 in 113 flights. Overall, failure probability estimates need to be interpreted in the context of the chosen schematisations, the available historical observations and the knowledge uncertainties (Vrijling *et al.*, 2004).

1.3 Risk assessment and management

1.3.1 Risk management and its applications

The risk assessment encompasses the identification, quantification and evaluation of risks associated with a given system. It is carried out because involved parties (designers, managers, decision makers) want to identify and evaluate the risks and decide on their acceptability. Outcomes of risk assessment can be used in the design process to decide on the required safety levels of new systems (e.g. a new tunnel) or to support decisions on the acceptability of safety levels and the need for measures in existing systems (e.g. a flood defence system). A quantitative measure of some form is needed to transfer decisions on acceptable safety into a technical domain (Voortman, 2004). Examples are choices in the design of civil structures, such as the height of a flood defence or the strength of a building. Overall, the risk assessment aims to support rational decision-making regarding risk-bearing activities (Apostolakis, 2004).

In general the following elements can be identified within risk assessment (figure 1-5) (based on (CUR, 1997; CIB, 2001; Faber and Stewart, 2003; Jongejan, 2006)):

- **System definition:** Definition and description of the system, its elements and the scope and objectives of the analysis.
- **Qualitative analysis:** Hazards, failure mechanisms and scenarios are identified and described.
- **Quantitative analysis:** The probabilities and consequences of the defined events are determined. The risk is quantified in a risk number or graph as a function of probabilities and consequences.
- **Risk evaluation:** With the results of the former analyses the risk is evaluated. In this phase the decision is made whether the risk is acceptable or not.

12 Omission of failure mechanisms could lead to an underestimation of the failure probability. This is undesirable, because it suggests that the system is safer than it actually is. The result could be an insufficient level of protection.

In addition, risk management also includes the element ‘risk reduction and control’:

- **Risk reduction and control:** Dependent on the outcome of the risk evaluation measures can be taken to reduce the risk. It should also be determined how the risks can be controlled, for example by monitoring, inspection or maintenance.

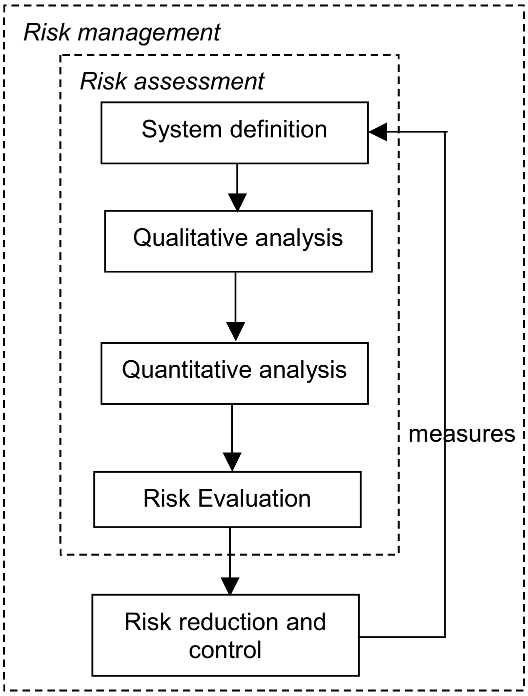

Figure 1-5: Schematic view of steps in risk assessment and risk management

Probabilistic and deterministic approach

The risk assessment is often indicated as the probabilistic approach. It is based on an inventory of probabilities and consequences for all possible accident scenarios. Next to the probabilistic approach a deterministic or scenario analysis is sometimes used for evaluation of the safety in the design phase. The deterministic approach analyses one (or a limited number of) design scenario(s) for which all conditions are uniquely given. This scenario is generally elaborated in a mostly qualitative and descriptive way and gives useful insight in (possible) event development. It mainly focuses on specific phases of the event development, such as escape or rescue actions. As the event’s causes are generally not involved in the analysis, it becomes difficult to give a complete analysis of measures.

The two approaches are complementary as the deterministic analysis focuses on one of the scenarios investigated in the probabilistic analysis. The application of one single accident scenario (i.e. a purely deterministic analysis) as a basis for a design without inclusion of probabilities and consequences does in general not contribute to an effective design. This implies that the uncertainty that is always present is neglected. In practice, the probability of a scenario is often implicitly considered in the deterministic analysis with the selection of the “representative” or design scenario. If the chosen design scenario is very severe but highly unlikely, the design becomes needlessly conservative at too high cost (and vice versa). Therefore it is assumed here that the probabilistic risk analysis (based on all scenarios) provides the best basis for rational decision-making regarding risks.

1.3.2 System definition

The first step in the risk assessment concerns the definition of the system, and the scope and objectives of the analysis. An accurate modelling of the system allows the identification of critical events and it provides insight in the range of possible measures to be taken in the system. A system is decomposed in a number of smaller components and / or subsystems. Based on (Vrijling and Stoop, 1997) a system can be defined in terms of its physical components and the related (human) organisation to make the system function.

Firstly, there are the **physical components** of a system, generally involving fixed objects such as infrastructure, buildings or flood defences. For transport systems it is possible to additionally distinguish moving artefacts, such as trains and airplanes. Another distinction can be made between components used for the regular functioning of the system and those that are included for use during calamities only. Examples of the latter type of components are the ventilation system in a tunnel or lifeboats on ships. Also, the **location** of a system and its interaction with the surroundings has to be considered.

An organisation is required for the functioning of the system. The organisation concerns different parties in the system. First, there are the **professionals** responsible for the normal operation of the system (e.g. operators of the train). They will have certain responsibilities and roles when an accident occurs in the system. A specific category of professionals concerns the **emergency services**, such as the fire brigade and medical services. They only take action if an accident occurs in the system in order to provide relief and aid. As a third category the internal users of the systems can be identified, for example the passengers in an airplane or the persons in a tunnel. Finally, certain **external parties**[13] can be exposed to the effects of the critical event, without being a direct user of a system. Generally the distinction is made between internal and external risk with regards to risk acceptability as well, e.g. for people inside and outside a tunnel. For some systems, e.g. flood defences, the distinction between internal users and external parties is less appropriate, as the exposed persons are all part of the same public. Also the influence of the circumstances in the **natural environment** (weather, day or night) during an accident have to be considered, as these can for example influence dispersion of physical effects and presence of the population.

Interactions between physical and organizational components have to be taken into account in the design and consequent risk analysis. For example, exit doors in a tunnel (physical components) will only be effective if the users of the tunnel receive a warning and know how to use the doors during the calamity (organisational factors). As every design is characterised by limited budget, the limited resources have to be distributed in an effective way over the different system elements. Preferably, the choice of the system layout and / or measures should be based on an optimisation process in which the risk reduction and costs of both physical and organizational measures are assessed. For example, this implies that the available capacities for emergency response are also a part of a risk optimisation process.

13 The terms internal and external have a basis in economics. An externality occurs when a decision causes costs or benefits to stakeholders other than the person making the decision. In the context of risk analysis, internal users make a decision to undertake a decision to undertake a risk bearing activity (e.g. as a user of a system or as personnel).

1.3.3 Qualitative analysis

In the analysis of hazards in a system one or multiple critical events will be defined. A critical event occurs if a limit state is exceeded, i.e. if the load is larger than resistance. The distinguished critical event(s) in the risk assessment depends on the purpose and scope of the analysis. Within the engineering domain generally a distinction is made between the Serviceability Limit State (SLS) and Ultimate Limit State (ULS). Exceedance of the SLS leads to temporary and/or partial failure or disfunctioning of the system. SLS mostly relates to interruption and delay of a system's processes and these can reduce the availability of the system. Consequences may concern delay and economic damages, which can be restored within reasonable time. The ULS is related to the occurrence of extreme events and the reliability of a system. If the ULS is exceeded, an object permanently ceases to function through failure and collapse. This will form a direct threat to safety and the consequences will potentially involve fatalities and economic damage. The difference between both limit states is illustrated with a simple example: the waves in a harbour could be too high for shipping during some hours or days (SLS) or the breakwater in front of the harbour could be destroyed in a storm (ULS). Risk assessments mostly consider the ULS.

Risk analysis can be applied to different phases of a project's lifetime. It can be divided in the following phases: 0) initiative; 1) design; 2) construction; 3) exploitation; 4) demolition. Different critical events will apply to different phases. Within one of these phases a critical event can occur resulting in a transition from normal operation to failure (figure 1-6). Thereby a second time axis is introduced, the accident sequence, which is elaborated in the next section.

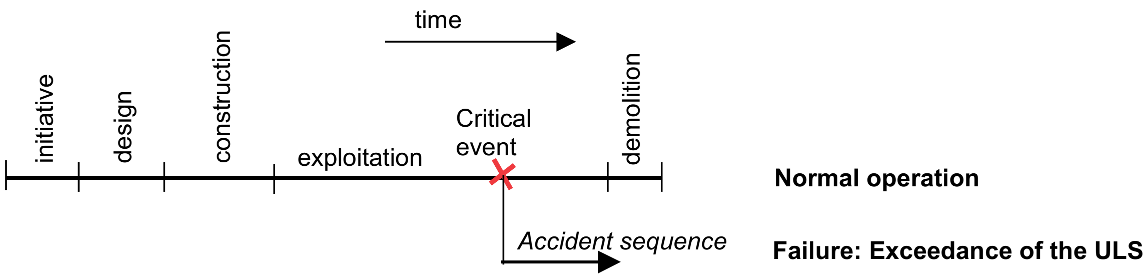

Figure 1-6: Project's lifetime and occurrence of a critical event

The next step is the identification and inventory of critical events that can occur in the system. Several techniques can be used to identify the possibilities of system failure. Examples of available techniques are the Preliminary Hazard Analysis (PHA), Failure Modes and Effect Analysis (FMEA), Failure Mode, Effect and Criticality Analysis (FMECA) and Hazard and Operability Studies (HAZOP). Also information from past incident data(bases) can be used to improve the knowledge and understanding of the (mal)functioning of the system.

1.3.4 Quantitative risk analysis

A quantitative risk analysis[14] (QRA) aims to provide a quantitative estimate of the risk level in a given system. It tries to answer the following questions (Kaplan and Garrick, 1981):

1) What can happen apart from the normal course of events?
2) How likely is it that it will happen?
3) What are the consequences if it does happen?

Figure 1-7 shows the accident sequence indicating the events leading to and following after a critical event. Certain causes can result in the occurrence of a **critical event** in an originally normally operating system[15]. This event can lead to the dispersion of **physical effects[16]** (e.g. heat and smoke from fire) within the exposed area. When people and/or objects are exposed to them, this can result in consequences. Certain consequence dimensions are quantified as a schematisation of the full range of **consequences**. By combining the probabilities and consequences of the elaborated scenarios the probability density function of consequences is obtained, as is schematically shown on the right hand side of figure 1-7. Here it is shown as a continuous probability density function (pdf), while in most cases it will be based on a number of deterministic accident scenarios, leading to multinomial pdf. The probability of zero damage is found by summation of the probability of no critical event and the probabilities of critical events without damage. The probability density function of consequences provides the basis for calculation of several risk measures, for example the expected losses or the risk curve (see also section 3).

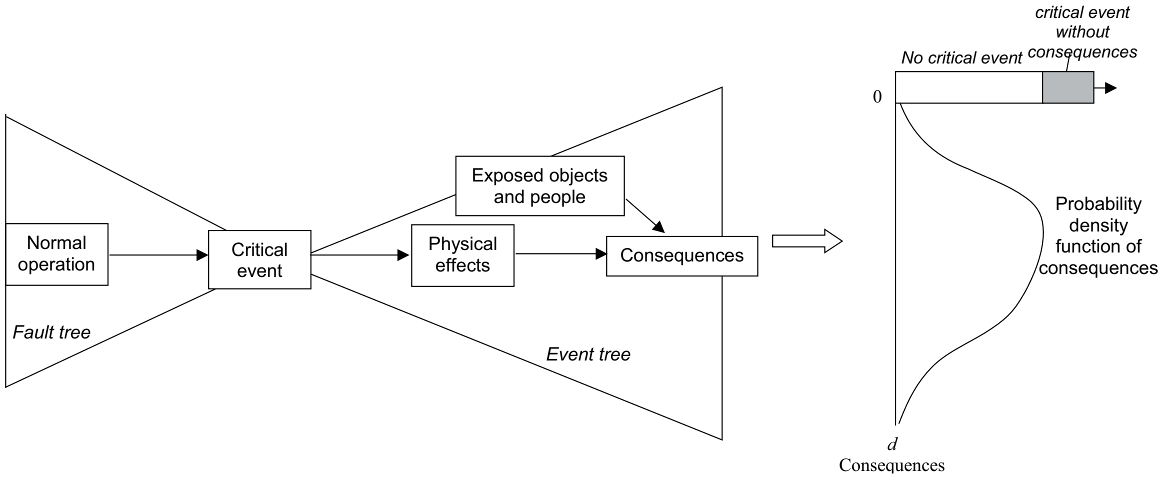

Figure 1-7: Evolvement of critical event and the accident sequence. The right part of the figure shows the probability density function of consequences that results from the risk analysis.

Techniques for risk analysis

Figure 1-7 schematically shows a connected fault and event tree. A fault tree is often used to determine the probability occurrence of a certain critical "top event", taking into account the possible causes and their sequence (i.e. it traces back in time). In an event tree all possible events following an initiating event are shown, and it is generally used to

14 Different terms are used in literature to refer to this process, such as probabilistic risk analysis (PRA) or probabilistic safety analysis (PSA).
15 A critical event can induce other critical events. These are sometimes indicated as "secondary events", "chain reactions", "domino effects", or "cascading consequences".
16 In many other works the term "effects" signifies the combination of physical effects and consequences. However, a clear separation of these two phases is proposed in order to allow a systematic analysis of consequences and measures.

assess the effects and consequences of a critical event (it goes forward in time). By connecting the fault and event tree a so-called bowtie model is obtained, with the intersection of the two trees at the critical event. Although the bowtie model gives an intuitively clear presentation, some remarks can be made with regards to this approach[17]. For some applications other presentations / modelling techniques might be more suitable, for example the application of an event tree only, or the use of cause consequence charts (CUR, 1997) and Bayesian Belief Networks (Jensen, 1996).

1.3.5 Risk evaluation and decision-making

In the risk evaluation phase it is determined what level of risk associated with a certain activity is acceptable. Or, in other words, it is attempted to answer the question "how safe is safe enough?" (Starr, 1967). The results of the quantitative risk analysis provide the input for risk evaluation and decision-making. Several political, psychological and social processes play an important role in the evaluation of the risk, making it a subjective process. Some important issues are outlined below:

- Judgement and acceptance of risks associated with certain (new) techniques or activities involves a societal trade-off between risk **costs** and **benefits**, or pros and cons. Examples are decisions with respect to genetic modification, the construction of a new polder, or the extension of an airport. It was first shown by (Starr, 1967) that the public is willing to accept larger risks from voluntary and beneficial activities than from involuntary activities. It is also important that expenditures on safety have to compete with other public interests, for instance public health and the development of new infrastructure.
- A specific concern is the **distribution** of the risks of the activity over the different parties involved. The concepts of equity and efficiency are related to the distribution of effects. Efficiency concerns the effective distribution of the risks over the population, while equity is concerned with the fact that an individual will not be disproportionally exposed to the risks.
- **Responsibilities** and **competencies** concerning the activity, for individuals, corporations or government. This will relate to the distribution of benefits of an activity, the associated risk and costs of measures over different parties. Individual considerations dominate the acceptance of the risks of drinking, smoking, or hazardous driving, although many governmental interventions are undertaken. However the decision-making on the acceptability of more large-scale public activities, such as the use of nuclear energy or the construction of flood defence systems will generally take place on a more aggregated societal level.

The process that generates the risk may be an important determinant in the acceptance of risks. In addition, risks seem to be evaluated differently when they are presented in different ways, as is shown in numerous experiments by Tversky and Kahneman. The choices with respect to the risk measurement techniques and the communication of results of risk analyses can thus have implications for the outcomes of decision-making. In this context

17 Two issues related to the bowtie model are: 1) One critical event is identified in the bowtie model. In reality many critical events can occur in a system, which are sometimes spatially distributed. For example a series of flood defences can fail through breaches at different locations. 2) All probabilities in the event tree are conditional on previous events. Elements in the event tree may be dependent on elements in fault tree. It is difficult to model these dependencies without repetition of elements.

we note that risk communication can be used to 'manage' the perception of a risk, but that it will not affect the periodically observable consequences of manifesting hazards (if no changes in the system are made).

Approaches for decision-making
Several quantitative approaches can be used to support decisions regarding the acceptability of risks associated with an activity. These are outlined below. More qualitative approaches for risk evaluation are summarized by Jongejan (2006).

A methodical framework for rational decision-making is available in the form of formal decision theory, see e.g. (Von Neumann and Morgenstern, 1943; Raiffa and Schlaifer, 1961; Benjamin and Cornell, 1970; Ditlevsen, 2002; Faber *et al.*, 2007). Decisions are treated in a utility framework. Decision alternatives can be ranked based on their expected utility. The optimal decision alternative is the one that leads to maximisation of utility (or the minimisation of disutility) (Maes and Faber, 2003). In a similar way the acceptable risk level can be determined in an (economic) optimisation, see e.g. (van Dantzig, 1956; Ditlevsen and Madsen, 1996). If the costs of measures to reduce the probability or consequences of an accident are known, an implicit or explicit optimisation can lead to a decision on the optimal level of protection and consequently to accepted level of risk. This prevents the choice of a safety level that is too high at too high cost, or too low with too much associated expected damage.

Alternatively, societal views on acceptable risk levels can be expressed in quantitative risk limits or regulatory safety goals. These indicate the acceptable probability of an event with certain consequences (e.g. by means of an FN limit line) or the acceptable level of personal risk. Such limits reflect the societal value judgement regarding an activity in a quantitative risk limit. As such, these risk limits will likely lead to a different outcome than the application of formal decision theory.

1.3.6 Risk reduction and control

Based on the outcomes of the risk evaluation phase, different decisions can be made:

- Avoid the risk by not proceeding with the system or adopting other technologies. In these cases the risks of the alternative or existing system also have to be considered;
- Reduce the risk: either by reducing the probabilities, physical effects or consequences;
- Accept the risk. One can also choose to transfer the risk through insurance or other financial mechanisms. The risk itself is not reduced but redistributed.

It is noted that certain mechanisms and regulations could be needed to assure that signals that indicate exceedingly high risk levels are transferred into actual decisions to reduce the risk. Different examples in history have shown that decision makers neglected such signals. An example concerns the recognition of deficiencies of the heat shield of the space shuttle. This problem later resulted in loss of the space shuttle Columbia in 2003, because the earlier signals regarding these problems were neglected (CAIB, 2003). Another example concerns the prediction of the possibility of extreme storm surges on the North Sea and the bad state of the flood defences by the Dutch engineer van Veen in the 1940's. In both cases the signals were neglected until the predictions became reality during a catastrophe (the loss of the space shuttle in 2003 and the floods in the Netherlands in 1953).

Risk reduction can be related to regulatory objectives. In some countries, e.g. the United Kingdom, it is required that risks are 'as low as reasonable achievable' (ALARA) if a certain risk level is exceeded. Application of the ALARA principle implies an (implicit) analysis of cost effectiveness.

A systematic analysis of risk reduction measures can be performed using the proposed system elements (section 1.3.2) and accident sequence model (figure 1-7). It should be investigated how either the probabilities of a critical event, the physical effects or consequences can be reduced by means of various measures. For every measure the costs and effects on the system risk level have to be determined. Measures have to be considered in the context of a project's life cycle. **Reversibility** and **flexibility** of decisions and measures will be important. For example, decisions on the location and route of infrastructure cannot be changed after the construction phase (except at very high cost). Certain measures are more flexible and can be included after the construction phase, for example fire extinguishers, evacuation procedures or emergency response capacity.

Risk control involves the continuous inspection and monitoring of the risks produced by a system. Information from inspection and monitoring should be used to re-evaluate risks and fed back into the risk assessment process. For corrective systems maintenance will influence the resistance of the system and thus the risk level.

1.4 Overview of this thesis

First, the background and problem definition are described (1.4.1). Consequently, the objectives and scope of the study are outlined in more detail (1.4.2). Finally, the research questions and outline of this study are presented (1.4.3).

1.4.1 Background and problem definition

Background: loss of life within risk assessment

The risk assessment process aims to support rational decision-making regarding risks. An important part of the evaluation of risk is the valuation of multidimensional consequences, such as the loss of life, economic damage, environmental damage and cultural losses. These consequences can be considered the different dimensions of the risk. Some authors suggest the combination of different consequence types into one indicator for severity by means of multi-attribute utility theory (Vlek, 1990)[18]. Unfortunately, limited insight exists in the relationship between the extent of different types of damage and the perception of the severity of an event[19].

Therefore a more simple approach is often adopted, in which risk is quantified in a one-dimensional number or graph, implying that one of the consequence categories is considered, e.g. loss of life. This outcome can be considered a schematisation[20] of the accident

18 Thereby, risk can be defined as a weighed combination of value judgements over different consequence types and the probabilities of occurrence of these consequences.

19 This relationship could be further substantiated due to psychometric research in the field of (social) psychology.

20 In analogy: a person's length is a schematic measure for the person, not a complete schematisation of the whole person that includes character and appearance.

footprint, which involves the full range of consequence types. In the context of risk assessment consequences are generally quantified in terms of economic damage and / or loss of life (Jonkman *et al.*, 2003). The advantages of using loss of life and economic damage as indicators in the risk assessment is that those types of consequences are: 1) quantifiable in an objective way (i.e. fatalities or monetary valuation) and 2) considered to be the most relevant and important losses in the public perception of disasters.

It is also expected that loss of life is related to other types of consequences, as accidents with large number of fatalities will generally cause large damage for other consequence types. Therefore loss of life can be considered a compound indicator (or proxy) for the (perceived) severity of an event. However, the above does not necessarily imply that a constant ratio exists between the number of fatalities and other consequence dimensions, e.g. where 1 fatality is on average accompanied by 10 injuries (see section 2.5 for a more detailed discussion). Moreover, the relative magnitude of various types of consequences could also differ between event types, as these will result in different accident footprints with regards to consequences. For example, for chemical accidents the loss of life and environmental pollution will rank amongst the most important consequence dimensions. For floods, economic damage and loss of life will be the most important consequence dimensions.

Overall, an accurate estimation of loss of life is important in order to be able to determine the risk level in a system and the effects of risk reducing measures. To allow a complete evaluation of the risk, it is advocated to present all relevant consequence types in their (qualitative or quantitative) dimensions to the decision makers (Walker *et al.*, 1994). Techniques such as multi-criteria analysis can be used to weigh the relative importance of the various types of consequences and to evaluate the effects various decision alternatives.

Problem definition

In general there is limited insight in the consequences of accidents. Especially loss of life estimates are uncertain (see below), while loss of life is a very important factor in risk evaluation and decision-making. Within risk assessment the methods for estimation of probabilities, such as the fault tree and event tree, are relatively well established and used in different fields. General methodologies for consequence and loss of life estimation have been standardized to a much lesser extent. There is some literature dealing with the quantification of loss of life consequences from technical failure for individual event types (see section 2 for an overview). However, parallels existing between different cases have mostly been neglected, and relatively little attention has been paid to the general principles of loss of life estimation. When trying to predict the number of lives lost due to accidents in the engineering domain and the associated risks it would be helpful to rely on some kind of general methodology.

When trying to estimate loss of life due to accidents it is attempted to predict the outcomes of disastrous situations that we try to avoid as much as possible. Due to ethical concerns, such accidents never occur in conditioned circumstances. This implies that the availability of empirical data for lethal accidents is limited. As a result, many of the existing loss of life models are validated to a limited extent, leading to fundamental problems with calibration and validation. In contrast to other engineering fields (where basic physical laws can be used to develop models), there is limited insight in the basic processes that influence loss of life. Human behaviour during disasters has an important influence on loss of life and this will remain uncertain to some extent. As an implication of the above, existing loss of life models often do not include all relevant factors that influence loss of life, such as the possibilities for evacuation. Therefore it is often difficult to give a good estimate of the loss of life and a complete analysis of the effectiveness of various risk reducing measures.

The general principles of life estimation methods and their application to risk quantification require further attention. Given the variety of factors involved and complexity of underlying processes, existing QRA models in different sectors mainly rely on numerical risk calculations. These approaches do not show how loss of life estimates are included in risk quantification. In addition, these is a lot of discussion in literature about how risk estimates can be properly presented and used for rational risk evaluation and decision-making (see e.g. Benjamin and Cornell, 1970; Vrijling *et al.* 1998; Evans and Verlander, 1997; Rackwitz, 2002; Pandey and Nathwani, 2004; Bedford, 2005).

Some of the general problems discussed above are particularly apparent in the assessment of flood risks in the Netherlands and for other low-lying areas protected by flood defences. Limited insight exists in the loss of life caused by potential floods and no uniformly established model for loss of life estimation is available. The existing methods in this field do not take into account the effects of all relevant factors, such as flood characteristics and possibilities for evacuation (see section 6). This is expected to cause inaccuracy in consequence and risk estimates. Methods for quantification of flood risk have been developed in the Netherlands in the last decades, see e.g. (van Manen and Brinkhuis, 2005; Rijkswaterstaat, 2005). However, these have not yet been established for standardized use and application in regulation. There is a discussion ongoing about the acceptable level of flood risk in the Netherlands (MinVenW, 2006; Adviescommissie Water, 2006). An important issue in this discussion is whether and how the risk of loss of life can be taken into account in risk evaluation and decision-making regarding flood risk in the Netherlands. One question is whether specific risk limits for the risks to people should be adopted.

1.4.2 Objectives and scope

Objectives

This thesis concerns the estimation of loss of human life within the context of (quantitative) risk assessment, with a focus on applications to the field of flood protection. Based on the above problem definition, the general objectives of this study are defined as follows:

1. To develop a general method for the estimation of loss of life in the context of quantitative risk analysis.
2. To investigate the possibilities for the improvement of methods for loss of life estimation and risk quantification for floods of low-lying areas protected by flood defences, with specific applications to the Netherlands.

Following these two general objectives the thesis is divided into two parts. The first part deals with general methods and the second with applications to floods.

Scope of the first part: general methods for loss of life estimation and risk quantification

Following up on the objectives, the event types considered in the first general part are defined further. This study focuses on:

1. Unintentional hazards, implying that intentional events, e.g. terrorism, vandalism and riots, are excluded.
2. Applications to systems within the engineering domain, where issues with respect to safety are often (partly) related to engineering design and technical measures. This implies that e.g. epidemics, famine and diseases are excluded, as these risks are not directly related to engineering design.
3. Events in which most fatalities occur directly due to exposure to the effects of a single accident. This implies that events with chronic exposure (e.g. to air pollution) and delayed mortality (e.g. due to nuclear radiation) are not explicitly considered. A further discussion on the categorisation of event types based on exposure and mortality after exposure is provided in appendix 1.I.
4. Events with large consequences due to a single event, i.e. accidents with multiple fatalities and large economic damage[21]. Sectors where multiple single fatality events occur with relatively high probability, e.g. traffic accidents, are not included.

Examples of considered events which comply with all four of the above criteria are: floods, tunnel fires, accidents with transport and storage of chemical substances, airplane crashes, and earthquakes. These often correspond to the category of societal risks or so-called "small probability – large consequences" in the engineering domain as is also shown in figure 1-8. It ranks different activities based on the probability of an accident, and their consequences.

Probability	**High**	Traffic accident Falling Smoking	Famine Epidemic
	Small	Bee sting Lightning	Flood Airplane crash Chemical accident Nuclear accident
		Small	**Large**
		Consequences	

Figure 1-8: Different activities and accidents ranked by accident probability and consequences per accident (based on (Ale, 2000))

The result of the first part of this thesis will be a general method for loss of life and risk quantification. It explicitly exhibits what kind of information is needed to estimate the loss of life for these types of accidents. The approach can thus be applied to various (and also new) terrains. The proposed general method can be used to estimate the loss of life and risk levels in a consistent way and thereby the foundation of consequence and risk quantification will be improved. Based on the proposed methods the effectiveness of different risk reduction strategies, e.g. evacuation or structural measures, can be assessed in a systematic way. The results can be used as input for the risk evaluation and decision-making. The elaborations in this thesis mainly focus on the quantification of risk levels. Some aspects related to the evaluation of risk (e.g. risk limits) are briefly discussed. However, given the

21 Indicative boundaries that indicate large consequences can be given. These concern events for which the number of fatalities N>10 fatalities; economic damage D>10million Euro;

complexity of the evaluation and decision-making regarding risks, this study does not aim at a complete analysis of the risk evaluation and decision-making process.

Scope of the second part: applications to floods
The second part of this thesis focuses more specifically on loss of life estimation for floods and it illustrates the applications of the general methods developed in the first part. There is a specific focus on (potential) loss of life caused by floods in the Netherlands, but the investigation will be presented from a more general and international perspective. The method developed in the second part of this thesis will be specifically applicable to assess the consequences and risks of flooding of low-lying areas protected by flood defences (see section 7.1.1 for a further discussion). These areas can be found in different areas around in the world, especially in river deltas. Breaching of flood defences in these areas can lead to flooding of extensive areas with severe consequences. A recent example of such a disastrous event was the flooding of New Orleans after hurricane Katrina in 2005. The method developed in this thesis could improve the possibilities to estimate the loss of life caused by floods and the associated flood risks. These insights will contribute to the ongoing discussion regarding the acceptability of flood risks in the Netherlands.

1.4.3 Research questions and outline

Based on the general objectives and the defined scope specific research questions are formulated.

Research questions related to the first objective (general methods for loss of life estimation):

- What are the main factors that determine the loss of life? Which elements should be included in a general approach for loss of life estimation for 'small probability – large consequence' events within the engineering domain? (section 2)
- How can the general approach for loss of life estimation be applied to risk quantification? (section 3)
- How will uncertainties in loss of life estimates affect the outcomes of risk quantification? (section 4)

Related to the second objective (applications to floods):

- Which information is available regarding loss of life caused by floods? Which factors should be taken into account in a model for loss of life estimation for floods? (section 5)
- Which models are available for the estimation of loss of life caused by floods? Are they applicable to estimate the loss of life caused by flooding of low-lying areas protected by flood defences? (section 6)
- Is it, based on empirical data, possible to develop an improved method for the estimation of loss of life caused by floods? (section 7)
- Which factors determined the loss of life caused by the flooding of New Orleans after hurricane Katrina? What was the relationship between flood characteristics and mortality? (section 8)
- How can the proposed method for loss of life estimation be applied to the quantification and evaluation of the flood risk in the Netherlands? (section 9)

The outline of this study follows the research questions, see also figure 1-9. Each section addresses one of the research questions indicated above. This thesis is divided into two parts. The first part presents the general methodology for loss of life estimation and risk quantification. An approach for the estimation of loss of life for single accidents is developed in section 2. In section 3 it is described how this approach can be further applied to the quantification of the risks to people (the individual and societal risk). Section 4 investigates the effects of uncertainties in loss of life estimates on the outcomes of risk quantification.

The second part deals with the application of the general approach to flood hazards. Sections 5 and 6 review the available information and existing models related to the loss of life caused by floods. In section 7 a new method is proposed for the estimation of loss of life caused by the flooding of low-lying areas protected by flood defences. During the course of this study hurricane Katrina caused catastrophic flooding in the city of New Orleans in the year 2005. A preliminary analysis of loss of life caused by this flood is included in section 8. Applications of the developed method for loss of life estimation to flood risk assessment in the Netherlands are presented for a case study area (South Holland) in section 9. Section 10 contains conclusions and recommendations.

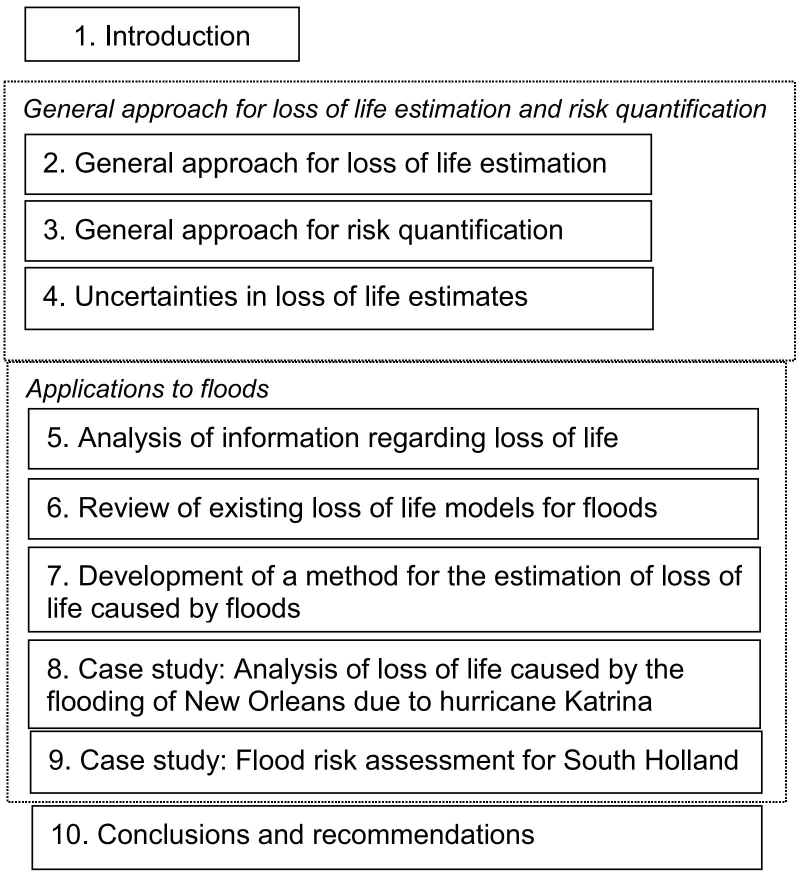

Figure 1-9: Schematic outline of this study

Part one:
A general approach for loss of life estimation and risk quantification

2 A general approach for loss of life estimation

Research question: What are the main factors that determine the loss of life? Which elements should be included in a general approach for loss of life estimation for 'small probability – large consequence' events within the engineering domain?

Keywords: loss of life, mortality, dose response function, evacuation, damage, consequence modelling

In this section a general approach is proposed for the estimation of loss of life for small probability – large consequences events within the engineering domain (section 2.1). In order to estimate loss of life it is often necessary to analyse the number of people exposed and the effects of evacuation, shelter and rescue (section 2.2). Methods for the estimation of the number of fatalities amongst the exposed population (so-called dose response functions) are described in section 2.3. The combination of evacuation and mortality analysis is discussed in section 2.4. The relationship between loss of life and other consequence categories (such as injuries) is explored in section 2.5. Section 2.6 summarizes the methods for the economic valuation of loss of life. Concluding remarks are given in section 2.7.

2.1 A general approach for loss of life estimation

2.1.1 Introduction and terminology

This section investigates the estimation of loss of human life within the context of quantitative risk analysis (QRA). Within the earlier proposed accident sequence (see also figure 1-6) the occurrence of a **critical event** leads to the release of physical effects at a risk source. The **physical effects** (e.g. smoke for fire or floodwater) can be dispersed over a certain area. When people are exposed to the effects in this area certain **consequences**, including loss of life, can occur.

The **exposed area** includes all locations exposed to the physical effects that are associated with the critical event. It represents the spatial footprint of the event, and for some types of events (e.g. airplane crashes) it is referred to as the **crash area**. It is noted that safe locations may exist that are surrounded by exposed area, for example high grounds in a flooded area (see also figure 2-2). For some events the extent of the exposed area will be similar for different critical events. An example is the flooding of a (small) polder[1] with a uniform terrain height. The polder will be completely filled due to breaches at different locations. For other events the extent of the exposed area could depend on: 1) the spatial variation in accident locations and 2) the dependency of effects on meteorological conditions (e.g. dispersion of toxic gasses due to wind). In this context the concept of **threatened area** is introduced. It includes all locations that are potentially exposed to a certain level of physical effects or harm. This implies that the notion of probability is included in the determination of the threatened area. Approaches for indication of the threatened area, for example by individual risk contours, are further discussed in section 3. Figure 2-1 illustrates the difference

1 Polder: relatively low-lying area protected from flooding by flood defences such as dikes. Drainage systems are needed to discharge rainwater from the polder and to prevent rise of the groundwater table.

between the threatened and exposed area for a hazardous installation and a flood prone area.

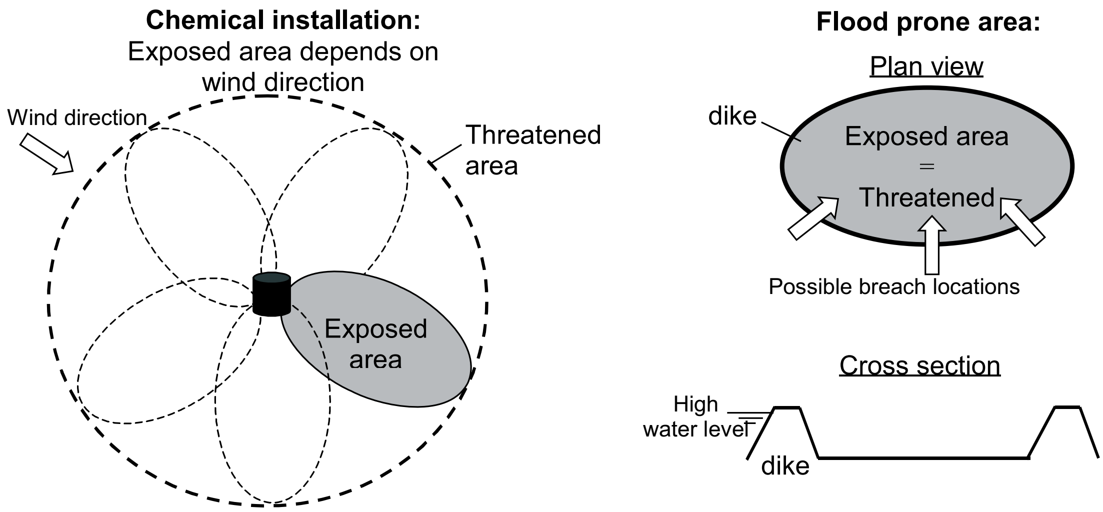

Figure 2-1: Schematic difference between exposed and threatened area

It is noted that certain indirect consequences could also occur outside the directly exposed area. For example, due to a flood, areas outside the flooded area could sustain damage due to the loss of electricity and the loss of business to customers inside the flooded area. This implies that the consequence analysis might have to be expanded outside the exposed area. However, for most disasters the majority of consequences occurs within the exposed area.

All the individuals that are present in the exposed area before any signs or warnings can be perceived are referred to as the **population affected, population at risk** or **people at risk:** N_{PAR}. For larger exposed areas it can often be approximated by the registered population in the area (N_{POP}), so that $N_{PAR} \approx N_{POP}$. However, in some cases it might be necessary to take into account population dynamics. The number of people at risk might be smaller than the original population. For example, when a part of the reference population will be working elsewhere most of the time. In other cases N_{PAR} might be larger than N_{POP}, for example when many people visit the exposed area. For other fields N_{PAR} can equal the (maximum) number of people expected to be present in a certain type of facility (people in cars during a traffic jam in a tunnel; all employees affiliated to an office etc.). More specific approaches for determining N_{PAR} are discussed in (Lentz, 2003; Lentz and Rackwitz, 2004a).

The actually **exposed population** involves all people exposed[2] to the physical effects of the disaster. The number of people exposed can be deduced from the population affected by taking into account the effects of evacuation, shelter, rescue and escape. A first description of these elements is given below, further explanation is provided in section 2.2.

Evacuation is defined in this study as: "the movement of people from a (potentially) exposed area to a safe location outside that area before they come into contact with physical effects". Within the area people may find protection within **shelters.** These are constructed facilities in the exposed area, which offer protection. Examples of shelters are high-rise buildings during floods, or emergency niches in a tunnel that are safe during a fire. In ad-

2 Exposure does not necessarily have to imply immediate and direct contact with the physical effects. For example during floods and earthquakes people inside buildings can be indirectly exposed to the physical effects.

dition (natural) **safe areas** may exist that offer protection, e.g. high grounds in a flooded area. A sketch of a flood prone area is given in figure 2-2 to illustrate the terminology.

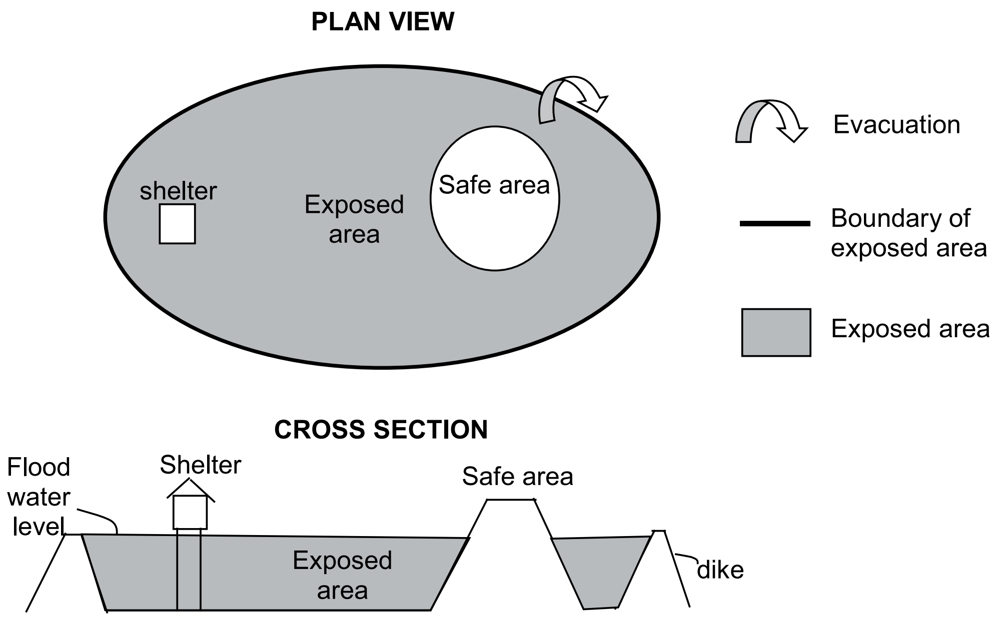

Figure 2-2: Sketch of the exposed area for a flooded area

After initial exposure of people to the event, the population exposed could be reduced due to escape and rescue. **Escape** refers to the movement of people by themselves through the exposed area, for example people running through a toxic cloud or moving through a flooded area. **Rescue** concerns the removal of people by others from an exposed area. Rescue and escape only prevent loss of life if people are rescued or escape before they will lose their life due to exposure.

Finally, the exposure of people to the physical effects of a disaster can result in **loss of life**. To provide an estimate, a mortality fraction is usually determined. **Mortality** is defined throughout this thesis[3],[4] as the fraction of fatalities amongst the exposed population[5]. It can be determined for one event ('event mortality') or on a more detailed level for different groups of the population ('subpopulations'), or locations affected by the event. In literature the following synonyms are used:

- Loss of life: fatalities, (number of) killed, (number of) deaths;
- Mortality: lethality, death rate, fatality rate, proportion of lives lost.

2.1.2 Existing approaches for loss of life estimation

A selection of loss of life models used in various sectors has been studied in order to derive general principles for loss of life estimation. An overview is given in table 2-1. All these models have been developed in the context of risk assessment. Special reference is made to the work by Friedman (1975) and Petak and Atkisson (1982) (both quoted in McClelland

3 Other studies might define mortality as a fraction of the population affected. The disadvantage of such a definition is that it does not take into account the actual number of exposed persons and effects of evacuation. In other contexts mortality is defined alternatively, for example as the number of killed per capita per year.

4 A slightly different definition has been used in section 4. There, mortality is also used to indicate the individual probability of death due to exposure.

5 Or alternatively: the proportion of the exposed population that does not survive.

and Bowles, 2002) as these discuss the general principles of loss of life modelling for different sectors on a conceptual level.

Table 2-1: Overview of models for estimation of loss of life for different fields of application

Field / disaster type	Model description and applications	Reference(s)
Various natural disasters	Broad (conceptual) models that could be applied to different hazards	Friedman (1975), Petak and Atkisson (1982)
Floods	Overview of methods for loss of life estimation for river, coastal and dam break floods	Jonkman *et al.* (2002), McClelland and Bowles (2002), section 6 of this thesis
Earthquakes	Earthquake Protection	Coburn and Spence (1992), Takahashi and Kubota (2003)
Volcanic eruption	Estimation of physical impacts and fatalities	Spence *et al*. (2005)
Tunnel accidents	Assessment of consequences for fires and explosion in road tunnels	Persson (2003)
Airport Safety	Method for determination of fatalities on the ground due to airplane crashes near Schiphol airport (NL)	Piers *et al.* (1992);
Chemical accidents	Dutch guidelines for estimation of consequences for chemical accidents	de Weger *et al.* (1991); CPR (1990); PGS (2003) (AIChE, 2000)

For some types of event, event mortality will be predictable without further extensive modelling: for example for airplane crashes the mortality amongst people present in the exposed or crash area appears to be relatively constant (Piers *et al.*, 1992). For other types of event, mortality shows a larger variation between different single events, due to their dependence on various event-specific variables. As an illustration, the number of fatalities is plotted against the number of people exposed for tunnel fires in figure 2-3. Combinations with constant mortality are plotted with dashed lines in this figure.

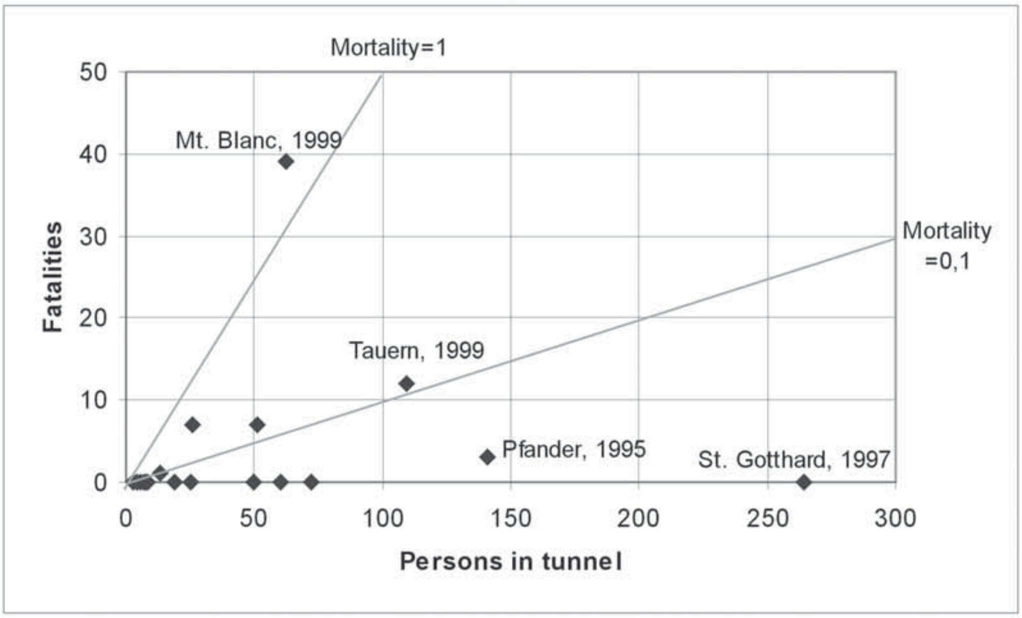

Figure 2-3: Fatalities and estimated number of people exposed [6] in tunnel fires ((Amundsen, 2001, analysis by O. Kübler) For some characteristic events tunnel name and year are indicated.

6 In this approach the number of people in the tunnel is assumed to be proportional to the tunnel length and traffic intensity.

Similar figures are available in literature for floods (Jonkman, 2005; see also section 5) and earthquakes (Coburn and Spence, 1992). These analyses indicate large variations in mortality between events within one domain. For these types of event, case-specific mortality can obviously only be predicted with sufficient accuracy when the event modelling itself moves into a sufficient level of detail and tries to include the relevant event-specific variables. Depending on these issues, loss of life modelling can be performed at different levels of detail:

1. **Individual level.** By accounting for individual circumstances and behaviour it is attempted to estimate the individual probability of death. For example, Assaf and Hartford (2002) propose a model for the assessment of the consequences of dam failure, which simulates individual escape behaviour.
2. **Group or zone level.** Groups of people, locations or zones with comparable circumstances are distinguished and mortality is estimated for these groups / zones. For example, Takahashi and Kubota (2003) estimate earthquake mortality for groups of people in different states (in home, car or in open air). Jonkman (2005) distinguishes different zones within a flooded area, applying a specific mortality function for each location (see also section 7 of this thesis).
3. **Overall event level.** One mortality fraction is applied to the exposed population as a whole. For the assessment of third party fatalities due to airplane crashes Piers *et al.* (1992) use one constant mortality fraction within the area affected by the crash.

It is important to note that for a proper calibration and validation of a loss of life model, the amount of available data has to be sufficient relative to the number of parameters included in the model. The eventually chosen level of detail of analysis depends on the available data for calibration of the model and the required ability to take into account the effects of risk reducing measures. In this respect so-called mechanistic[7] or causal models are mentioned (see e.g. Piers *et al.*, 1992). These models generally analyse accident processes at a detailed (often individual) level and take into account causes of death. In practice, accident processes are often complex and involve many factors, whilst the availability of accident data is limited. Therefore a mechanistic approach is generally not feasible on a fully empirical basis.

2.1.3 Proposal for a general approach for loss of life estimation

When trying to predict the number of lives lost due to accidents in the engineering domain, it is helpful to rely on a general methodology. Such an approach is useful to estimate loss of life and to measure the effect of a risk reduction strategy in a systematic and consistent way. It is explicitly shown what kind of information is necessary to estimate the loss of life for an activity. Therefore a general approach is proposed for the estimation of loss of life due to 'small probability – large consequence' accidents in the engineering domain, such as floods, tunnel fires and chemical accidents (see also section 1.4.2 regarding the scope of this thesis). The proposed approach is mainly applicable to accidents that are characterised by dispersion of harmful physical effects and some possibilities for evacuation or escape.

7 Covello and Merkhoffer (1993) use a more narrow definition for mechanistic models as being dose response functions that are developed based on theoretical assumptions concerning biological processes.

It has been observed that the existing approaches of life estimation in different fields include three general elements[8], which correspond to general elements in the QRA (see also section 3):

1. The assessment of **physical effects** associated with the critical event, including the dispersion of the effects and the extent of the exposed area;
2. Determination of the **number of people exposed** in the exposed area, taking into account the initial population at risk and the possibilities for evacuation, shelter, escape and rescue;
3. Estimation of the **mortality** and **loss of life** amongst the exposed population[9], taking into account the extent of physical effects and the number of people exposed.

By combining these three main elements loss of life can be estimated as is shown in the general framework in figure 2-4. A critical event with physical effects (*c*) is assumed to occur. *c* Is a general vector signifying the event's intensity of physical effects, and it represents dimensions, such as arrival time of effects, concentration, spatial extent, etc.. The number of people at risk depends on the extent of the exposed area, which is a function of the physical effects, leading to $N_{PAR}= N_{PAR}(c)$. The exposed population (N_{EXP}) is found by correcting the population at risk for the population fractions that are able to evacuate ($F_E(c)$) or shelter ($F_S(c)$). Both fractions depend on the development of physical effects *c*:

$$N_{EXP}(c) = \left(1 - F_E(c)\right)\left(1 - F_S(c)\right)N_{PAR}(c) \qquad \text{(Eq. 2-1)}$$

After initial exposure the exposed population could be further reduced by rescue and escape. These phenomena could be accounted for in quantitative modelling in the same way as evacuation and shelter, so formulas are omitted below for reasons of brevity.

Event-specific mortality is generally determined by means of so-called dose response functions, which determine mortality (F_D) as a function of the (intensity of) physical effects: $F_D(c)$. In this section[10] we assume that the dose response function returns one certain (expected) number of fatalities. The number of fatalities (N) for an event with intensity *c* is now found by estimating the number of evacuated and sheltered people, in combination with the mortality amongst the exposed population (see also (Lentz and Rackwitz, 2004a)):

$$N(c) = F_D(c)N_{EXP}(c) = F_D(c)\left(1 - F_E(c)\right)\left(1 - F_S(c)\right)N_{PAR} \qquad \text{(Eq. 2-2)}$$

F_D, F_S and F_E can be formulated as typical distribution functions, with values: $0 \leq F \leq 1$. Their forms and characteristics are discussed in later sections. Based on the above elements the general framework for loss of life estimation is shown in figure 2-4.

8 Other authors have proposed frameworks that include similar elements, see for example (Friedman, 1975) and (Ramsbottom *et al.*, 2003).

9 This step is often indicated as vulnerability assessment, see e.g. (Friedman, 1975; Nussey *et al.*, 1995)

10 Further implications of the uncertainty in the number of fatalities for a single release are discussed in section 4.

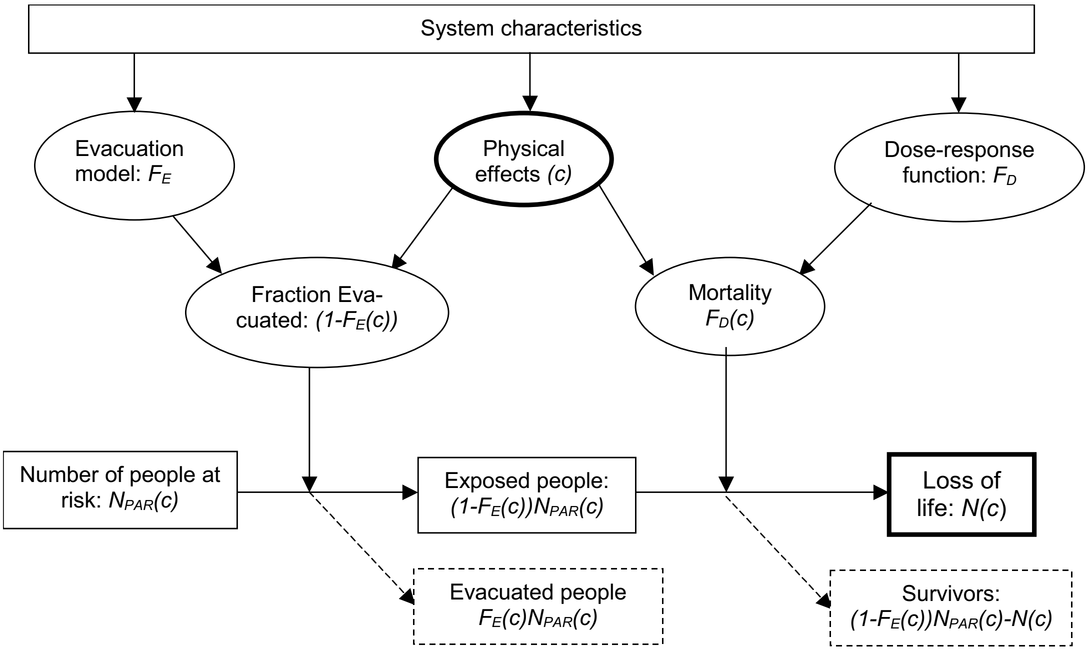

Figure 2-4: Framework for loss of life estimation (Note: For clarity of the figure shelter, rescue and escape are not included in figure 2-4, i.e. it is assumed that $F_S(c)=0$.)

In loss of life estimation the influence of **system characteristics** on evacuation, development of physical effects, and mortality has to be considered, as is shown in the upper part of the figure. Relationships between system characteristics and evacuation or dose response functions can be quantified. For example, evacuation progress will depend on the capacity of roads and exits; development of physical effects will depend on the topography and configuration of the area (e.g. tunnel or polder dimensions) and meteorological conditions.

Figure 2-4 forms the basis for further elaborations of the next section. Section 2.2 describes the assessment of the number of people exposed and evacuation, including shelter and rescue (the left part of the figure). Section 2.3 discusses the methods for estimation of mortality (the right part of the figure). The combination of both evacuation and mortality analysis is outlined in section 2.4.

2.2 Evacuation, escape, shelter and rescue

In order to estimate the extent of exposed population the number of people at risk and the effects of evacuation, escape, shelter and rescue have to be considered. Approaches for determining the number of people at risk (N_{PAR}) have been discussed in section 2.1.1 and in (Lentz, 2003; Lentz and Rackwitz, 2004a). This section concerns the analysis of evacuation, escape, shelter and rescue. First, general definitions (2.2.1) and modelling approaches (2.2.2) for evacuation and escape are described. Consequently the factors that influence the time available for evacuation (2.2.3) are analysed. Based on a literature review (Frieser, 2004) the phases that determine the time required for evacuation are outlined in section 2.2.4 to 2.2.8. Finally, shelter (2.2.9) and rescue (2.2.10) are discussed.

2.2.1 General definitions of evacuation and escape

Evacuation is defined in this study as: "the movement of people from a (potentially) exposed area to a safe location outside that area before they come into contact with physical effects"[11]. Different 'types' of evacuation are distinguished based on the timing of displacement of people relative to the occurrence of the event:

A) **Preventive evacuation**: Evacuation before occurrence of the event. An example is the preventive evacuation of a flood prone area before dike breach.
B) **Forced evacuation**: Evacuation during event development, where evacuating people are not exposed to physical effects. An example is the evacuation of people out of a building during a fire, before they are exposed to smoke.
C) **Escape** refers to the movement of people through an exposed area, for example people running through a toxic cloud or moving through a flooded area. Movement can be impeded by physical effects, e.g. due to limited visibility, reduction of walking speed or sustained injury. Eventually the exposure can lead to the death of the escaping person.

For a schematised situation, figure 2-5 shows the development of physical effects as a function of location (*x*) and time (*t*) in a so-called ***x,t*** **diagram**. In the left figure the development of physical effects (grey line), and different evacuation situations are depicted. In the right figure some examples of individual evacuation paths are shown with lines 1 to 4. These show 1) preventive evacuation; 2) Forced evacuation; 3) Failed escape. Line 4 shows that combination of evacuation and escape is possible, e.g. when an initially evacuating person is "overtaken" by the physical effects, but still manages to move out of the exposed area.

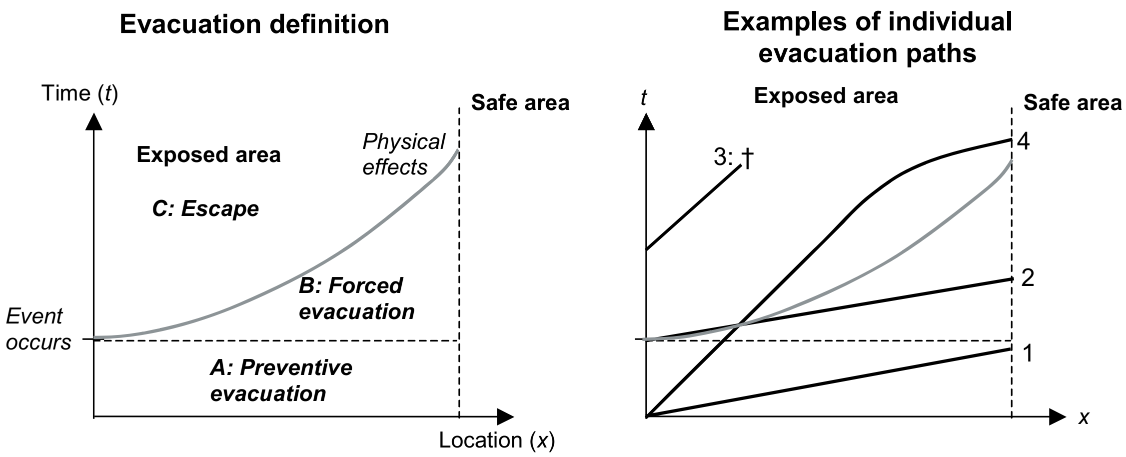

Figure 2-5: *x,t* diagram showing different evacuation phases (left) and examples of individual evacuation paths (right)

In general the possibilities for successful evacuation will depend on the time available until occurrence and arrival of the physical effects (T_A) and the time required for evacuation (T_R).

11 In contrast to other studies the level of organization is not considered as a separate variable in the definition. For example, COT (1995) defines evacuation as the organised displacement of persons before event consequences occur.

The **time available** (T_A) is the time between the first signs and the occurrence of physical effects (at a location). It depends on the extent of spatial and temporal development of physical effects, i.e. $T_A = T_A(c)$. The time available depends on the type of hazard. Obviously, an event with a fast development (e.g. an explosion) leads to potentially lethal conditions faster than a slower developing event, see also section 2.2.3.

A general timeline for elements in the analysis evacuation is shown in figure 2-6. It shows the different phases of evacuation and the situations that mark the boundaries between the phases. Lindell *et al.* (2002) and Opper (2000) suggest similar evacuation timelines. A general classification of the phases of the evacuation process is supported by the literature, as the relevant evacuation phases are very similar for different disasters. For example, Mileti and Peek (2000) state that the principles of how humans respond to warnings remain constant across hazard agents as diverse as floods, earthquakes, tornadoes, explosions, and toxic chemicals. The classification proposed below is believed to be useful for the analysis of evacuation for different types of event and at different levels of detail (for individuals and fpr a whole population, see next section).

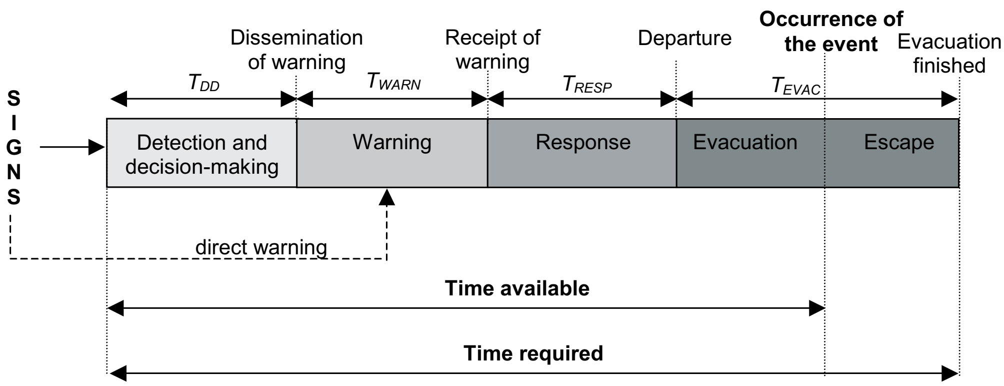

Figure 2-6: General evacuation timeline (Frieser, 2004)

The **time required** (T_R) for evacuation equals the time needed to complete the following four phases (abbreviations for the phases are indicated in the figure):

1. **Detection and decision-making:** A critical event is often preceded by signs, which can lead to its prediction, detection and consequent decision-making on an evacuation;
2. **Warning:** Following the above decision or direct warning by signs the threatened population is warned;
3. **Response:** This phase includes perception, interpretation and reaction to warning and / or the threat of the hazard;
4. **Actual evacuation:** This phase concerns the movement of people from an initial location to a safe area.

For some applications, e.g. tunnel and fire safety, the first three phases are jointly indicated as the wake up time. The different phases that determine the time required are discussed in more detail in sections 2.2.4 to 2.2.7.

2.2.2 Modelling of evacuation

Depending on the event characteristics, evacuation can be analysed at different levels of detail.

Analysis of the evacuation of a population

For larger affected populations the different phases of time required can be described by distribution functions, which can be combined in one overall distribution for evacuation $F_E(t)$. It describes the fraction of the population that can be evacuated as a function of time t. Figure 2-7 schematically shows the distribution curve of the time required for the evacuation process. The different phases are distinguished. The partial "failure" of different phases of evacuation has to be accounted for by including the failure of warning (fraction not-warned) and the fact that people do not respond to warnings (fraction of non-compliance). In case of a successful evacuation, the time required is smaller than the time available. Thus, the probability of successful evacuation is found as follows:

$$P(T_R \leq T_A) = F_E(T_A) \qquad 0 \leq F_E(t) \leq 1 \qquad \textbf{(Eq. 2-3)}$$

If the time available is deterministically known, $F_E(T_A)$ describes the fraction of the population at risk (N_{PAR}) that is able to leave the exposed area before conditions become potentially harmful.

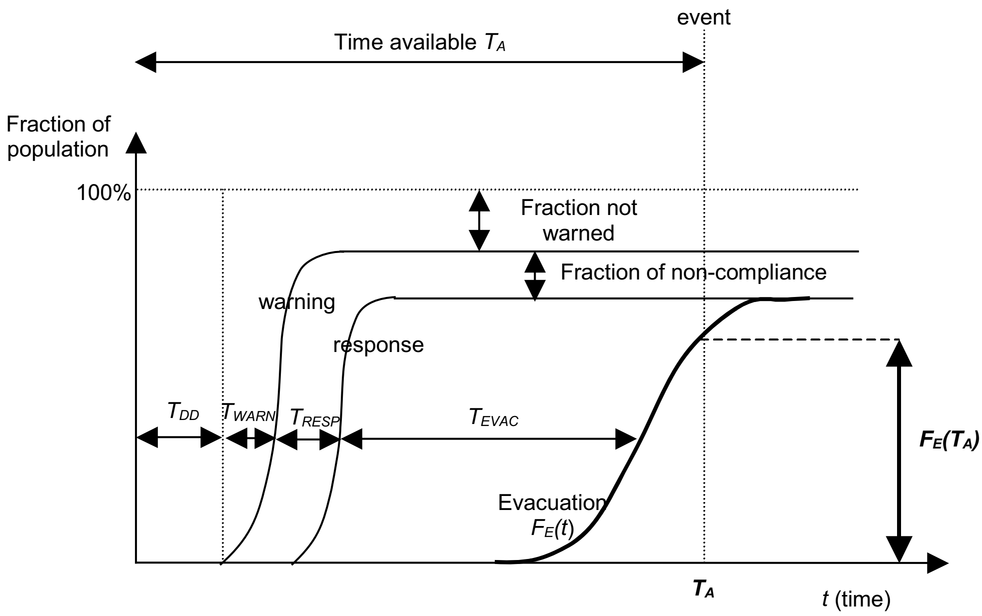

Figure 2-7: Distribution function of time required for evacuation $F_E(t)$, based on different phases of evacuation

If the time available is uncertain it is possible to give a probabilistic evaluation of equation 2.3. A probability density function (pdf) describes the uncertainty in the time available. By combining the pdf with the distribution curve for the time required, the probability density function of the fraction of the population that has evacuated is obtained, see figure 2-8 (A more extensive discussion of a similar elaboration is given in section 3). From this pdf the distribution function of the number of evacuated people and the expected magnitude of the evacuated population can be obtained.

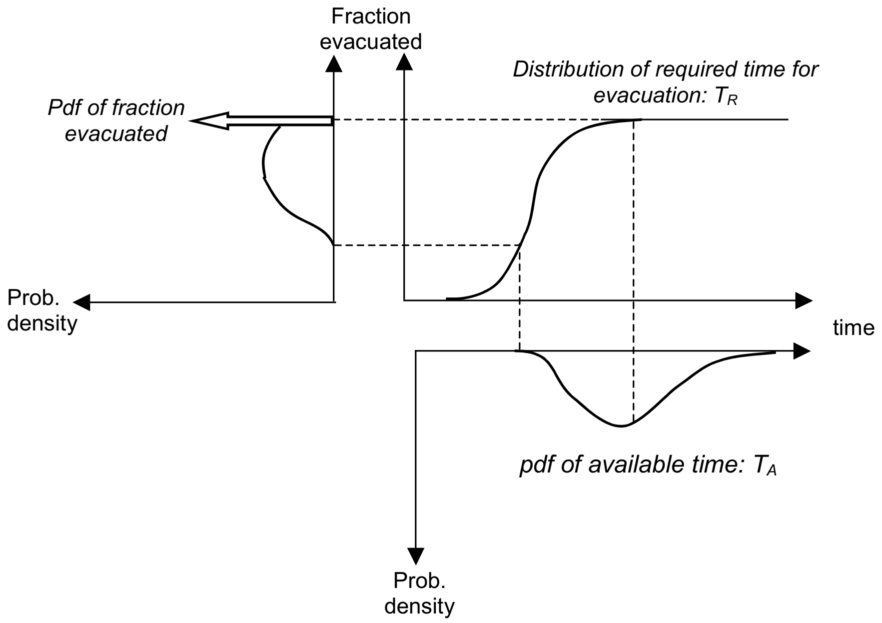

Figure 2-8: Analysis of the evacuated fraction of the population based on the pdf of time available and the distribution function of time required

Analysis of the evacuation of an individual

For certain events, such as fires in tunnels or buildings, a more detailed analysis of evacuation at an individual level is preferable. In this case, the progress of an escaping individual can be schematically shown in an *x,t* diagram and it can be combined with development of physical effects, see figure 2-9. Assume that the event occurs at a certain location or origin $x = 0$ and that the exit location lies at distance x_E. The time available until exposure to physical effects depends on a persons' location relative to this origin. The required evacuation time is found as follows: $T_{EVAC}=x_E/v$ (i.e. distance to the exit divided by the movement speed of the evacuating person v). The distance to the exit depends on the size of the area exposed. The figure shows that evacuation will become particularly hazardous when the dispersion velocity of physical effects is larger than the movement speed of people (see also section 2.2.3). There are also situations, in which a person escapes through physical effects and still manages to reach a safe area. In that case, it is often difficult to treat the analysis of effects, evacuation and injury / mortality completely independently. The combination of these elements is discussed in more detail in section 2.4.

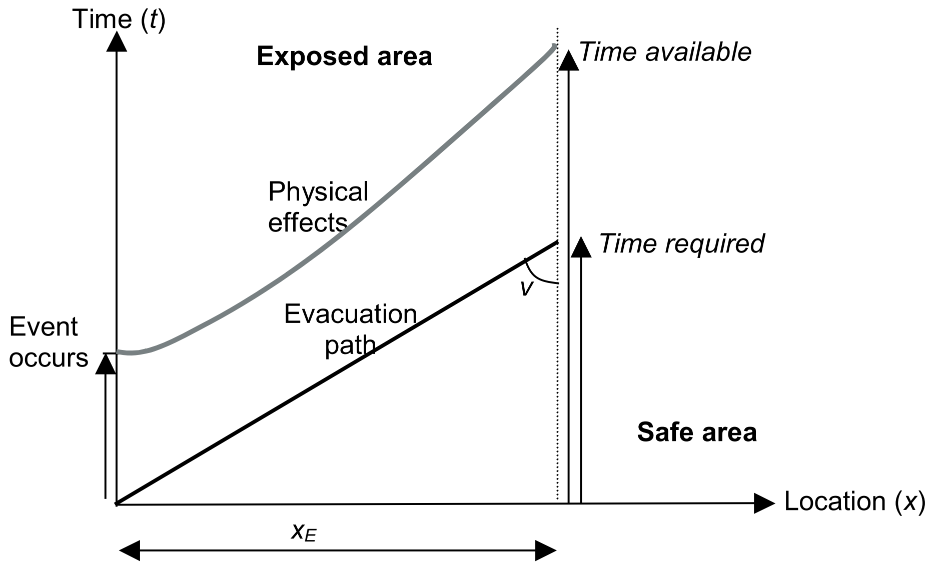

Figure 2-9: ***x,t*** **diagram indicating development of physical effects and escape progress for a person who starts to evacuate before the occurrence of the event.**

The above analysis treats evacuation and escape of an individual in one spatial dimension. In practical situations the problem has to be analysed in two dimensions or even three dimensions when both horizontal and vertical movement are possible. The possibilities for evacuation will be determined by the location of escape routes and exits relative to the development direction of physical effects. Some conceptual situations are shown in figure 2-10. For example for dam break in a narrow canyon, it is only safe to move out of the canyon up the hill. In a tunnel fire or toxic release safe escape might be possible in directions opposite or perpendicular to development of effects.

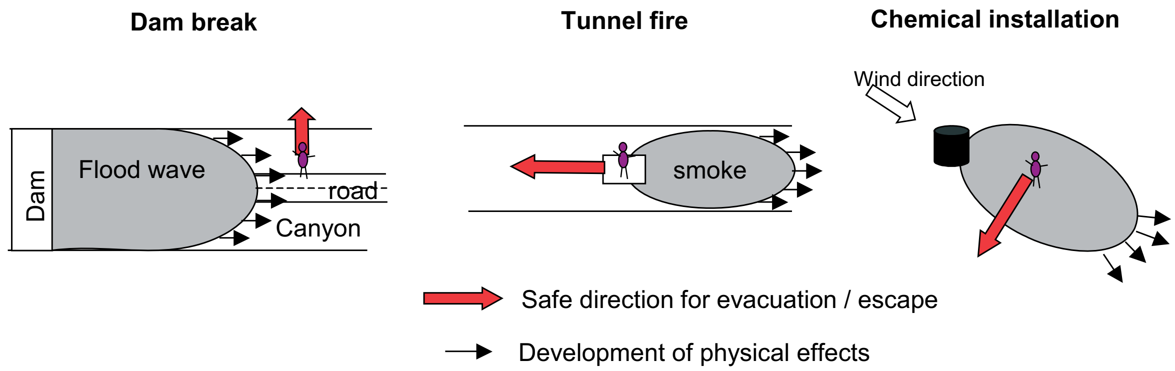

Figure 2-10: Safe escape routes relative to exposed area and development of physical effects

Choice of a modelling approach for evacuation

In practice a choice between the two modelling approaches (individual vs. population analysis) has to be made. It will depend on the characteristics of the situation and the preferred level of detail of output. For example, for flood evacuation one can choose to model the spatial and temporal development of individual evacuation in a detailed traffic model or to use the general population evacuation curves for the whole area. The first approach results in a spatial distribution of the evacuated fraction. The second approach results in one constant evacuated fraction for the whole area, which is independent of the location of people in that area. It can be shown that both approaches (individual and population analysis) are equivalent. Appendix 2.I proofs that the distribution of the number of evacuated people over time can be obtained by combining the analysis of the individual escape in an *x,t* diagram with the population density.

2.2.3 Time available for evacuation

The **time available** is the time between the first signs and the occurrence of physical effects. Two elements determine the time available for evacuation at a certain location, see figure 2-11 for an example:

1) The time available between the first signs and the initial release of physical effects at the hazard source;
2) The time available between occurrence of the critical event (at the hazard source) and the arrival of effects at a certain location.

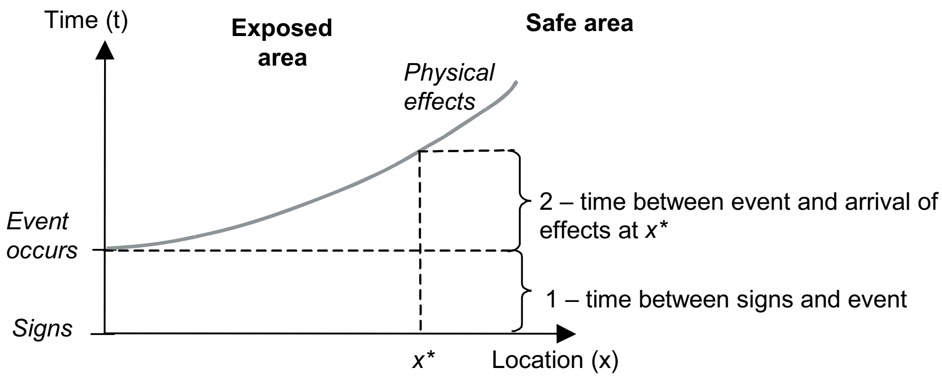

Figure 2-11: Elements determining the time available for location x*

Ad 1) The time available before onset of the critical event is an essential variable determining the possibilities for evacuation. Petrucelli (2003) states "evacuation can be simple to perform before a catastrophic event – if the event can be predicted sufficiently in advance with reasonable certainty". The possibility to predict, warn and evacuate before the event occurs largely depends on the type of hazard (see also table 2-2).

Ad 2) The time span between occurrence of an event and arrival of physical effects at a location depends on the dispersion velocity of physical effects $v_{effects}$ [m/s][12]. Approximate indications of dispersion velocity of physical effects for different types of event are given in table 2-2. Evacuation after initiation of an event could be effective if the evacuation speed is larger than the dispersion velocity of physical effects, so if: $v > v_{effects}$
As movement speed of people approximately varies between ±1 m/s (walking) and ±10 m/s (car), only events with lower dispersion velocities will allow evacuation after occurrence of the event. For practical development of evacuation strategies, contour plots can be used that show the arrival time of physical effects for an area.

12 Events with very large movement speeds of the physical effects, e.g. explosions, can be considered as acting instantaneously. Event development can be approximated in the x,t diagram (Figure 2-9) with an (almost) horizontal line as *dx/dt* is very large (and $dt/dx \approx 0$).

Table 2-2: Approximations of time available before occurrence of critical event and dispersion velocity of effects for different hazards

Type of event	Time available between first signs and occurrence of event	Dispersion velocity of effects
Airplane crash	0 to seconds	Instantaneous
Explosion	0 to seconds[13]	100 to 2000 m/s
Earthquake	Seconds to minutes	100 to 1000 m/s (from epicentre)
Toxic release dispersed by wind	Seconds to minutes	several m/s (depends on wind speed)
Fire	Seconds to minutes	1 to several m/s (depends on ventilation)
Dam breach	Seconds to hours	10-100 m/s
Tsunami	Seconds to hours (depends on warning system)	several m/s (on land)
Coastal flood	Hours	1 to several m/s (on land)
River flood	Hours to days	1 to several m/s (on land)

The possibilities to reduce loss of life by evacuation will differ between types of event. Sudden events with rapidly moving effects will allow neither evacuation before the event, nor sufficient time for escape after the event. These can be characterised as "self-reporting accidents" (Ale, personal communication). Examples are explosions, airplane crashes and earthquakes. For such events it is reasonable to assume that $F_E = 0$, thus the whole population at risk is exposed. For cases where the time available is too small to allow evacuation, shelter might be an option to reduce the number of people exposed . For example, during fires in long road tunnels people are unable to leave the tunnel by foot, but they might find shelter in emergency niches. Other events, such as river floods will be predictable in advance and the physical effects develop relatively slowly. For these events evacuation will be an important factor for the reduction of loss of life and it has to be taken into account in loss of life estimation.

The above issues are supported by analyses of statistics on natural disasters. On a global scale average event mortalities appear to be relatively high for events with little or no warning possibilities, such as earthquakes and flash floods (Jonkman, 2005). With regard to landslides, Guzzetti (2000) and Alexander (2004) show that fast-moving failures were responsible for more than 80 percent of deaths and injuries, while slow-moving landslides rarely resulted in casualties.

2.2.4 Time required for evacuation: Detection, prediction and decision-making

Signs of a possible disaster could initiate the evacuation process if they are noticed. An example of such sign is a high river discharge in a river. The possibility to detect and predict an event depends on the event signs, the awareness of the potential danger and the availability of prediction systems. For some events, accurate prediction is not achievable as the time between the signs and occurrence of the event is too short (e.g. for an explosion or airplane crash).

13 Not all explosions will occur suddenly and unexpectedly. Some types of explosion, e.g. a so-called boiling liquid expanding vapour explosion (BLEVE), can be caused by heating of vessel containing gas. This type of explosion can sometimes be predicted in advance.

After detection of a hazard it will be observed and monitored (e.g. water levels on a river). This information needs to be communicated to the responsible decision makers to consider the necessity of an evacuation. Early warning and evacuation can prevent serious consequences, but on the other hand it can result in unnecessary evacuation with the associated costs if the event does not occur. Postponement of the decision will allow the collection of more information. This can result in a better prediction (of the probability of) occurrence of disaster. However, the consequences might be larger if the disaster occurs because evacuation was initiated too late or not at all. Decision-making is concluded by a notification to the appropriate community officials in order to start spread evacuation warning

A review of literature by Frieser (2004) showed that the time between the detection of the first signs and final decision-making may span several days for threatening natural disasters. However, if an event has already occurred the time required for this phase ranges from a few minutes to several hours. For example, for accidents with hazardous materials Bellamy (1986) concludes that official warnings after the disaster come with a delay of about 1,5 to 3 hours.

2.2.5 Time required for evacuation: Warning

People at risk can be warned by either by direct perception of the threat (for example smoke, heat, smell) or indirectly by other sources, which can include:

- Media: television, radio, internet;
- Warning systems: loudspeakers, sirens;
- Personal dissemination: by emergency personnel, or the social network;
- Other communication systems: (mobile) telephones, e.g. with text messages.

The effectiveness of warning depends on warning characteristics and it differs between the different warning sources. In general, the possibilities to spread the official warning amongst the whole affected population depends on the level of preparation (e.g. on the presence of disaster plans) and the possibilities for communication between authorities and the public. Warning is crucial for the initiation of the evacuation process. Due to difficulties in the dissemination of the warning a certain fraction of the population may not be warned at all. For example, during river floods in 2000 in the UK, only 30% of the questioned people did receive warning prior to their house being flooded (Ramsbottom *et al.*, 2003).

For larger scale events (hurricanes, floods) most people will be warned within several hours. However, for more immediate and small-scale events, such as building or tunnel fires warning times might be much smaller due to direct warning, e.g. by alarm systems or direct perception.

2.2.6 Time required for evacuation: Response

The response phase includes the perception, interpretation and reaction to warning and / or the threat of the hazard. The principles of how humans respond to warning remain constant across diverse hazards such as floods, earthquakes, tornadoes, explosion, and chemical accidents (Mileti and Peek, 2000). Therefore a general framework for the response phase is shown in figure 2-12, which is based on work by Rogers and Sorensen (1989) and (Canter, 1990).

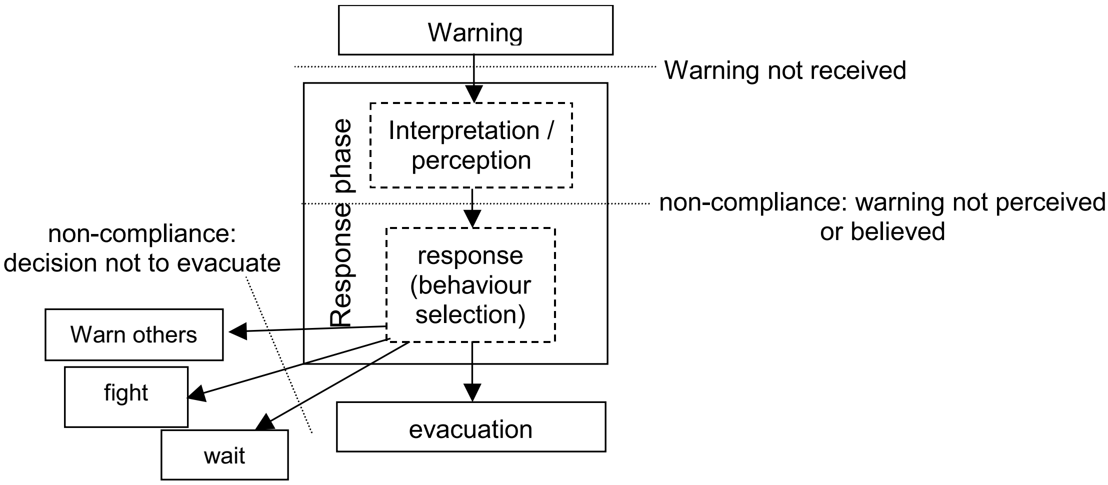

Figure 2-12: framework for response to warning in case of an emergency (based on (Rogers, 1989) and (Canter, 1990))

Within the response phase two sub-phases are distinguished: 1) the interpretation and perception and 2) the response behaviour selection. Barriers exist between different phases. These are shown with dashed lines to account for people who do not receive the warning, and non-compliance to the warning.

Interpretation and perception of warning

The response phase starts with the receipt of a warning (either by official warning or direct warning by the physical effects). The interpretation / perception of the warning and the corresponding hazard strongly depends on the type of warning. When the danger is imminent, for example when the heat is felt and the smoke is seen and smelt, people tend to respond relatively fast. For less immediate threats people may respond slower. In many cases "The initial response to a disaster warning is disbelief" (Drabek, 1986). Rogers and Sorensen (1989) give empirical evidence for two accidents with the transportation of hazardous materials, in which the majority of the warned population (59% and 81%) disregarded initial warning information. In order to improve perception of the warning people tend to seek confirmation of the warning from other sources. It has been observed for fire cases (Fischer *et al.*, 1995) that people tend to move to the accident site in order to investigate the hazard. A related form of behaviour concerns so-called 'disaster tourism', when people move towards the hazard source to observe the event unfolding. Thereby they might become part of the exposed population themselves. This type of behaviour has been reported during relatively recent events, for example the fireworks disaster in Enschede (Netherlands) in 2000.

According to Fischer *et al.* (1995) several variables appear to increase the likelihood of warning being taken seriously and acted on properly. These variables include the clarity and consistency of the warning message(s), the frequency of warning and the type of authority which is giving the message, the accuracy of past warnings, and the frequency of the disaster. In addition to these the time of the day (day / night) is considered as an important factor in compliance to warnings.

Response
Figure 2-12 shows that the warning-response process is not a direct stimulus response process, as it follows a series of decisions (Mileti and Peek, 2000). Behaviour selection includes an (implicit) weighing of costs and benefits, as people will attempt to minimize their damage and injury. As an outcome of the decision, different actions can be undertaken. Apart from actual evacuation, other possible actions include: "warn others", "fight" or "wait" (Canter, 1990). Several aspects may influence people's responses and the resulting behaviour. People in emergency situations have the tendency to continue the behaviour they show in normal situations. This normal role taking behaviour can have an important influence on their behaviour during emergencies. It is often argued that experience with the event and its effects are important determinants for compliance and behaviour selection. However, for the case of hurricanes no consistent relationship has been documented for whether or not individuals who experienced a hurricane before are more likely to evacuate (Whitehead *et al.*, 2000).

Non-compliance
Figure 2-12 indicates two types of non-compliance. Firstly a warning can be received but not perceived, believed or understood. Observations from different types accidents and experiments showed that people neglected observable signs of immediate danger (Boer, 2002). In the case of the second type of non-compliance the warning is perceived, but is consciously decided to undertake action other than evacuation. "Property binding", the fear of theft or lack of options to evacuate might motivate people to stay inside the (potentially) exposed area.

The above considerations may partly form an explanation of non-compliance to warning orders observed in multiple cases. Lindell *et al.* (2002) report non-compliance rates for hurricane warnings in the United States between 35% and 64%. For chemical accidents the range of non- evacuees was between 2 and 74% of those warned (Bellamy, 1986).

The actions (or non-actions) of people in the response phase can be crucial for survival. Psychological studies stress the importance of providing people with information to facilitate decision-making and effective actions. The information should be informative and given rapidly, and early action should be emphasised.

Response time
The time required for response can be characterised as the passage of time between the receipt of the warning message and the start of actual evacuation. The response time is needed for interpretation of the warning and the preparation of evacuation. Rogers and Sorensen (1989) indicate an average response time of an hour for two hazardous materials transportation accidents in the United States. Lindell *et al.* (2002) give distributions of response times for hurricanes in the United States, showing that 90% of the population was prepared to leave about 6 hours after warning. If immediate danger is perceived lower response times can be expected. Thus, estimates of response times are case specific and they are generally not directly transferable to other types of event.

2.2.7 Time required for evacuation: Actual evacuation

This phase covers the actual movement from an initial location to a safe area. Several characteristics of the population at risk can influence the development of an evacuation. These include the magnitude and the spatial and age distribution of the population. Evacuation will also depend on the area size and type, and capacity and configuration of escape routes and exits. Other conditions, such as weather and time of the day, may play an important role in the evacuation development. Some authors have analysed the relevance of some of the above factors. For chemical accidents, Bellamy (1986) concludes that the number of evacuated people does not appear to have a very large effect on increasing evacuation times. The data on different types of accidents provided by Hans and Sell (1974) indicates that more time is required for evacuation as population density decreases. Firstly it is suggested that road networks decrease as population density decreases. Secondly, dissemination of the warning may become more difficult as population density decreases leading to an increase of warning time.

Furthermore organizational aspects may influence escape and evacuation. An example is the management of evacuation traffic flows to prevent clogging of cars at bottlenecks in the road network. Also specific difficulties may be associated with the evacuation of vulnerable groups such as disabled people, elderly or tourists who are not familiar with local circumstances. Experience from practical evacuations (Fischer *et al.*, 1995; COT, 1995) suggests that during mass evacuation only a small percentage of the evacuated population uses public transportation (in the order of magnitude of 10%) and that most people evacuate by themselves.

Behavioural aspects of evacuation: panic
Often panic[14] is indicated as a major factor in accidents, which has an important influence on behaviour. Sime (1990) argues that observed "panic" behaviour is in fact often an adequate and predictable[15] reaction (e.g. pushing others to run away from a nearby fire). (Hans and Sell, 1974) and (Mileti and Peek, 2000) state that systematic research of real crowds in emergencies has failed to find empirical support for the existence of this type of behaviour. However, Bellamy (1986) gives some observations of inappropriate behaviour during chemical accidents, for example running towards the danger, and estimates that about 20% of the people show inappropriate behaviour.

Escape
In the case of escape people move through the physical effects. Firstly, the effects can reduce escape speed since movement through the exposed area is impeded, e.g. by water or smoke[16]. The reduction of escape route capacity due to physical effects should be accounted for (Urbanik, 2000): for example roads that are flooded or damaged by an earthquake. Another factor concerns the limited orientation and visibility of escape routes and exits, e.g. a room full of smoke. In addition, injuries sustained due to exposure to physical effects might decrease movement speed. Finally, the physical effects might lead to an altered perception, change of consciousness, and thus changes in behaviour.

14 Panic is a sudden irrational feeling of great fear.

15 In this respect Canter (1990) mentions that behaviour is defined by the setting in which it takes place.

16 Jin (1997) shows how walking speed of people in fire smoke is reduced due to limited visibility.

Estimation of the evacuation time
An estimation of the time required for (actual) evacuation has to account for the main factors mentioned above. Several models have been developed to provide evacuation time estimates (ETE's) for different fields of application. These models generally contain relationships between the number of vehicles or people on the escape way and the possible evacuation rate (people / time unit). Three types of evacuation models can be distinguished (Petrucelli, 2003):

- Dissipation rate models: aggregate formula for estimating evacuation time based on size and shape of the system and number of people in it;
- Manual capacity modelling: uses techniques to allocate people to the escape network, while taking into account capacities;
- Micro simulation: simulates evacuation on a micro-, often individual level.

Existing evacuation models mainly consider technical elements, (number evacuating people and the capacity and configuration of the escape ways and exits). Helbing *et al.* (2000) have developed a model for the movement of people through exits in which psychological aspects (e.g. group behaviour) as well as physical aspects (interacting "push" forces between humans, and exit capacity) are integrated. In general, analyses of evacuation time have to address technical as well as behavioural elements.

2.2.8 Time required for evacuation: Summary of main factors

Based on the above review of literature some main factors that influence the time required for evacuation are summarized in table 2-3. Factors have been categorised[17] according to the evacuation phase, and category of system elements. Physical effects are included as a separate category as these can also have an important influence on evacuation progress.

Table 2-3: Main factors influencing the time required for evacuation.

	System configuration	**Procedures and organisation**	**Physical effects**
Prediction and decision-making	• Prediction and detection systems	• Decision-making	• Signs
Warning		• Official warning systems • Warning source • Fraction not- warned	• Direct warning by physical effects
Response		• Warning message and characteristics and belief of warning • Selection of action • Fraction non-compliance • Level of preparation	• Perception and awareness of physical effects
Evacuation	• Configuration and capacity of escape routes and exits	• Evacuation management • Number of people and characteristics • Behaviour (direction of flight)	• Threat of physical effects • Reduction of escape routes

From the overview it can be seen that organisational factors are most relevant in the warning and response phases. The final evacuation / escape phase is dominated by the interac-

17 The categorisation by system element is a generalisation, because there will always be interactions between the different types of system elements. For example, prediction itself will require a physical measurement system (for example for gauges for water levels), people interpreting the data, and a decision-making structure.

tion between system configuration and organisational factors. The (threatening) physical effects can strongly influence all four stages.

2.2.9 Shelter

Within the exposed area people may find protection in **shelters.** These are constructions[18] in the exposed area, which offer protection to people. Examples of shelters are high-rise buildings during floods, or emergency niches in a tunnel that are safe during a fire. For floods, shelter within the exposed area is often indicated as **vertical evacuation**. Given the meaning attributed to evacuation in this study, that term is not adopted here.

Different types of shelters can be distinguished, see also FEMA (2001). Single-use shelters are constructed with the sole purpose to provide shelter during disasters. Examples are special cyclone shelters constructed in Bangladesh and emergency niches in the tunnel. In many cases it is more efficient to develop facilities that have a certain regular function during normal conditions, but serve as shelter during an disastrous event. These are indicated as multi-use shelters. An example is the use of a sports stadium as a hurricane shelter. These types of shelter facilities should be designed to withstand the loads in disaster conditions safely. For some types of event constructions that were originally not designed as shelters could provide shelter, for example high-rise buildings during floods.

There are some important issues related to the effects shelters on loss of life. For an adequate utilisation of shelters it is important that people are warned before the disaster and that they have information regarding the presence of shelters and the accessibility of shelters before the onset of the event. During the disaster shelters should preferably still be accessible and recognisable. For example during a tunnel fire the visibility of emergency niches is a point of concern. Another issue is that shelters may only offer partial protection, as people in the shelter may still be exposed to a certain level of physical effects. For example during nuclear or chemical accidents, radiation or concentration levels may be only partially reduced by the shelter. Finally, it is noted that adverse health conditions may develop in shelters when many people have to stay there for a long period. Sheltering is generally an attractive risk reduction strategy when evacuation of the whole population is not feasible (see also section 2.2.3).

2.2.10 Rescue and emergency actions

The emergency services include the police, fire brigade, medical services and professional rescuers. Their actions can influence loss of life in several ways. Based on the general steps for loss of life estimation, the effects of rescue and emergency operations can be categorised. These can:

- Reduce physical effects (c) or prevent their further development;
- Reduce the number of people exposed (N_{EXP}) by rescue;
- Influence mortality (F_D) and loss of life, by means of treatment of injured people that would not have survived otherwise and / or due to the occurrence of additional fatalities amongst the rescuers.

18 Shelters concern human built constructions. The absence of a shelter at a considered location would imply that a person at that specific location would be exposed.

Given the scope of this section, the reduction of the number of people exposed and loss of life are further discussed. **Rescue** (often indicated as search and rescue) concerns the removal of people by others from (potentially dangerous locations inside) an exposed area. For example, removing people from houses or trees in a flooded area can reduce the number of people exposed. Rescue can only prevent loss of life if people are rescued before they become a (potential) fatality. Thus, the effects of rescue on loss of life have to be considered relative to survival of people as a function of time after the disaster. For example, Kuwata and Takada (2004) analyse the effectiveness of rescue after earthquakes based on the probability of survival under debris as a function time. This implies that there will be a certain critical period in which rescue is still possible. For example for earthquakes search and rescue are reported to be critical within the first 48 hours (Tsai *et al.*, 2001). Slager (1992) reports that for the 1953 flood in the Netherlands most people were rescued within the first 48 hours. For other types of event, such as tunnel and building fires, less time is available to save people from the exposed area. In this respect the delay in the initiation of rescue actions will be very important. Depending on the event type and region, the delays in the actions of emergency services can range from about 15 minutes (e.g. for tunnel and building fires) to hours or even days (e.g. for floods and earthquakes). In addition, the capacity of emergency services has to be taken into account relative to the number of people that have to be rescued. In the analysis of search and rescue actions the environment in the exposed area is important. The physical effects in the area could hamper rescue operations (e.g. limited visibility) or require the use of special equipment. Whether mortality can be prevented by medical treatment of injured people will also depend on the type of injury.

Additional fatalities may occur amongst those that perform rescue actions. Experiences with some large accidents (Twin Towers 9-11-2001, Mont Blanc tunnel fire in 1999) have shown that additional deaths may occur amongst rescuers who undertake, when analysed afterwards, inappropriate action. An investigation in the Netherlands (IOOV, 2004) showed that in the period 1989-2003 (16 years) 28 firemen lost their lives during operation. Knowledge of appropriate rescue operations in difficult circumstances (e.g. swift water rescue) could contribute to reduction of fatalities amongst rescuers.

Depending on the type of event and the level of detail of analysis, the actions of emergency services could be considered in loss of life estimation. In this context it is noted that the influence of rescue actions might already be included in some loss of life models, because these were empirically derived using data from historical disasters in which emergency services operated.

2.3 Estimation of mortality

2.3.1 General approach

The physical effects of a critical event could affect people and various types of objects and assets. Different damage types could result, such as loss of life, economic damage and damages to ecological, cultural and historical values. This thesis focuses on the estimation of loss of life.

In the reporting and analysis of fatalities due to disasters a distinction is often made between fatalities caused by either the direct or indirect exposure to the event, see e.g. Combs *et al.* (1999). **Directly** related deaths are those (directly) caused by the physical effects of the event. **Indirectly** related deaths are those caused by unsafe or unhealthy conditions that occur because of the anticipation to, or actual occurrence of the disaster. The occurrence of direct fatalities can be conceptually modelled with the load-resistance concept (which is similar to the hazard-vulnerability approach), see figure 2-13. If the load of physical effects exceeds the resistance of an individual, mortality will occur due to a certain failure mechanism or medical cause. For example, the hydraulic load on a person in flowing water could exceed a person's resistance to withstand the flow and lead to instability (failure mechanism) and possibly consequent drowning.

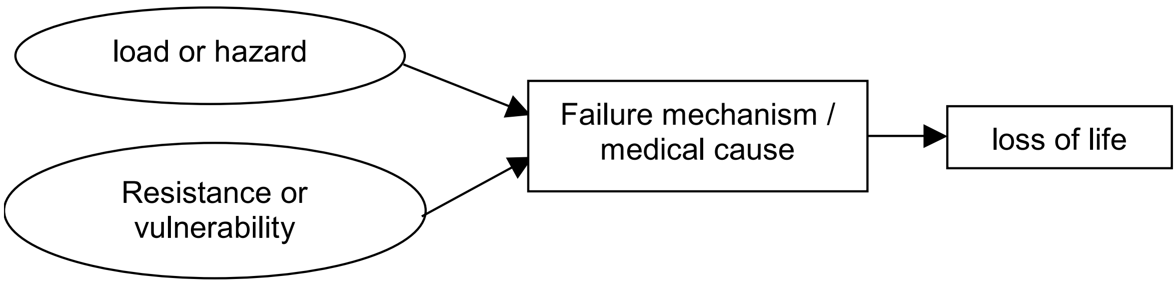

Figure 2-13: Load and resistance factors that result in loss of life due to a specific medical cause

In the analysis of loss of life different death causes might be accounted for. Direct fatalities can be caused by (van der Torn, 2002):

- Mechanical impacts: energetic impact of shock waves, projectiles and other physical impacts;
- Radiological, Nuclear, Biological, Chemical (RNBC) impacts;
- Thermal impacts due to temperature and heat radiation;
- Other impacts: asphyxiation, drowning and others.

Indirect fatalities might also be associated with psychological effects (e.g. stress leading to heart attacks) and diseases and illnesses caused by the event. Based on the above general approach it is possible to define more specific categorizations of death causes for event types, see for example (Jonkman and Kelman, 2005) for floods and (Chan *et al.*, 2003) for earthquakes.

2.3.2 Dose response functions

A **dose response function** gives a relationship between the (intensity of the) physical effects and the mortality in the exposed population[19]. It shows how the occurrence of mortality in the population is associated with the degree of exposure to physical effects. In this thesis **mortality function** is used as synonym. A dose response function is conceptually similar to so-called fragility or vulnerability curves. These are used to model the probability of structural failure of buildings as a function of loads, e.g. for earthquakes.

A dose response function forms the distribution function of resistances in a population. Its shape reflects the variability of resistances in a population. A general formulation for the dose response function can be given based on the load-resistance approach. We assume

19 In other contexts dose response functions are also used to model other non-lethal health effects, such as injury and hindrance due to noise. A more general definition, not restricted to mortality, is given in (Covello and Merkhoffer, 1993): "A dose response model is a functional relationship between the dose and an adverse health response."

exposure of a population to a certain intensity[20] of physical effects *c*. This represents the load. The lethal resistance intensity for a human is c_R. Now the dose response function can be formulated as follows[21]:

$$F_D(c) = P(c_R < c) \qquad\qquad 0 \le F_D(c) \le 1 \qquad \textbf{(Eq. 2-4)}$$

Dose response functions are usually applied to estimate one certain (expected) number of fatalities in an exposed group. It is also possible to analyse the uncertainty in the outcome of exposure of people to a given load, e.g. due to model uncertainty in the dose response function. This topic is further elaborated in section 4.

The intensity of physical effects *c* is generally characterized by means of one variable, which is expected to be associated with the main causes of death. For example, flood mortality is estimated as a function of water depth because drowning becomes more likely when the water gets deeper. For some applications, the combined influence of multiple characteristics of the physical effects will be relevant for loss of life. If one variable is included in the dose response function, other variables could be implicitly included because these are associated with the primary variable[22]. Some characteristics of the physical effects could have a certain physical relationship with each other. For example, it is expected that floods with large water depths are also characterised by larger rise rates and flow velocities (see section 7.2).

Two main types of variables are used within the dose response function to indicate the intensity of effects: the instantaneous intensity of physical effects and the dose of physical effects over a certain time period[23]. The **instantaneous** intensity is used for phenomena where instantaneous exposure is important and injury / mortality occurs when some threshold value is exceeded. For toxic substances the intensity is generally expressed as a concentration, but depending on the field of application other determinants can be used to express intensity, e.g. water depth for a flood (see section 7) or air pressure associated with an explosion. Usually the maximum intensity during exposure is representative.

The **dose** of physical effects is considered when the cumulative effect of exposure over a certain time frame is relevant. This could be the case for the assessment of the adverse health effects due to an inhaled dose of toxic substances over time. When the intensity of effects varies over time it must be specified by a time-varying concentration, i.e. *c(t)*. The dose is found by integrating this concentration over time. This approach is generally used in the estimation of mortality due to exposure to toxic substances for chemical accidents, for example with so-called probit functions (see also below).

The dependency of mortality on the intensity of physical effects has been discussed above. For many applications the probability of getting killed due to exposure will also depend on the state or situation in which a person is present. Dose response functions can be developed for various relevant situations. For example, Takahashi and Kubota (2003) estimate

20 The intensity of physical effects could refer to a (instantaneous) concentration of physical effects or to a dose of effects sustained over a certain time. (exposure concentration over a certain period).

21 Equation 2-4 gives the probability that the lethal intensity cR is smaller that the exposure intensity c.

22 In epidemiology, these implicitly included variables are indicated as uncontrolled confounding factors (Hennekens and Buring, 1987).

23 An analogy is found in mechanics where the (instantaneous) force on a construction can be considered or the impulse associated with a force acting over a certain time period.

earthquake mortality for groups of persons in different states (in home, car or in open air). Sometimes it is possible to relate the dose response function directly to the physical failure mechanism that results in failure or loss of life. An example is the function used for the determination of human instability in flowing water. It can be derived from the momentum equilibrium of a person standing in a water (Abt *et al*, 1989; section 6.3 of this thesis). At a detailed level the eventual estimation of consequences to humans, might necessitate an assessment of the impacts of physical effects on structures or objects in which the humans are present. However, in many applications it is chosen to develop one general dose response function, which is applicable over the exposed population as a whole, regardless of the exact states of the individuals.

2.3.3 Derivation of dose response functions

General

Theoretically, a dose response function could be derived by testing the response of a population to exposure to physical effects in controlled settings. For phenomena with direct and acute response a fictitious experiment could be defined. The intensity of physical effects is gradually increased and it is recorded when members of the tested population perish as a function of the measured intensity. The result would be a cumulative distribution of the number of fatalities as a function of the intensity of physical effects. Scaling of the number of fatalities to the exposed population results in the mortality or response fraction. The resulting series of observations could be connected by a stepwise cumulative distribution. Especially if there are a large number of measurements, the line can be reasonably approximated by a continuous distribution. Figure 2-14 shows a fictitious example for 10 observations regarding exposure to a dose of certain physical effects. Each observation represents roughly a 10 percent response fraction. The connecting (stepwise) cumulative distribution and a normal distribution as a continuous approximation are shown.

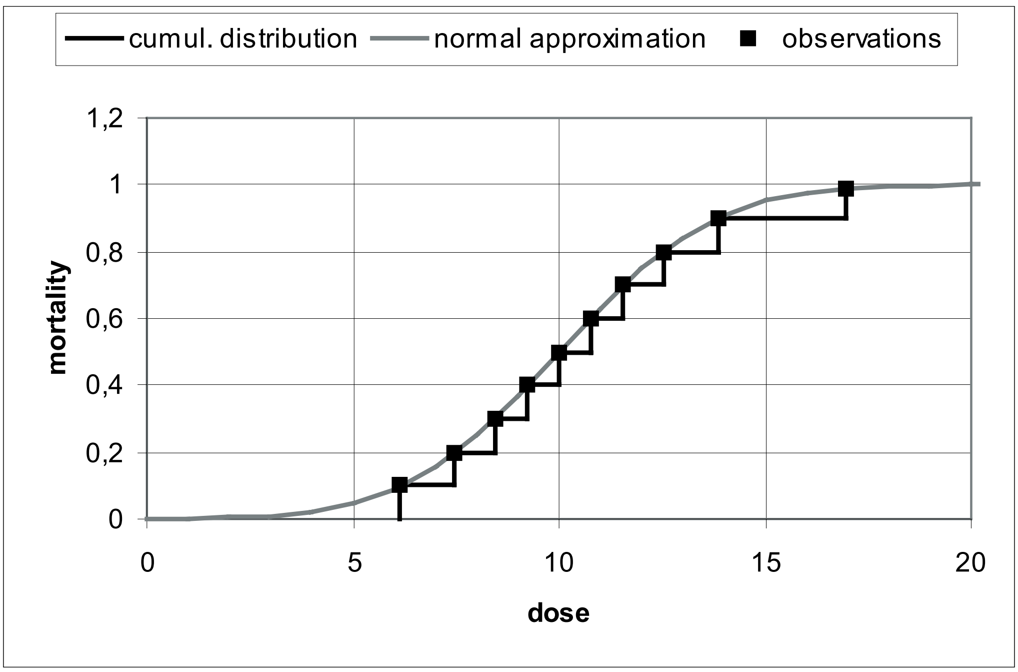

Figure 2-14: Example of mortality distribution as a function of exposure dose.

For phenomena where the response follows with some delay after exposure a typical test layout is as follows (see e.g. Zwart and Woutersen (1988)); Multiple populations are exposed to various levels of physical effects. Over a certain period the occurrence of mortality is observed. Mortality fractions are plotted as a function of the sustained doses and a bestfit dose response function is derived from this dataset.

The above shows that a dose response function is generally derived based on data obtained from a specific population. Formally, this dose response function can only be applied to populations that have the same characteristics as the original population. In practice it is often (implicitly) assumed that the studied population has the same characteristics as the original population.

Data sources for derivation of dose response functions
Obviously, due to ethical concerns, it is impossible to undertake controlled and repeated lethal experiments with humans in practice. Therefore, two types of sources are generally used to derive dose response functions: empirical data from observations regarding human mortality during past disasters or the results of animal tests.

Observations regarding human mortality during past disasters[24] have the advantage that they are realistic[25], but data are often difficult to obtain during crisis situations and will be collected under uncontrolled circumstances. As a result data on important determinants of loss of life could be unavailable. Biases might be introduced in the derivation of the dose response function because data from specific events are selected, e.g. only high fatality events are included in the analysis. In addition, the available measurements from different disasters could represent different (unmeasured) conditions and populations with different vulnerabilities. As few toxicity data for man are available, especially in the higher response fractions, human dose response functions can be derived by extrapolating data from **animal tests**. Scaling factors have been established to account for differences in breathing volume, lung area and body weight. These tests have the advantage that they can be performed in controlled settings. However, large uncertainties exist with respect to scaling the results to humans (mechanisms, routes of transportation). A more extensive discussion of strengths and limitations of animal tests and epidemiological studies is provided by Covello and Merkhoffer (1993).

2.3.4 Characteristic forms of dose response functions

The simplest form of a dose response function assumes a constant mortality fraction F_D amongst the exposed population, irrespective of the magnitude of physical effects. Examples of such functions are the values applied to ground fatalities for airplane crashes (F_D =0,28 within the crash area (Piers *et al.*, 1992)). For some other types of event variations in mortality could exist between locations or situations. Nevertheless, it could sometimes still be reasonable to assume a constant mortality, because average event mortalities are generally in the same range. For example for storm surge floods, a mortality value F_D=0,01 seems a good first order approximation (see section 5).

24 Within epidemiology such analyses would indicated as a retrospective cohort study (Hennekens and Buring, 1987). Retrospective because they are carried out after exposure. Cohort study because only the people that are exposed are included.

25 In this respect Dominici *et al.* (2005) mention: “High exposures associated with disasters can provide a natural experiment. ” and ”Ultimately, as perverse as it may sound, epidemiologists must view disasters as important opportunities to learn.”

The dependency of F_D can also be displayed in discrete form with a step function. When no harmful effect occurs until a certain level of exposure is exceeded, a so-called threshold phenomenon is observed. If the critical threshold value of physical effects (c_{cr}) is exceeded, mortality equals a certain (constant) value q [-]:

$$F_D = 0 \qquad c < c_{cr}$$
$$F_D = q \qquad c \geq c_{cr} \qquad 0 \leq q \leq 1 \qquad \textbf{(Eq. 2-5)}$$

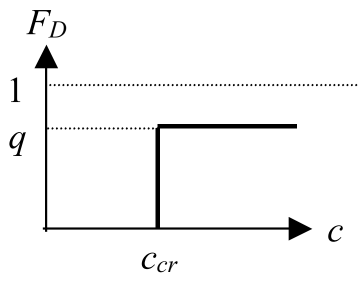

Figure 2-15: Discrete dose response function

An example of such a discrete dose response function is the so-called threshold exposure limit, see for example (SAVE, 2002) and the Acute Exposure Guideline Level (AEGL) system proposed by the United States Environmental Protection Agency[26]. The threshold exposure limit is used to express the dose level at which the general population could experience certain health effects. Such values are used in emergency response to express the dose or concentration at which the general population could experience certain health effects. In general three limits are proposed to account for 1) discomfort; 2) health effects; 3) life threatening health effects or death. The suggested values are aimed at the more susceptible groups of the population[27]. In using the threshold exposure limit for loss of life estimation it is often assumed that the whole exposed population will decease if the limit is exceeded. It is questionable whether this is a correct representation of the variation in population's response as the resistance distribution over the population is neglected. If the exposure intensity exceeds the threshold limit higher resistances of certain persons in the exposed group are neglected, and consequence and risk levels might be overestimated. Similarly consequences can be underestimated, for dose values below the threshold limit. Given these considerations it seems that the resistance distribution of the population gives a more appropriate representation of the variability of responses. A further discussion on the application of discrete threshold exposure limits is provided in appendix 2.II.

Discrete mortality values for different situations and levels of physical effects can be displayed in a table, resulting in a multinomial distribution. Graham (1999) gives an example of this approach for dam break floods. Earthquake-induced building collapse includes so many side constraints that it is impossible to express F_D other than in tables listing typical values for different building types, failure mechanisms, etc., see e.g. (Coburn and Spence, 1992; Murakami, 1992).

26 http://www.epa.gov/oppt/, accessed July 2006.

27 Therefore they are generally considered to be equivalent to a lethal response in small fractions of the population. The life threatening AEGL value is assumed to correspond to a mortality of 10-2 (PGS, 2003).

In some cases, data are insufficient for establishing an absolute dose response function over the whole range of response values between 0 and 1. Then, one can alternatively relate a change in dose to a change[28] in response over a limited exposure range with a linear relationship, i.e. $\Delta F_D/\Delta c$=constant. Such an approach is generally used, when an epidemiological study is concerned with a phenomenon associated with chronic exposure and small response fractions. An example is a study on the effects of air pollution on mortality, see e.g. (Samet *et al.*, 2000).

Dose response functions have been developed which express mortality as a (continuous) function of the intensity of physical effects. Some typical shapes found in literature are discussed below.

Lind and Hartford (2000) use a **normal distribution** function to account for uncertainties in occurrence of instability of people in flowing water.

Empirical analysis of historical data shows that the correlation between flood mortality and water depth can be described with a rising **exponential distribution** (Jonkman, 2004; see also section 7 of this thesis), see equation 2-6. A disadvantage of this type of function is that mortality F_D>0 for c=0:

$$F_D(c) = e^{\frac{c-A}{B}} \qquad 0 \le c \le A$$
$$F_D(c) = 1 \qquad c > A$$

(Eq. 2-6)[29]

Where: *h* - water depth [m]; *A,B* - parameters of the distribution curve [m](Note that A equals the intensity of effects for which mortality becomes 1).

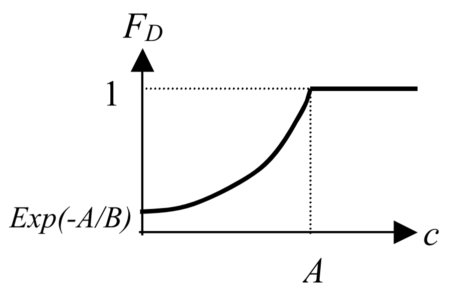

Figure 2-16: Exponential dose response function

Covello and Merkhoffer (1993) describe some additional shapes of dose response function that are not discussed in detail here. These functions include the logit and Weibull distributions.

28 This approach encompasses the determination of the derivative of the dose response function over a small range of exposures.

29 Often the exponential distribution is written in another form:

$$F_D = Ce^{Dh} \qquad 0 \le h \le -\ln(C)/D$$

where C=exp(-A/B) and D=1/B. The benefit of the formulation in eq.2-6 is that it directly indicates the domain of the function.

Probit function (=lognormal dose response function)
The most commonly used dose response function is the probit function (Finney, 1972). This model assumes that the relationship between the logarithmic value of the dose and mortality can be described with a cumulative normal distribution. The result is an S-shaped relationship between dose and mortality, see figure 2-17. Probits are used to model both lethal and non-lethal health effects for different substances. In (CPR, 1990) probit functions are given for the response of humans to explosions, toxic substances and heat radiation. The general expression for the probit value is:

$$\Pr = a + b\ln(c^n t) \qquad \textbf{(Eq. 2-7)}$$ [30]

Where: *a,b,n* - probit constants that are used to influence shape and position of the distribution function (see below)[-]; *c* - concentration (often expressed in [mg/m^3] for toxic substance, but e.g. [kN/m^2] for explosion pressure); *t* - exposure duration (often expressed in [min])

The mortality fraction (F_D) is found as follows:

$$F_D(\Pr) = \Phi_N\left(\frac{\Pr - \mu_D}{\sigma_D}\right) \qquad \textbf{(Eq. 2-8)}$$

Where: Φ_N– Cumulative normal distribution, *Pr* - probit value [-], $\mu_D = 5$, $\sigma_D = 1$.

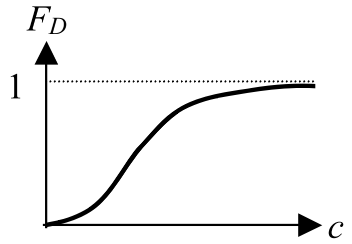

Figure 2-17: Probit or lognormal function

It can be shown that the current probit approach can also be formulated by means of the **lognormal distribution** with two constants**.** It is also interesting to note that the product of (a large number of) independent stochastic variables has a lognormal distribution. The probit represents the combined influence of different factors on mortality. For exposure to a constant concentration, the terms *c* and *t* can be separated and we find **(Eq. 2-9)**:

$$F_D(c) = \Phi_N\left(\frac{a + b\ln(c^n t) - \mu_D}{\sigma_D}\right) = \Phi_N\left(\frac{a + bn\cdot\ln(c) + b\ln(t) - \mu_D)}{\sigma_D}\right) = \Phi_N\left(\frac{\ln(c) - \frac{1}{bn}(\mu_D - a - b\ln(t))}{\sigma_D/(bn)}\right)$$

Thus, mortality can be determined as a function of the intensity of physical effects with a lognormal distribution with two constants:

$$F_D(c) = \Phi_N\left(\frac{\ln(c) - \mu_N}{\sigma_N}\right)$$

$$\mu_N = \frac{1}{bn}(\mu_D - a - b\ln t) \qquad \sigma_N = \sigma_D/(bn) \qquad \textbf{(Eq. 2-10)}$$

30 The original general expression for the probit can also be formulated as: Pr=a+b1ln(c)+ b2 ln(t); with b=b2 and n=b1/b2.

In this formulation the mortality has a normal distribution when it is plotted as a function of ln(*c*). Mortality has a lognormal distribution when it is plotted as a function of *c*([31]). The value of *a* mainly influences the horizontal position of the dose response function. The values of *b* and *n* indicate the relative importance of concentration and exposure duration and they influence the standard deviation. In practical applications values of *b* and *n* are held constant, e.g. *bn*=2 (PGS, 2003). This implies that the standard deviation of the lognormal distribution is fixed. For some typical values of *b* and *n* that are applied in practice, the corresponding lognormal distributions functions have been derived in Appendix 2.III. Equation 2-9 shows that for a given probit function (*a*,*b* and *n* known) and a known exposure duration *t*, mortality can be directly expressed as a function of the concentration with the lognormal distribution.

The existing probit approach uses two equations, which include five constants (a, b, n, μ_D and σ_D). Instead, a direct derivation of a lognormal distribution of mortality based on the available observations is more insightful. This limits the number of equations (one) and constants (two).

Fractional effective dose
The Fractional effective dose (FED) approach is used to model the individual injuries caused by smoke and heat (ISO, 2002). It is generally applied to the assessment of fire hazards for buildings. The FED values are determined by integrating sustained concentration of toxicants or heat exposure over time for an individual. As the accumulated sum of the substances exceeds a predefined threshold value of 1,0 a sufficient dose of toxic substances has been inhaled to cause incapacitation through confusion and loss of consciousness. The general expression for the FED is as follows[32]:

$$FED = \sum_{i=1}^{n} \sum_{t_1}^{t_2} c_i / (ct)_i \Delta t \qquad \textbf{(Eq. 2-11)}$$

Where: n – number of toxic gases; t_2, t_1 – boundaries of the investigated exposure duration [min]; c_i - The average concentration of an toxic gas *i*, expressed as a volume fraction [ppm]; Δt The chosen time increment [min]; $(ct)_i$ - The critical exposure dose that would prevent occupants' safe escape [ppm*min]

The above formulation shows a linear relationship between dose and FED value[33]. Application of the FED function requires the determination of a value for the critical dose $(ct)_i$. Although FED's are used to determine incapacitation[34], different studies (e.g. Persson, 2003) assume that a FED value of 1,0 corresponds to a lethal value. This seems a somewhat conservative but appropriate assumption for events for which the physical effects increase over time, for example for tunnel fires.

31 Then the mean and standard deviation of the lognormal distribution (μ_{LN} and σ_{LN}) have the following values: $\mu_{LN}=\exp(\mu_N+0{,}5\sigma_N^2)$ and $\sigma_{LN}=\mu_{LN}(\exp(\sigma_N^2)-1)^{0,5}$. The median value of the lognormal distribution (i.e. the value where mortality is 0,5) equals exp(μN). In the remainder of this thesis the format of equation 2-10 is used.

32 Note that the formula included in (ISO, 2002) includes a printing error: $FED = \Delta t \sum_{i=1}^{n} \sum_{t1}^{t2} c_i / (ct)_i \Delta t$

33 Other forms of FED's are available which take into account the non-linear relation between sustained dose and response (i.e. FED value).

34 The determination of incapacitation by means of the FED approach corresponds conceptually to the analysis of the so-called Service Limit State (SLS) as a person has temporary lost consciousness. Estimation of mortality corresponds to the Ultimate Limit State (ULS).

2.4 Combination of evacuation and mortality analysis

Finally, to estimate loss of life the analyses of evacuation and mortality have to be combined. For this combination there is the choice between the two modes static and dynamic (named sudden and non-sudden by Lentz and Rackwitz (2004a)).

Static approach
For some applications it is possible to analyse evacuation and mortality independently and as separated steps. This approach is static; people are either exposed or evacuated. In this case, the framework proposed in figure 2-4, is elaborated linearly. First, the evacuated fraction of the population is estimated. Then, the mortality amongst the exposed population is predicted by means of the dose response function. In this type of application usually a dose response function is used which uses a instantaneous or maximum intensity of physical effects as input. The static approach is especially appropriate for instantaneous events with little possibilities for evacuation, and for larger-scale events where evacuation predominantly takes place before arrival of physical effects. As an implication the presence of population during event becomes static and independent of time.

Dynamic approach
In some situations it is often difficult to treat the analysis of effects, evacuation and consequence completely independently. Then, a dynamic approach could be used, in which the spatial and temporal developments of physical effects, evacuation and the sustained injury have to be considered. For cases such as slowly rising floods or tunnel fires, people can escape/survive the danger in a certain zone at a given moment, and have to undertake another escape/survival in the next moment due to the spatial propagation of the danger zone (see also the *x,t* diagram in figure 2-9). An individual can only survive the whole event, if he/she survives each single time step. In this application, the sustained dose of physical effects over time will be relevant and it might be necessary to account for weakening of a person due to progressive exposure. For example, when a person escapes through fire, walking speed might be reduced due to limited visibility and irritation of airways. Possible reductions of movement speed due to a sustained level of injury could be accounted for.

It is possible to schematise the dynamic approach using the previously introduced x,t diagram, as is shown in figure 2-18. The concentration at a distance x from the risk source at a time t can be plotted in a three dimensional graph. In addition an escape path of an individual who moves through the area can be depicted. By integration of the exposure concentration during the escape path over time the sustained dose is obtained. By combination with a dose response function, this can be used to assess the level of injury. A further elaboration is this approach is given in appendix 2.IV.

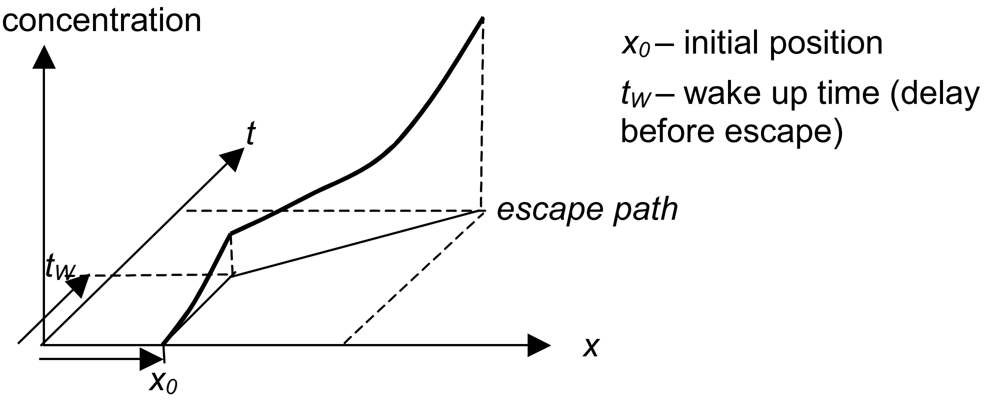

Figure 2-18: ***x,t*** **diagram indicating escape path and exposure concentration during escape**

Modelling considerations
In practice a choice between the static and dynamic approaches has to be made, depending on characteristics of the event and the situation and the preferred level of detail of analysis. For some detailed elaborations a full modelling of the exposed population over time is necessary. In such an approach the movement of people between different states (safe area, exposed area, shelter) has to be modelled by means of dynamic balancing account. In the period after the event, the extent of the exposed population will be reduced, because rescue and escape progress over time. For example for floods, it is expected that all people who were initially present in the flooded area will eventually be removed from it at some point in time. The effects of rescue and escape on loss of life have to be considered relative to the survival of people over time within the exposed area in the conditions after the disaster.

However, for many applications the initially exposed population at the time of the occurrence of the event is used in loss of life estimation, because a) a large part of loss of life occurs during or shortly after initial exposure; b) the number of escaped and rescued people during the first phase of the disaster are often relatively small relative to the exposed population. In this case the initially exposed population is found by correcting the population at risk for evacuation and people who find shelter before the event. So if no evacuation and shelter occur N_{EXP}=$N_{PAR.}$

2.5 Relationship between the number of fatalities and other consequence types

General
The risks associated with different consequence categories can be presented conceptually in a multi-dimensional graph with the probability of exceedance on the vertical axis and the consequence categories on the horizontal axes, see figure 2-19a. Because the same indicator can be used for fatalities, injuries and exposed (i.e. number of people) they can be presented in a simpler two-dimensional graph, see figure 2-19b. Such curves can provide useful information for emergency management. They show the probability of scenarios with a certain number of killed, injured and people exposed. This provides information regarding the number of people that require treatment and on required rescue and shelter capacities. It is thus interesting to investigate the relationship between the number of fatalities and the extent of other consequence types. The existence of such relationships would allow a

relatively easy estimate of the accident footprint in terms of different types of consequences (see also section 1.4.1).

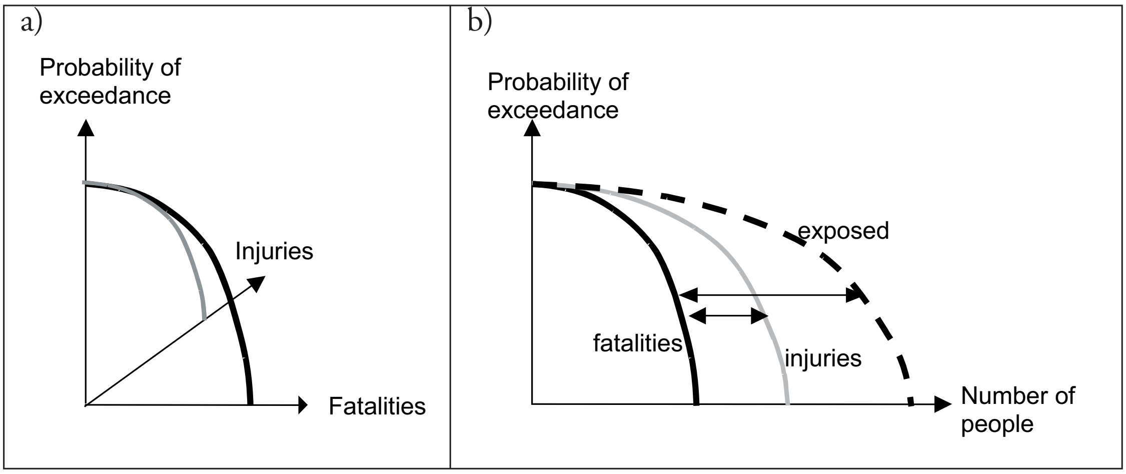

Figure 2-19: a) three dimensional display of probability of injuries and fatalities; b) FN curve in which the probability of number of injuries and exposed are also shown[35].

The **number of people exposed** is related to the number of fatalities via mortality[36]. Economic damage in an exposed area is often related to the number of people exposed and fatalities, because densely inhabited areas generally have a large economic value[37] as well.

Relationship between the number of fatalities and injuries

Another important consequence category concerns the number of injuries, although it might be difficult to give a uniform operational definition of injury. Some authors suggest that it is also appropriate to assume that a constant ratio exists between the number of fatalities and injuries per accident. For example in (SAVE, 2001; pp.52) it is mentioned that on average 1 fatality is accompanied by 10 injuries for toxic releases. In this case is it is possible to directly draw an F-injury curve on the basis of the FN curve. Below, the existence of such a constant relationship between fatalities and injuries is further investigated.

Jongejan (2006) investigated data on the number of injuries and fatalities for industrial accidents in the European Union. His analysis did not indicate a constant relationship between the number of injuries and fatalities. Instead, he found that the most industrial accidents resulted in either injuries or fatalities, see figure 2-20.

35 The same intersection with the vertical axis is assumed for all the curves. However, the curves for different consequence types can intersect at different points, e.g. because accidents can occur that lead to injuries but not to fatalities.

36 Mortality = nr. of fatalities / nr. of exposed;

37 It is noted that the effects of evacuation could reduce the number of fatalities, while economic damage remains.

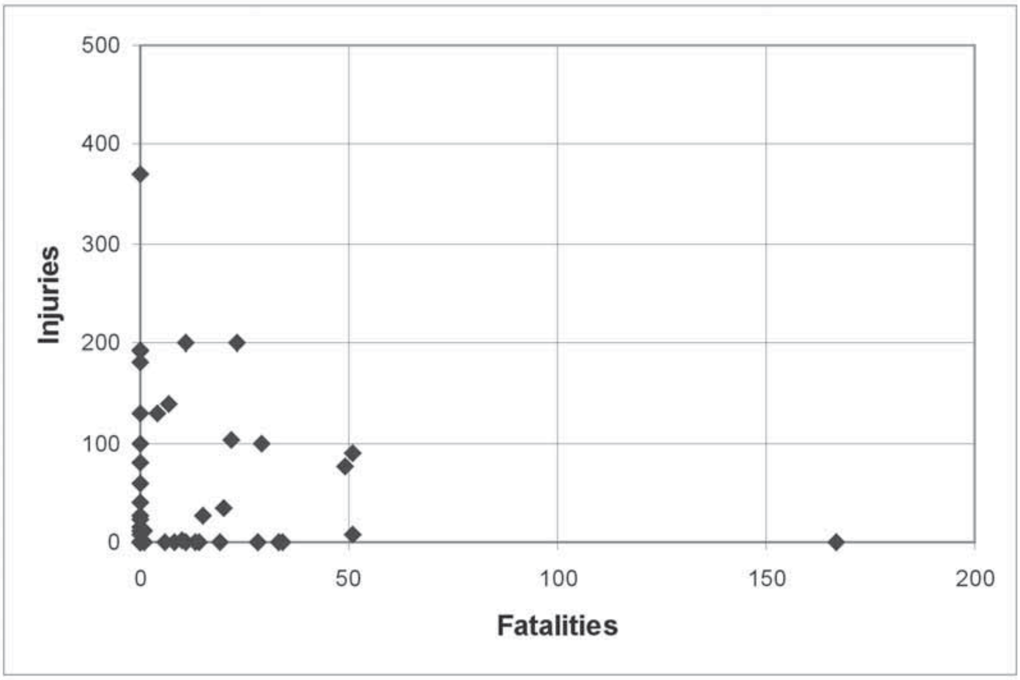

Figure 2-20: Number of injuries versus number of killed for industrial accidents in the European Union (data from EM-DAT, figure by Jongejan (2006))

The existence of a constant relationship between injuries and fatalities can also be analysed from a more theoretical point of view by comparison of dose response functions for injury and mortality. Schematically the number of people exposed during a disaster will be distributed over three categories: fatalities, injuries, and healthy people:

$$\textit{fatalities} + \textit{injuries} + \textit{healthy people} = \textit{Number of exposed} \quad \textbf{(Eq. 2-12)}$$

At every moment in time these three groups are mutually exclusive. A person killed in accident cannot become an injured or healthy person. We assume a mortality ratio F_D and an injury ratio in the surviving population F_I. When determining the injuries as a fraction of the original population, the fraction of the population that has already been killed has to be taken into account. If equation 2-12 is divided by the exposed population, the following expression is obtained:

$$\begin{array}{llll} \textit{fatalities} + & \textit{injuries} & + \textit{healty people} & = N_{EXP} \\ F_D & + F_I(1-F_D) & + (1-F_D)(1-F_I) & = 1 \end{array} \quad \textbf{(Eq. 2-13)}$$

The second term in the equation is indicated as the corrected injury ratio (F_I*) and it indicates the fraction of the original population that is injured, so that $F_I^* = F_I(1-F_D)$. The ratio between the number of fatalities and injuries can be expressed as follows:

$$\frac{N}{N_I} = \frac{F_D N_{EXP}}{F_I^* N_{EXP}} = \frac{F_D}{F_I(1-F_D)} \quad \textbf{(Eq. 2-14)}$$

With this equation the ratio between the number of fatalities and injuries can be examined using typical formats for dose response functions for mortality and injury. Available literature (PGS, 2003) suggests that the occurrence of mortality and injury[38] can both be modelled by a probit function. The probit for injury is then generally shifted horizontally

38 In literature few dose response functions are given for injury.

relative to the mortality probit, by varying the value of parameter *a*, while keeping the values of *b* and *n* identical (see also section 2.3.4). The ratio between the number of fatalities and injuries is considered as a function of the exposure dose, assuming exposure of the population to one deterministic dose. For two hypothetical probit functions the resulting value of the ratio between fatalities and injuries is plotted in figure 2-21.

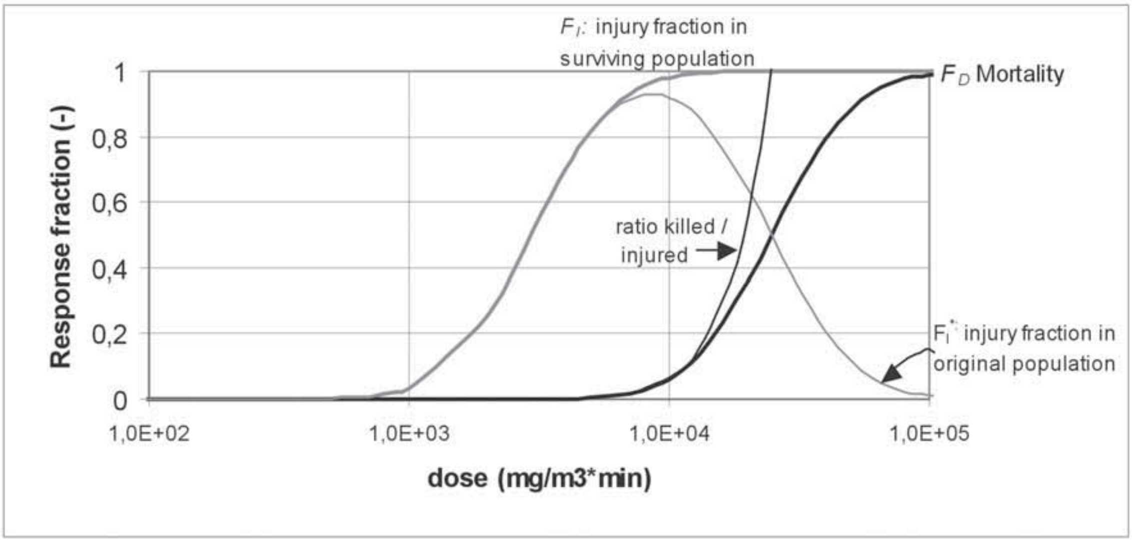

Figure 2-21: Mortality and injury fractions, and ratio between the number of fatalities (Hypothetical probits used: injury: *a* =-8,5; *b*=1,69; *n*=1; mortality *a*=-12,1; *b* = 1,69; *n*=1)

For these conditions it is shown that the ratio between the number of fatalities and injuries will not be constant for different exposure doses. With equation 2-14 it can also be shown that the ratio between fatalities and injuries will not be constant for other types of dose response functions that are shifted horizontally, such as linear or quadratic functions.

Figure 2-21 shows that the ratio between fatalities and injuries is a function of the dose of physical effects. It equals 0 at some interval and than quickly rises to infinity. This can be interpreted as follows: there are either fatalities or injuries, because the interval where they occur both is relatively small. The magnitude of the exposure dose determines whether fatalities or injuries occur. It is interesting that practical observations from industrial accidents from figure 2-20 confirm the theoretical findings.

A constant relationship between fatalities and injuries is only expected when the intensity of physical effects is the same for each accident, i.e. every accident leads to the same release[39]. However, the concentration to which people are exposed will generally differ between accidents. In addition, the spatial distributions of population density and exposure concentration affect the consequences. Overall, neither empirical data nor the analysis of dose response functions support the existence of a constant ratio between fatalities and injuries.

39 This corresponds to a Bernoulli distribution for the initial release, see also section 4.3.

2.6 Economic valuation of loss of life

As a first step in the evaluation of the risk it is important to know the (potential) number of fatalities. After that it is possible to give an economic valuation of loss of life. In literature on risk management the economic valuation of human life is often depicted as a difficult problem as it raises numerous moral questions. Some claim it is unethical to put a price on human life because life is priceless. The actual expenditures on risk reducing prospects show however that the investment in the reduction of risks to humans is always finite. Based on earlier work (Jongejan *et al.*, 2005a) this section presents an overview and discussion of methods for the economic valuation of loss of life. Two types of methods can be distinguished 1) behavioural valuation; 2) valuation based on macro-economic indicators. These approaches are described in the first two sections. Consequently a discussion of the methods is provided.

2.6.1 Behavioural valuation

Human life can be valued based on either stated or revealed preferences concerning the expenditures on risk reduction.

Stated preferences can be obtained from contingent valuation surveys. This method is used in economics to value facilities, services or other benefits for which prices cannot be obtained from the market. A survey can reveal how much people are willing to pay, e.g. for safety measures. Such a study makes it possible to calculate the Value of a Statistical Life (VoSL) by comparing the willingness to pay (WTP) for certain measures and the resulting reduction of the expected number of fatalities ($\Delta E(N)$)[40]:

$$VoSL = \frac{\sum_{i=1}^{R} WTP_i}{R \cdot \Delta E(N)} \qquad \textbf{(Eq. 2-15)}$$

Where: R – number of respondents [-]; WTP_i – willingness to pay for respondent i [€/yr]

Pidgeon and Hopkins (2000) give an example of contingent valuation for traffic safety. However, in this study no relationship between the WTP and the expected number of fatalities could be found.

Revealed preferences are obtained by an a-posteriori evaluation of expenditures related to risk reduction. These methods are based on the assumption that economic behaviour reflects the values implicitly assigned to intangibles. For instance, compensating wage differentials for more dangerous professions could be assumed to reflect people's willingness to accept (WTA) certain occupational risks.

Investments in safety measures can be related to their resulting reduction of potential loss of life, by expressing the cost of saving an extra statistical life (CSX) (see also Vrijling and van Gelder, 2000):

40 Instead of the change in the expected number of fatalities, also the change in the expected number of life years lost can be taken into account. Then, the value of a statistical life year (VoSLY) is calculated.

$$CSX = I / \Delta E(N)$$ **(Eq. 2-16)**

Where: I – investments in safety measures, expressed here per year [€/yr]
The cost of saving an extra life year (CSXY) can be determined by involving the life expectancy. For large exposed populations[41] the expected number of fatalities can be converted to a number of life years, by multiplication with the average life expectancy of the average population.

Tengs *et al.* (1995) performed an extensive study of CSXY values in various sectors. This study showed that CSXY values vary widely across and within different sectors. As regards the use of CSX / CSXY values, it should be noted that the benefits of measures not only consist of saving human lives, but also of the prevention of damage in other fields (economics, environment). A better approach would be to look at societal decisions where the only benefit is an increase in human safety, thus a decrease of the probability of loss of life. Decisions in the field of public health can be of such nature. The effectiveness of medical treatments or precautions is often represented with Quality Adjusted Life Years (QALY's) and Disability Adjusted Life Years (DALY's) (Hofstetter and Hammit, 2001). One QALY is the increase of the life expectancy with a year of optimal quality. DALY's measure the lost life years and years lived with disability compared to a hypothetical life quality profile.

2.6.2 Macro-economic valuation

The valuation of loss of human life can be based on macro-economic indicators. According to the human capital approach, life is valued in proportion to a person's potential economic production. Van Manen and Vrijling (1996) proposed a method of valuation according to the Nett National Product per capita. For the Netherlands they estimate a value of a statistical life of approximately 500.000 Euros. Ramsberg (2000) argues that a person's contribution to the national economy should be calculated by discounting the production minus consumption over the years the person had lived if he hadn't died. The result is a lower economic value of loss of life. Application of these macro-economic valuation methods implies that the value of human life depends on a nation's wealth. This may seem unethical, but the advantage is that risk reduction measures are affordable in the context of the national economy.

A disadvantage of macro-economic valuation is that people are only seen as production factors and that life quality is not valued. A method that links life quality to macro-economic indicators is the Life Quality Index (LQI) approach (Pandey and Nathwani, 2004). The LQI is a social indicator for life quality. The method can be used to evaluate risk reduction initiatives that would improve safety and quality of life. The LQI method can be applied to quantify the societal willingness to pay, which is an acceptable level of public investment for an increase of life expectancy. For developed countries the value of a statistical life according to the LQI would be between 1 and 4 million euros depending on the adopted discount rate (Pandey and Nathwani, 2003).

41 For a large exposed population and accidents with multiple fatalities it is reasonable to assume that the fatalities have the characteristics of the average population.

2.6.3 Discussion of methods for the valuation of loss of life

Different methods can be used to give an estimate for the value of human life. Table 2-4 gives an overview of typical ranges of estimates for the economic value of a statistical life for developed countries.

Table 2-4: Value of a statistical life according to different valuation methods (Jongejan *et al.*, 2005a)

Valuation method		Approximate value of a statistical life (million Euro)
Behavioural valuation	Stated preference (WTP)	Not available
	Revealed preference (CSX)	0 - 10^{10}
Macro-economic valuation	Macro-economic valuation	0,5
	Life Quality index	1-4

The values according to macro-economic valuation will be relatively stable as they depend on macro-economic indicators. The value of human life based on macro-economic valuation can be used as input for the cost benefit analysis and economic optimisation (Vrijling and Van Gelder, 2000). The value of loss of life is added to other damage types such as direct economic damage. Neglecting the economic value of loss of human life in the economic optimisation will lead to lower expected damages and thus to a lower optimal safety level.

The values obtained by means of behavioural valuation will depend on contextual factors related to the activity, such as the risk perception. Especially the CSX values vary widely across and within different sectors. Vrijling and van Gelder (2000) show how the determination of CSX can be linked to the economic optimisation[42]. They derive the following expression for CSX:

$$CSX = \frac{I}{(p_{f,0} - p_{f,opt})N \cdot PV} \qquad \text{(Eq. 2-17)}$$

Where: $p_{f,0}$ – initial failure probability [1/yr]; $p_{f,opt}$ – optimal failure probability following from economic optimisation [1/yr]; N – number of fatalities in case of failure; PV – present value factor [-]

The above equation shows that the CSX value strongly depends on the initial risk level, represented by $p_{f,0}$. It is also expected that the initial risk level will be related to the perception of the activity. Activities for which the risks are perceived as dreadful, e.g. nuclear accidents, are expected to have a low initial risk level. Measures in such a sector are expected to result in a high CSX value. Activities that are perceived as less dreadful, e.g. traffic accidents, will have a higher initial risk level. Then safety can be improved at relatively low cost. Therefore it is expected that at least part of the variation in CSX values between sectors can be explained by relating them to the initial safety level of the system and the risk perception of the activity, see figure 2-22 and also (Bohnenblust and Slovic, 1998). The perception of the severity activity can be characterised by a so-called policy factor β, see (Vrijling *et al.*, 1995) and section 9.5.1 for further details. Some bandwidth in the observed CSX values will probably remain, due to differences in the effectiveness of measures

42 Vrijling and van Gelder (2000) also show that the CSX value is not equal to the macro-economic valuation of loss of life.

implemented in the past[43]. Future research on the above relationship is recommended, in order to evaluate whether typical ranges of CSX values can be found for different activities based on their risk perception characteristics and initial risk level.

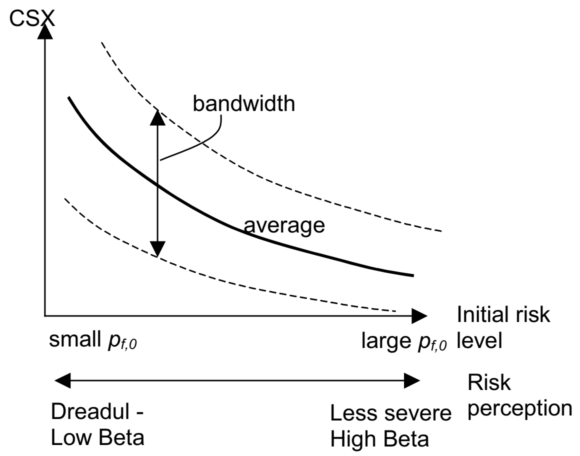

Figure 2-22: Relationship between CSX and risk perception expressed by the policy factor β.

The cost effectiveness of measures can be specifically related to the reduction of loss of life with the CSX. Given the dependence on initial safety level and risk perception, the CSX does not seem suitable to compare the effectiveness of measures between different sectors. However, it seems to be a useful measure to assess the cost effectiveness of measures within one domain. For a certain project, the CSX values for alternative measures can be determined to provide insights for decision-making regarding the effectiveness of measures that reduce loss of life.

2.7 Concluding remarks

Based on the observation that the existing approaches for loss of life estimation in different fields include similar elements, a general approach for loss of life estimation is proposed. It can be used for various applications and provides a general basis for efficient and standardised consequence estimation for different fields. The methodology takes into account the intensity of physical effects, the reduction of the number of people exposed due to evacuation, shelter and rescue and the estimation of mortality amongst those exposed. The method can be applied to small probability – large consequence events within the engineering domain, particularly to types of event that are characterised by dispersion of harmful physical effects and some possibilities for evacuation or escape.

The general characteristics of evacuation have been discussed. Evacuation is possible when there is sufficient time before the initiation of the event and / or when physical effects are dispersed slowly. These insights can be used to develop effective emergency strategies for different types of events, for example by means of evacuation and shelter plans.

Dose response functions are used in different fields to relate mortality in the exposed population to the intensity of physical effects. A dose response function generally indicates the distribution of resistances over the population. The use of a discrete dose response

43 An important assumption when using the observed CSX values for future decision-making is that the risk level obtained after measures in the past represents an acceptable level of risk.

function (or threshold value) in consequence or risk estimates can lead to an over- or under estimation of consequence and risk levels. One often-used type of dose response function is the probit function, which is equivalent to a lognormal distribution. The existing probit approach uses two equations, which include five constants. It has been discussed that a direct derivation of a lognormal distribution for the dose response function based on the available observations could be more insightful, as this limits the number of equations (one) and constants (two).

In order to achieve more realistic consequence estimations a further empirical foundation of loss of life models based on past accidents is important. Recording and storage of data on loss of life and evacuation and the use of this information in validation of the existing methods is recommended. Estimation of loss of life often requires a multi-disciplinary approach, which expands outside the traditional engineering domain. For example, knowledge from toxicology is needed to establish dose response functions. Study of evacuation requires insight in psychological issues regarding human reaction to disasters. Further co-operation between such involved disciplines is encouraged in order to improve the analysis and estimation of loss of life.

This section mainly dealt with the estimation of loss of life for one single event. The next section will demonstrate how the approach can be integrated in risk quantification. Uncertainties in loss of life and risk estimates are discussed further in section 4.

3 A general approach for the quantification of individual and societal risk

Research question: How can the general approach for loss of life estimation be applied to risk quantification?

Keywords: Quantitative risk analysis, individual risk, societal risk, risk measures

3.1 Introduction

Within a quantitative risk analysis (QRA) the risks for a given system are quantified as a basis for risk evaluation and decision-making. In different sectors, e.g. the chemical and aerospace sector, there is substantial experience with QRA, see e.g. (Bedford and Cooke, 2002). To indicate the risks to people, the outcomes of the QRA are generally expressed by means of the measures individual and societal risk. Individual risk is concerned with the probability that an individual (at a certain location) gets killed, whereas societal risk is concerned with the probability of a multi-fatality accident. Definitions are described in more detail in section 3.2.

Given the variety of factors involved and the complexity of underlying processes, quantitative risk analyses (QRA's) mainly rely on numerical risk calculation models. However, these models provide limited insight in the underlying schematisations and the consistency of the outcomes. This section proposes general analytical formulations that can be used to quantify individual and societal risk. The novelty of this approach is that existing elements are combined in one coherent and broadly applicable framework. As such it will strengthen the foundation of methods for risk quantification. The proposed approach gives insight in the factors that determine individual and societal risk and it will allow the improvement of the consistency of risk analyses. It also offers the possibility to clarify the relationship between individual and societal risk.

The general approach can be used for different existing domains and it will also allow a relatively easy application of QRA to new terrains. It is mainly applicable to situations in which most fatalities occur directly due to exposure to the physical effects of an accident. In these cases mortality can be estimated with a dose response function. The approach is most suitable for large-scale disasters that expose larger areas with many people exposed and multiple (potential) fatalities. The formulations can be used for events characterised by dispersion of physical effects (e.g. a toxic gas plume) from a risk source and / or for events characterized by a spatially variable accident locations (e.g. airplane crashes). Approaches discussed in this section are thereby most applicable to small probability – large consequence accidents in the engineering domain, such as floods, chemical accidents and airplane crashes (see also section 1.4.2 regarding the scope of this thesis). The elaborations in this section mainly focus on risk quantification, although some aspects related to risk evaluation (e.g. risk limits) are briefly discussed.

Section 3.2 gives an overview of definitions for individual and societal risk. In section 3.3 general formulations for risk quantification are derived based on reliability theory. Section 3.4 explores the relationship between individual and societal risk. Section 3.5 shows how specific elements (evacuation, spatially distributed risk sources, and meteorological conditions) can be incorporated in the general formulations. To illustrate the application of the general formulations several schematised but indicative examples are presented in section 3.6. Concluding remarks are given in section 3.7.

3.2 Definitions of individual and societal risk

A risk measure is defined as an expression or graph which quantifies or depicts risk as a mathematical function of the probabilities and consequences of a set of undesired events (see section 1). Different risk measures have been proposed in literature that deal with various consequence types, see Jonkman *et al.* (2003) for an overview. Given the scope of this thesis, risk measures related to loss of (human) life are further elaborated. These are generally expressed as individual or societal risk.

Individual risk

The individual risk is used to indicate the distribution of the risk over the various individuals in the population at risk. Ichem (1985) defines the individual risk as "the frequency at which an individual may be expected to sustain a given level of harm". In the external safety domain[1] in the Netherlands it is defined as "the probability that an average unprotected person, permanently present at a certain location, is killed due to an accident resulting from a hazardous activity"[2] (Bottelberghs, 2000). Due to the assumption of permanent presence, the individual risk becomes a property of a location[3] and as such it may be useful in land use planning. Following this above definition the individual risk can be shown on a map with so-called (iso-) risk contours.

In order to determine the risk to an actual person, other definitions consider whether or not the individual is actually present (see e.g. TAW, 1985; Bohnenblust, 1998). In these cases the individual risk can still be displayed as a function of a location by correcting for the (probability of the) actual presence of persons at that location. Presence of the population can be influenced by time of the day and / or be reduced by means of evacuation, as will be discussed further below. For some applications, for example for the estimation of risks for passengers in tunnels, the individual risk becomes a characteristic of a specified user, and it is often indicated as personal risk. Covello and Merkhoffer (1993) mention some alternative definitions for individual risk. Examples are the maximal individual risk, expressing the highest risk to the (hypothetical) person in an exposed population, and the average individual risk in a population. Bedford and Cooke (2002) give an overview of other measurements to express individual risk, such as the fatal accident failure rate (FAFR) and the activity specific hourly mortality rate.

1 The external safety domain is concerned with (the risks) of transport and storage of dangerous goods, and airport safety in the Netherlands.

2 Following the definition of Ichem (1985), the probability is expressed with a frequency: [yr-1]

3 It is than often labeled "local" risk.

Societal risk

Ichem (1985) defines societal risk as "the relationship between frequency and the number of people suffering from a specified level of harm in a given population from the realization of specified hazards". Often a more narrow definition is used, and societal risk is expressed as the probability of exceedance (in one year) of a certain number of fatalities due to one event in a given population. Then, societal risk can be depicted in the FN curve, which shows the probability of exceedance of a certain number of fatalities on a double logarithmic scale. Various other measures are used as well to express societal risk, for example the expected number of fatalities. These are discussed in more detail in section 3.3.3.

3.3 General formulations for the quantification of individual and societal risk

3.3.1 Elements in quantitative risk analysis

In a quantitative risk analysis the probabilities and consequences of a set of defined critical events are determined as a basis for risk evaluation. More specific, the following general elements can be distinguished within risk quantification.

1. **Determination of the probability of occurrence of a critical event and the intensity of released physical effects:** The occurrence of a critical event at the risk source[4] will lead to failure of the system and a consequent release of physical effects. The probability of failure is indicated by p_f, which is generally considered for a period of one year. Following failure, certain initial physical effects with intensity[5] (c_0) will be released at the risk source. The intensity of such effects can, for example, be expressed as the heat release rate of a fire, explosion pressure, or the inflow discharge of water through a breach. The conditional pdf of the intensity of initial effects given failure is denoted as $f_{C0|f}(c_0)$. One (deterministic) initial release is generally indicated as a scenario. The (non-conditional) pdf of the intensity of initial effects in one year $f_{C0}(c_0)$.may be obtained as follows if p_f is small (see figure 3-1a for a sketch of the pdf):

$$\begin{aligned} f_{C0}(c_0) &= 1 - p_f & c_0 &= 0 \\ f_{C0}(c_0) &= p_f f_{C0|f}(c_0) & c_0 &> 0 \end{aligned} \qquad \textbf{(Eq. 3-1)}$$

2. **Assessment of the dispersion of physical effects:** Spatial and temporal dispersion of effects can be assessed with a dispersion model. The dispersion pattern depends on the substance properties, local topography, and climatic conditions, etc.. The intensity of physical effects *c* at location (x,y) depends on the intensity of the initial release and the dispersion model and it is indicated as: $c(c_0,x,y)$. The intensity of effects generally decreases with the distance to the risk source, see figure 3-1b.
3. **Determination of the number of people exposed (N_{EXP}):** This is determined based on the extent of the area exposed to physical effects (*A*) and the population density *m(x,y)* in that area. If relevant, the effects of evacuation and shelter could be taken into account.

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4 In the general formulations one risk source at a fixed location is assumed. Spatially distributed risk sources and corresponding spatially variable failure probabilities are treated in section 3.5.

5 The intensity of physical effects could refer to a (instantaneous) concentration of physical effects or to a dose of effects sustained over a certain time.

4. **Estimation of mortality and loss of life amongst the exposed population.** Mortality depends on the local intensity of physical effects. It can be estimated by means of a dose response function $F_D(c)$, which gives a relationship between the intensity of physical effects and the mortality in the exposed population (see figure 3-1c). By combining it with the number of people exposed the actual number of fatalities can be estimated.

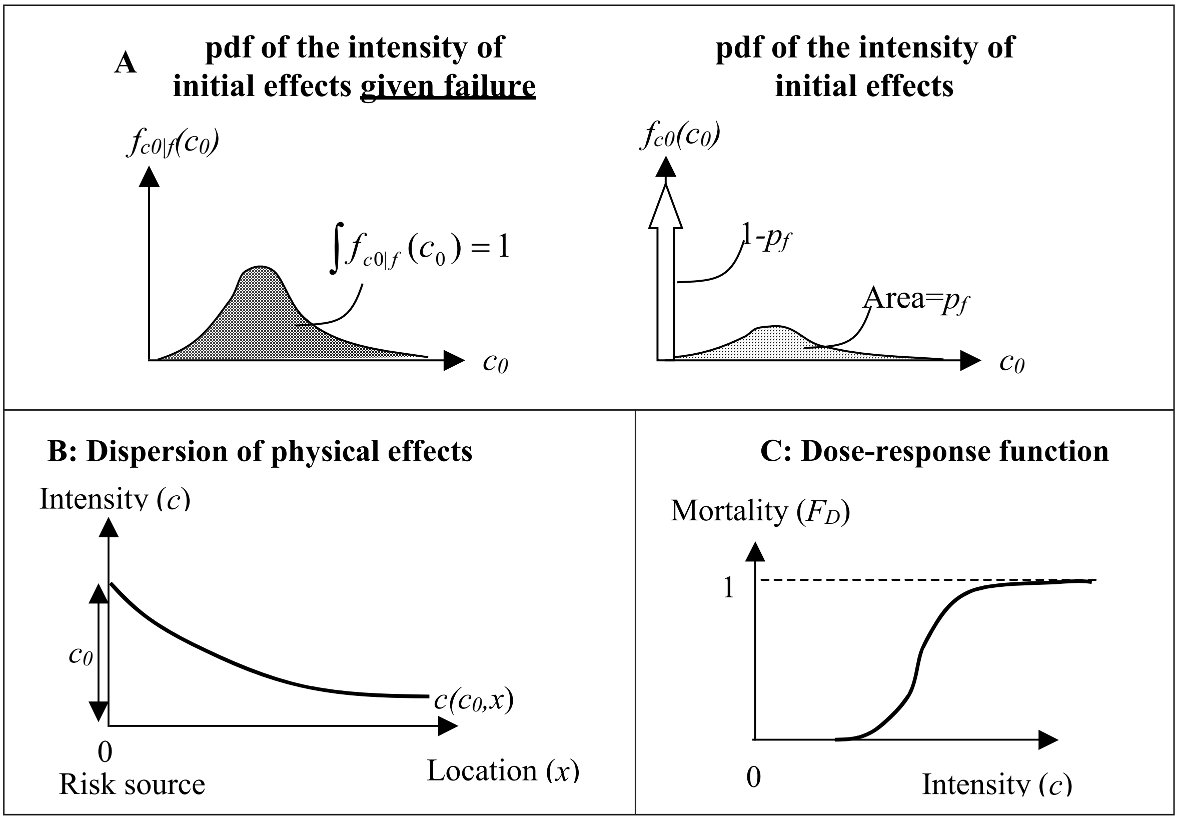


Figure 3-1: Schematic presentation of a) pdf of intensity of initial effects b) dispersion of physical effects c) dose response function.

It is noted that the four elements overlap above with the general elements needed for loss of life estimation (see section 2). Here, the first step has been added to allow quantification of the probability of a critical event. These four elements are also useful to analyse risk reduction measures in a systematic way. One can try to reduce the probability of occurrence of effects, limit the dispersion of effects, or reduce consequences by decreasing the number of people exposed (e.g. with evacuation) and mortality amongst those exposed (e.g. by building protective facilities).

Assumptions
In the consequent elaboration general formulations for the above elements are adopted.
It is assumed in this section that the dose response and dispersion functions give a **deterministic outcome**. For example, this implies that the dose response function results in one deterministic mortality fraction for every exposure intensity. Possible uncertainties in loss of life estimates, e.g. due to model uncertainties in the dose response function, are not further treated in this section, but elaborated in section 4.

The formulations in this section are developed for events with a small probability of occurrence, so the value of p_f is small. It is also assumed that the pdf of the intensity of the initial release $f_{C0|f}(c_0)$ and the dose response function $F_D(c)$ are continuous and differentiable functions. In many applications of QRA the whole spectrum of possible initial releases is split into a limited number of discrete failure scenarios, or exemplified discrete failures. In this case a multinomial distribution is obtained, e.g. different fire heat release rates (small, medium and large) or flood scenarios with corresponding probabilities of occurrence.

As a result of the above assumptions concerning continuous functions, the analysed risk measures, such as individual risk and the FN curve, are also presented as continuous functions in this section. However, in practice the FN curve will only exist for whole numbers of fatalities.

3.3.2 General approach for risk quantification

General formulations for risk quantification can be obtained based on reliability theory. Expressions for individual and societal risk can be derived from the classical load – resistance paradigm. The probability of death can be derived using the limit state function *Z* in its standardized form:

$$Z = R - S \qquad \text{(Eq. 3-2)}$$

Here, *R* is the resistance and *S* the load (or solicitation). In the applications considered here the load consists of physical effects to which people are exposed and the resistance concerns the human resistance. The limit state function can be reformulated as:

$$Z = c_R - c_S \qquad \text{(Eq. 3-3)}$$

In this equation c_S represents the (random) load on human beings and it consists of the intensity of physical effects. The critical intensity at which human failure or death occurs equals c_R. The distribution of human resistance is represented by the dose response function, leading to the general formulation of the dose response function:

$$F_D(c) = P(c_R < c) \qquad \text{(Eq. 3-4)}$$

The probability density function of mortality is obtained by combining the pdf of physical effects and the dose response function, see figure 3-2. The area under the pdf of mortality signifies P(*R* < *S*) = P(*Z*<0), and gives the probability of death. This concept forms the basis for further determination of the general expressions for individual and societal risk.

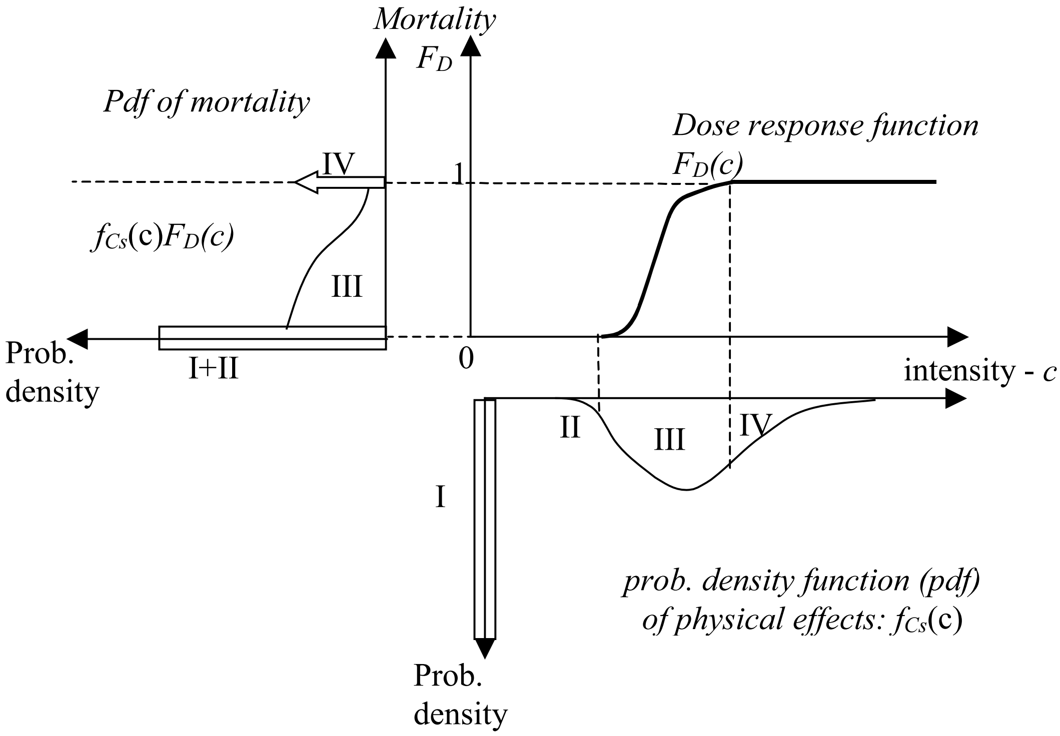


Figure 3-2: Combination of load (*S* – pdf of physical effects c) and resistance (*R* – in this case the dose response function $F_D(c)$) to obtain the pdf of mortality. Note that: 1) the pdf of mortality can also be found by combining (1-$F_C(c)$) and $f_D(c)$ 2) Regions I to IV indicate specific areas of probability density[6].

To elaborate the limit state function (equation 3-2) it is necessary to obtain a load and resistance term. The four general elements can be combined in two different ways (see figure 3-3), which lead to the same results. Firstly, for some applications it might be insightful to obtain a probability density function for exposure of location (x,y) to intensity *c,* i.e. $f_c(c,x,y)$. In this case, the pdf of the intensity of initial effects and the dispersion model are combined. This first approach is discussed in appendix 3.I but not further elaborated in this section.

A second approach is used in this study and it combines the dispersion model and dose response function by substitution. The resulting expression gives the probability of death at location (x,y) for a certain initial release (c_0):

$$F_D(c) = F_D^*(c_0, x, y) \qquad for \quad c(c_0, x, y) \tag{Eq. 3-5}$$

This expression is indicated as the combined dose response function and it can be used as the distribution for the resistance term in equation 3-3. The pdf of the intensity of initial effects $f_{C0}(c_0)$ is used as the load term. This approach has the advantage that the initial release term remains intact, and it forms the basis for further elaboration of individual and societal risk below. For the assessment of societal risk the actual presence of people (represented by the population density) is taken into account.

6 Region I: $f_{Cs}(c)$ has a peak c=0, signifying the density of no failure and no physical effects; II: probability density corresponding to intensities where no mortality occurs; III: probability density corresponding to an intensity c with $0<F_D(c)<1$; IV: probability density corresponding to an intensity where $F_D(c)=1$.

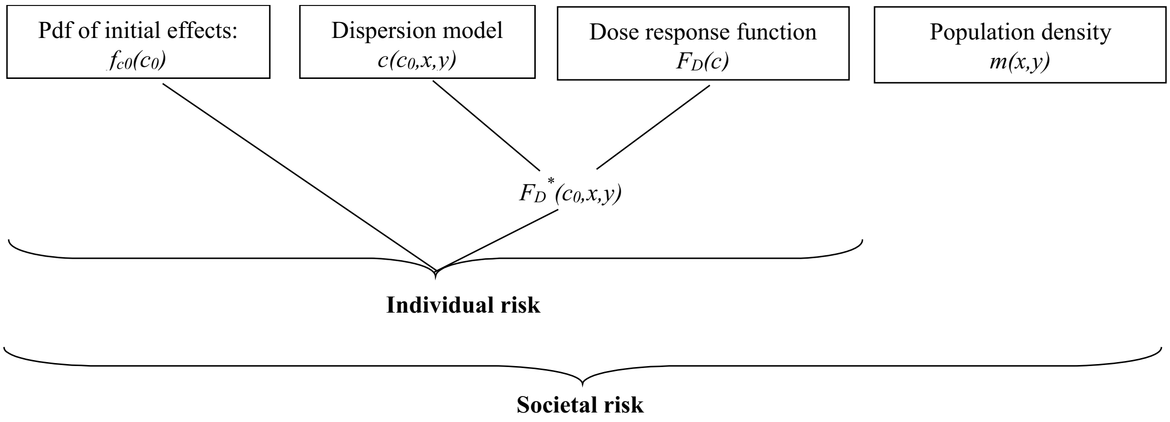


Figure 3-3: Schematic view of determination of individual and societal risk.

3.3.3 Determination of individual and societal risk

In this section it is shown how individual and societal risk can be determined analytically.

Individual risk

Individual risk gives the probability of death at location (x,y) in one year and it can be found based on the limit state function derived above. Following assumptions stated in section 3.3.1, the IR is calculated for an individual permanently present. The probability of "failure of the individual" (i.e. death) at location (x,y) is found by integrating all initial releases that can expose the location:

$$IR(x,y) = P(Z(x,y) < 0) = \int_0^\infty f_{C0}(c_0) F_D^*(c_0,x,y)\,dc_0 = \int_0^\infty p_f f_{C0|f}(c_0) F_D^*(c_0,x,y)\,dc_0 \qquad \textbf{(Eq. 3-6)}$$

Calculation of individual risk basically involves the multiplication of the probability of failure and the mortality given failure. As the mortality fraction is never larger than 1, it is therefore logical that individual risk can never become larger than the probability of failure of a system.

Societal risk

The number of people exposed (N_{EXP})[7] to a certain accident can be found by integrating the population density over the exposed area A:

$$N_{EXP} = \iint_A m(x,y)\,dxdy \qquad \textbf{(Eq. 3-7)}$$

The number of fatalities N will be a certain function of the initial release (c_0). It can be found by combining the dose response function, the dispersion model and the number of people exposed. Thus, the number of fatalities for one initial release (scenario) yields:

$$N = g(c_0) = \iint_A F_D^*(c_0,x,y)\,m(x,y)\,dxdy \qquad \textbf{(Eq. 3-8)}$$

7 We assume that all people living in the area are actually exposed, thus *NEXP=NPAR* (see also section 2). The effects of evacuation are not accounted for here. It is shown in section 3.5.2 how these can be incorporated in risk quantification.

Derivation of the probability density function and the expected number of fatalities
Most of the existing risk measures of societal risk are based on (moments of) the probability density function of the number of fatalities in one year (Jonkman *et al.*, 2003; Vrijling and van Gelder, 1997).

The pdf of the number of fatalities $f_N(n)$ can be obtained from the pdf of initial effects by using the Jacobian, see also (CUR, 1997). If a relationship exists between variables *u* and *v*, the Jacobian can be used to derive the pdf of variable *v* from the pdf of variable *u*. Suppose that variable *v* is a function *h* of variable *u*, so that $v = h(u)$ and $u=h^{-1}(v)$, see also figure 3-4.

$$f_V(v) = f_U(u)\frac{du}{dv} = f_U\left(h^{-1}(v)\right)\frac{d\left(h^{-1}(v)\right)}{dv} \qquad \textbf{(Eq. 3-9)}$$

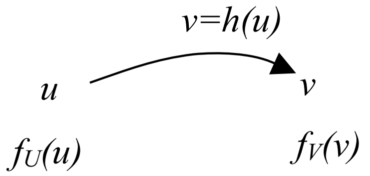


Figure 3-4: Schematic presentation of derivation of the pdf of *v* from the pdf of *u*

Equation 3-9 can be used to derive the pdf of the number of fatalities. The functional relationship between initial effects and the number of fatalities is given by equation 3-8 ($n=g(c_0)$). As a result, the following expression is obtained:

$$f_N(n) = f_{C0}(c_0)\frac{dc_0}{dn} = f_{C0}\left(g^{-1}(n)\right)\frac{d\left(g^{-1}(n)\right)}{dn} \qquad \textbf{(Eq. 3-10)}$$

The distribution function[8] of the number of fatalities is obtained by integration:

$$F_N(n) = \int_0^n f_N(n)dn = \int_0^{g^{-1}(n)} f_{C0}(c_0)dc_0 \qquad \textbf{(Eq. 3-11)}$$

Societal risk is often expressed in an FN curve, showing the probability of exceedance in one year of a certain number of fatalities, so $1\text{-}F_N(n)$. The FN curve is thus a way of presenting the complement of the distribution curve of the number of fatalities[9]. The various criticisms concerning the FN curve (see e.g. Evans and Verlander, 1997; Bedford, 2005) can therefore only refer to the application of FN limit lines to risk evaluation and decision-making. The above elaboration shows that the FN curve can be derived analytically from the pdf of initial physical effects and that it can be modelled as a continuous function. Societal risk can also be expressed with the first moment of the pdf of fatalities, the expected number of fatalities ($E(N)$):

8 Note that a different convention can be found in other published works, in which the symbol F signifies the probability of "x or more" fatalities per year, so the CCDF.

9 The probability in the FN curve is generally expressed as a probability per unit time, i.e. as a frequency (per year). For values much smaller than 1 probability and frequency can be used interchangeably. However, for accidents that occur frequently (more than once per year), the curve displaying the frequency of N or more fatalities cannot be directly related to the distribution function of the number of fatalities any more.

$$E(N) = \int_0^{\infty} f_N(n) n dn \qquad \textbf{(Eq. 3-12)}$$

In literature Potential Loss of Life (PLL) is often used as a synonym for expected value of the number of fatalities. Vrijling and van Gelder (1997) prove mathematically that the expected value of societal risk can also be found by integrating the area under the FN curve and this is also discussed by (Ale *et al.*, 1996a). Other statistical moments of this probability density function, such as the standard deviation of the number of fatalities, are used in other risk measures.

Derivation of the distribution of the number of fatalities given failure

For some purposes, for example decisions regarding emergency capacity, it might be interesting to have information regarding the likelihood of a certain number of fatalities in the case of an accident. The above approach also allows the derivation of the conditional pdf of the number of fatalities given failure $f_{N|f}(n)$:

$$f_{N|f}(n) = f_{C0|f}(c_0)\frac{dc_0}{dn} = f_{C0|f}\left(g^{-1}(n)\right)\frac{d\left(g^{-1}(n)\right)}{dn} \qquad \textbf{(Eq. 3-13)}$$

Comparison of previous equations (3-13, 3-10 and 3-1) shows that the transition from the conditional pdf of fatalities given failure to the non-conditional pdf corresponds to multiplication by the failure probability p_f (for c_0>0 and n>0). In the FN curve this can be shown as a vertical transition by a factor p_f, as will be shown in the example in section 3.6.1. Consequently, also the expected number of fatalities given failure can be determined. Different types of distributions that can be used to model the number of fatalities given failure are discussed in more detail in section 4.6.

3.3.4 Other measures of societal risk

Several authors have proposed alternative measures of societal risk. Many of these give more weight to large accidents with many fatalities to account for societal risk aversion. Most of these measures can be (re)formulated as an "expected disutility criterion" (Jonkman *et al.*, 2003) or an "α-disutility function" (Bedford, 2005), with the following general expression:

$$U = \int_0^{\infty} C n^{\alpha} f_N(n) dn \qquad \textbf{(Eq. 3-14)}$$

Where: U – Disutility; C - constant [-]; α- risk aversion coefficient [-]

The value of α expresses the disutility of experiencing n fatalities. A situation where α=1 is called risk neutral and (if C=1) the above equation gives the expected number of fatalities. Risk aversion can be modelled by weighing the number of fatalities with α>1 (see figure 3-5). Table 3-1 summarizes the risk measures proposed by different authors and these are reformulated using the above general expression.

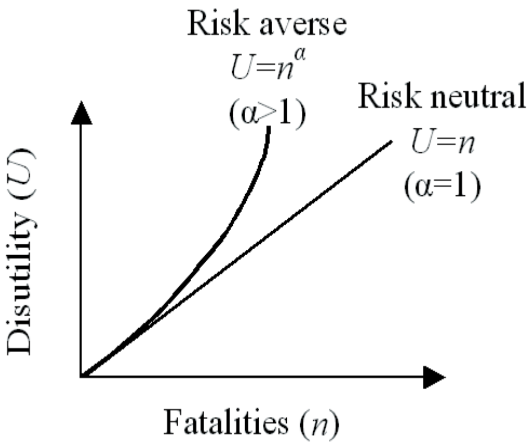


Figure 3-5: Conceptual presentation of disutility and risk aversion

Table 3-1: Summary of some proposed measures of societal risk

name / reference	Expression	α	C
Risk integral (Carter and Hirst, 2000)	$RI = \int_0^\infty n(1-F_N(n))dn$	2	0.5
RI_{COMAH} (HSE) (Carter, 2002)	$RI_{COMAH} = \int_0^\infty n^\alpha f_N(n)dn$	≥1	1
Smets (Stallen *et al.*, 1996)	$\int_1^{1000} n^\alpha f_N(n)dn$	1-2	1
Bohnenblust (1998) Bohnenblust and Slovic (1998)	$R_P = \int_0^\infty n\varphi(n) f_N(n)dn$	1	*φ(n)*
Kroon and Hoej (2001)	$RI_{COMAH} = \int_0^\infty n^\alpha f_N(n)dn$	1-2	*P(n)*

Vrijling and van Gelder (1997) have shown that the risk integral an be expressed as:

$$RI = \int \frac{1}{2} n^2 f_N(n)dn = \frac{1}{2}(E^2(N) + \sigma^2(N)) \quad \text{(Eq. 3-15)}$$

It is striking that some authors propose a value of constant *C* that is also dependent on *n*, see the measures of Bohnenblust and Kroon and Hoej in table 3-1. In these cases the risk aversion coefficient α is partly 'hidden' in the other constant. For example, for the values of $\phi(n)$ proposed by Bohnenblust (1998), it can be deduced that $\phi(n) \approx \sqrt{0{,}1n}$, resulting in C=0,32 and α=1,5.
Vrijling *et al.* (1995) propose an alternative measure, indicated as Total Risk (TR). It is composed of the expected value of the number of fatalities and the standard deviation, which is multiplied by a dimensionless risk aversion factor *k*:

$$TR = E(N) + k\sigma(N) \quad \textbf{(Eq. 3-16)}$$

The total risk takes a risk aversion index *k* [-] and the standard deviation into account and is therefore called risk averse. It is noted that when the number of fatalities has a binomial distribution, the units of the expected value and standard deviation (of the number of fatalities) are not the same, see appendix 3.II for further explanation. For accidents with small probabilities and large consequences the standard deviation $\sigma(N)$ is large relative to E(N), so that $TR \approx k\sigma(N)$. As $E(N^2)=E^2(N)+\sigma^2(N)$ we can write that: $\sigma^2(N) \approx E(N^2)$. Then, the expression of TR becomes:

$$TR^2 \approx k^2\sigma^2(N) \approx k^2 \int n^2 f_N(n)dn \quad \textbf{(Eq. 3-17)}$$

This formulation shows some similarity with the general formulation of the expected disutility function given by equation 3-14, with C=k^2 and α=2.

Above, the possibilities to determine the risk to people have been discussed. Similar principles can be used to determine several risk measures for the expression of economic risk, such as the frequency-damage (or FD) curve, expected economic loss and standard deviation of losses, see also Jonkman *et al.* (2003).

3.4 The relationship between individual and societal risk

This section explores the relationship between individual and societal risk. The general relationship is investigated in section 3.4.1. Implications for practical risk analyses are treated in section 3.4.2. More specifically, the relationship between the individual risk contours and the FN curve (3.4.3) and the possibilities to determine and display local contributions to societal risk (3.4.4) are investigated.

3.4.1 General discussion on the relationship between individual and societal risk

Individual risk, according to the definition of Bottelberghs (2000), gives the probability of death at a certain location regardless of the presence of people. Individual risk contours can be shown on a map and IR is therefore directly applicable for land use planning and corresponding zoning purposes. Societal risk takes into account the actual presence of people and gives a risk number for a whole area, no matter precisely where the harm occurs within that area. The difference between individual and societal risk is schematically shown in figure 3-6. Both situations A and B have the same individual risk levels (shown by IR' and IR). Due to the larger population density of situation B, it has a larger societal risk than situation A.

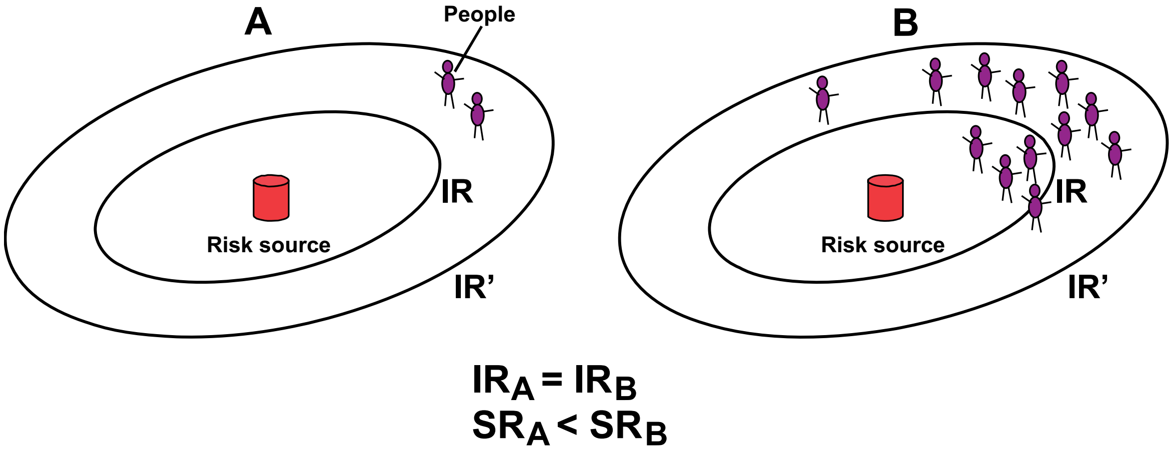


Figure 3-6: The difference between individual and societal risk (based on Stallen *et al.* (1996))

Several authors discuss that individual and societal risk are linked via the expected value of number of fatalities (see e.g. Ale *et al.*, 1996a, 1996b; Alp and Zelensky, 1994; Ball and Floyd, 1998; CIB, 2001; Francis *et al.*, 1999; Trbojevic, 2004, 2006). However, a final confirmation of their precise relation is not given other than with numerical calculations (Ball and Floyd, 1998). In order to check the mutual consistency of individual and societal risk calculations, the formulations for the expected number of fatalities that are obtained with both approaches are compared[10].

The expected value of the number of fatalities <u>from individual risk</u> follows from integration of individual risk contours with population density (see e.g. Ale *et al.*, 1996a; Laheij *et al.*, 2000; CIB, 2001):

$$E(N) = \iint_A IR(x,y)m(x,y)dxdy = \int_0^\infty \iint_A f_{C0}(c_0)F_D^*(c_0,x,y)m(x,y)dxdydc_0 \qquad \textbf{(Eq. 3-18)}$$

Many authors, e.g. (Francis *et al.*, 1998), now state that this equation must be identical to 3-12 (i.e. $E(N) = \int_0^\infty f_N(n)ndn$), but they do not give a further substantiation of this statement. This check can be achieved by using this expression for the expected number of fatalities <u>from societal risk</u>. Substitution of the expression for the number of fatalities for one initial release (equation 3-8) yields:

$$E(N) = \int_0^\infty f_N(n)ndn = \int_0^\infty f_N(n) \iint_A F_D^*(c_0,x,y)m(x,y)dxdydn \qquad \textbf{(Eq. 3-19)}$$

Consequent substitution of the Jacobian of eq. 3-10 (i.e. $f_N(n)=f_{C0}(c_0)\ dc0/dn$) gives[11]:

$$E(N) = \int_0^\infty \iint_A f_{C0}(c_0)F_D^*(c_0,x,y)m(x,y)dxdydc_0 \qquad \textbf{(Eq. 3-20)}$$

10 A similar comparison is made in (Ale *et al.*, 1996b). The difference is that in this thesis the general formulations and the Jacobian (eq. 3-10) are used to show that expected values from individual and societal risk are fully equivalent.

11 It is reasonable to assume that no fatalities will occur if there is no initial release: n=0 if c_0=0.

Since equation 3-20 is identical to equation 3-18 we conclude that the expected values obtained from individual and societal risk are equivalent. This confirms the relationship between individual and societal risk.

3.4.2 Practical implications: comparison of expected values from individual and societal risk

Although it is theoretically obvious that individual and societal risk calculations should lead to identical expected values, several assumptions and modelling choices in risk calculations might influence this relationship in practice. Ale *et al.* (1996a) give a comparison between expected values obtained from individual and societal risk (indicated as PLLI and PLLF respectively) using outcomes of risk analyses for different hazardous installations in the Netherlands. It is stated that the results for PLLI and PLLF are not necessarily equal, since the individual risk is calculated for an unprotected individual, whereas the societal risk is calculated by taking into account protection e.g. by buildings (Laheij *et al.*, 2000). Thus, it would be expected that PLLI is larger PLLF for all installations. Other limitations may weaken the relationship between PLLI and PLLF, e.g. the limited availability of data and the simplifying assumptions used in these calculations. Figure 3-7 gives a (modified version of) the comparison between PLLI and PLLF values from Ale *et al.* (1996a). The dashed line represents situations where PLLI=PLLF.

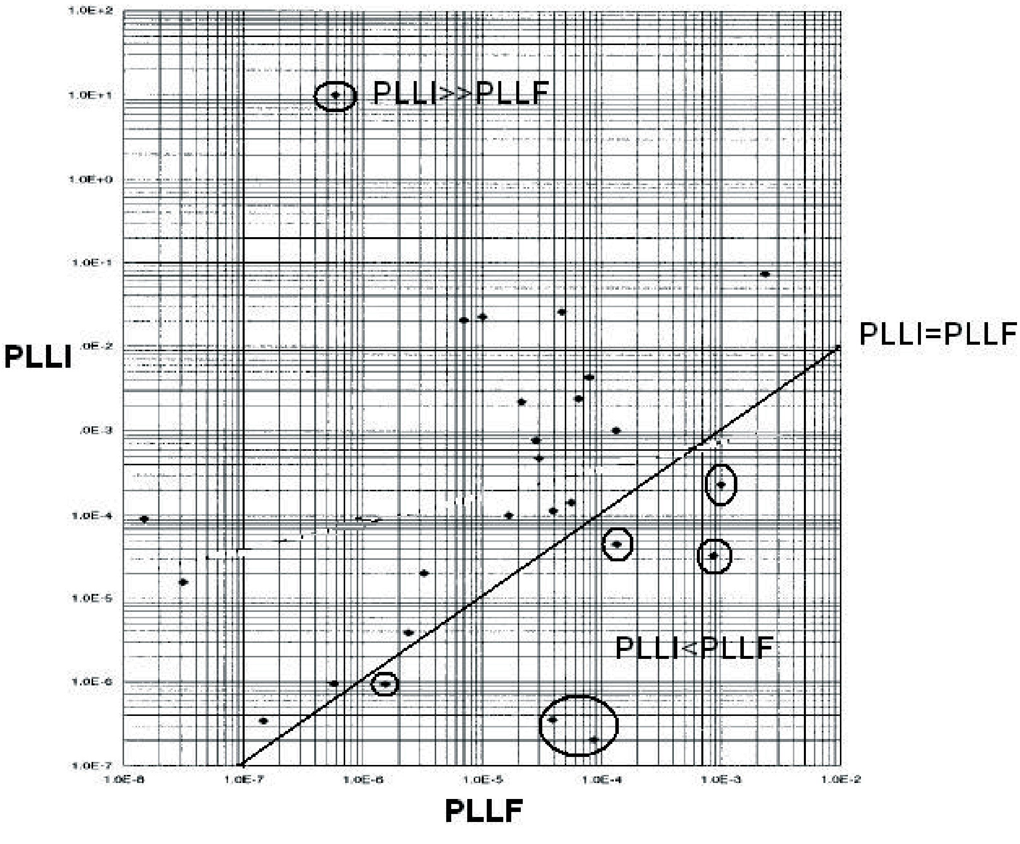


Figure 3-7: Comparison between expected values based on individual risk (PLLI) and societal risk (PLLF). Dots represent calculations for single installations (figure modified from Ale *et al.*, 1996a)

It is striking that for some installations the PLLF is larger than PLLI. This might be due to the fact that the actually calculated risk contours for installations have been schematised in (Ale *et al.* 1996a) as circular contours. This can lead to an underestimation of the individual risk levels at population concentrations and thus to an underestimation of PLLI. In addition, the differences between both PLL's span orders of magnitude for some cases. For example, for the location indicated in the upper left part of the figure they deviate a factor 10^7.

Given all the limitations mentioned above, a complete explanation of these deviations cannot be given for the above. However, such analyses indicate the relevance of a verification of the relationship between PLLI and PLLF. The two different "routes" of calculating the expected number of fatalities can be followed to verify the consistency of individual and societal risk calculations for a given installation. After consistency is assured, assumptions in individual and societal risk calculations could be differentiated, e.g. with respect to presence and protection of people.

3.4.3 The relationship between individual risk contours and the FN curve

The two previous sections have described the general relationship between individual and societal risk. A related issue is the relationship between individual risk contours and the FN curve. This is further explored in this section. The issue considered here is how the FN curve changes when new housing developments are added outside a certain IR contour.

For clarity we use a simplified notation for individual and societal risk in a one-dimensional system. Individual risk is calculated for an (hypothetical) individual permanently present at location *x*:

$$IR(x) = P_E(x) F_{D|E}(x) \qquad \textbf{(Eq. 3-21)}$$

Where: $P_E(x)$ – probability of exposure at location *x* in one year; $F_{D|E}(x)$ – probability of death given exposure at location *x* (integrated over all intensities of physical effects)
The (expected) number of fatalities at location *x* equals:

$$N(x) = F_{D|E}(x) N_{EXP}(x) \qquad \textbf{(Eq. 3-22)}$$

Where: $N_{EXP}(x)$ – number of people exposed at location *x*[12]

The relationship between the individual risk contours and the FN curve is considered for two typical situations, see figure 3-8. The first situation consists of a risk source at a fixed accident location, e.g. a hazardous installation. The accident leads to exposure of an area, in which both the intensity of physical effects and mortality will generally decrease with distance from the risk source due to the dispersion of effects. The second situation considers a spatially variable accident location, in which a relatively small area is exposed (see more details in section 3.5.3). An example of this type of accident is the crash of an airplane. The probability of exposure decreases with distance from the risk source (e.g. because the probability of a crash becomes smaller at larger distance from the airport). The probability of death given exposure is the same for all accident locations. Both situations lead to identical individual risk contours and FN curves if $N_{EXP,I}$=100 people are (constantly) exposed at the 10^{-4} risk contour. However, the FN curves for the two situations will change in different ways when additional population(s) of 100 people are added at the 10^{-5} and 10^{-6} IR contours. These additional populations are $N_{EXP,II}$ and $N_{EXP,III}$ respectively, so that $N_{EXP,I} = N_{EXP,II} = N_{EXP,III} = 100$.

12 It is assumed that a group of people is exposed in one single location.

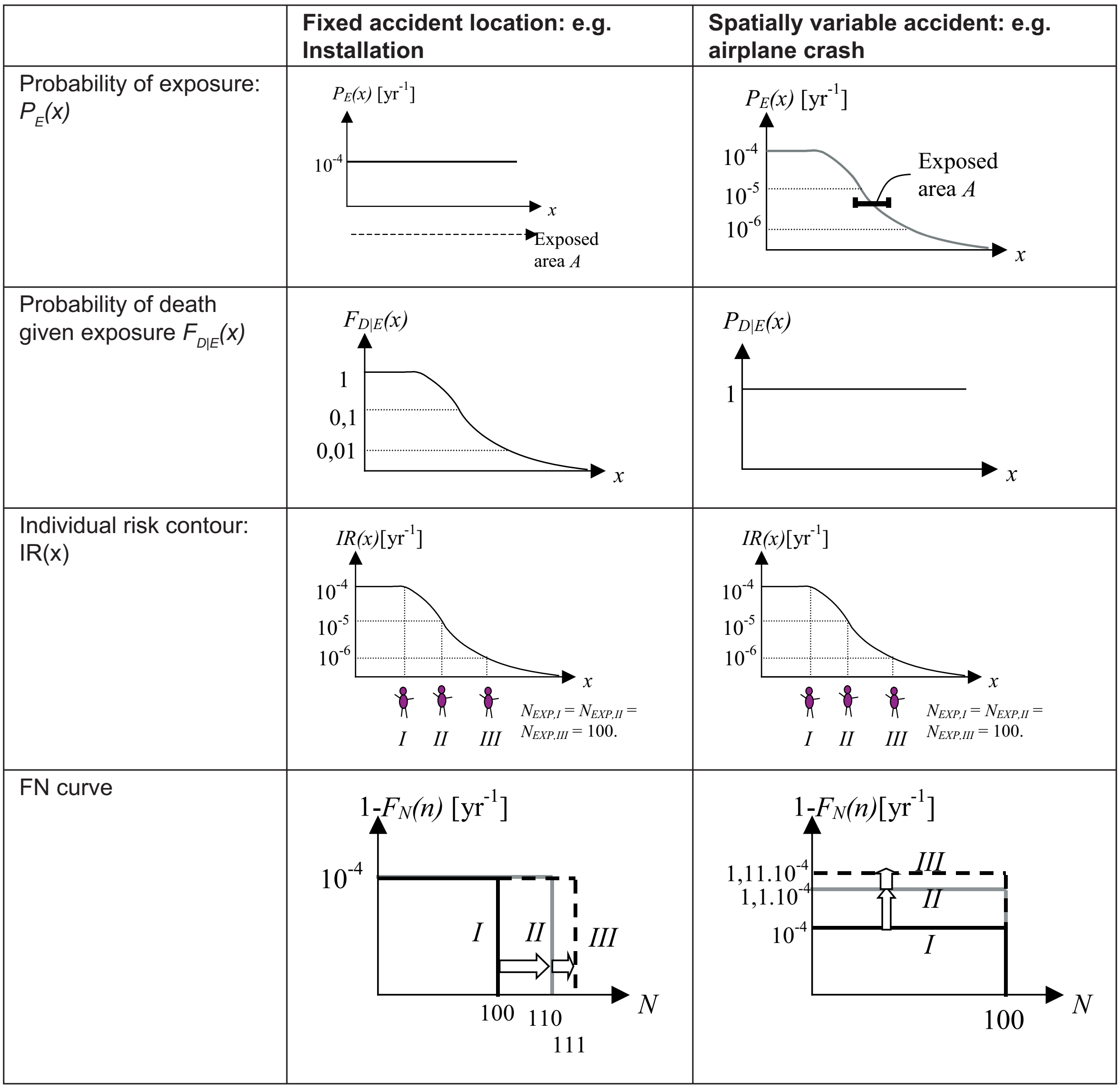


Figure 3-8: Individual risk and FN curve for two situations

It is shown that for the fixed installation addition of populations II and III leads to an increase of the consequences. For the spatially distributed accidents, addition of people at more distant risk contours increases the probability of an accident, while the consequences in case of an accident remain identical.

The effects on the FN of adding new populations at a certain known IR contour value can be determined based on the ratios of IR values at two locations:

$$\frac{IR(x)}{IR(0)} = \frac{P_E(x)P_{D|E}(x)}{P_E(0)P_{D|E}(0)} \qquad \textbf{(Eq. 3-23)}$$

Where: $P_E(0)$ – probability of exposure at the risk source in one year; $P_{D|E}(0)$ – mortality at the risk source.

In the above typical situations it can be assumed that either the probability of exposure (for a fixed installation) or the mortality (for spatially distributed accidents) is constant for all locations. In these situations the effects on the FN curve of addition or movement of population can be derived from the above formula. Further explanation and examples are given in appendix 3.III.

The above analyses give insight in the relationship between IR contours and the FN curve. Based on the above findings it will be possible to develop rules of thumb to show the effects in the FN curve of adding population at a certain IR contour value. It has also been shown how zoning measures have different effects for different situations. For a fixed installation, zoning measures reduces the consequences of an accident and leads to a horizontal shift in the FN curve. For situations where the probability of an accident is spatially variable, zoning leads to a change in the probability of exposure and a vertical shift of the FN curve. For cases where both the probability of exposure and mortality are spatially distributed, it will be less straightforward to determine the effects of zoning on the FN curve.

3.4.4 Presentation of local contributions to societal risk

It is interesting to investigate how the contribution of certain locations to the societal risk of the whole area can be analysed and presented. This offers the possibility of effective reduction of societal risk due to spatial measures and (in combination with risk limits) could provide insight in tolerable housing developments at certain locations within an area. Several authors have investigated (aspects of) the so-called area specific approach to societal risk (Piers, 1998; Post *et al*, 2005; van Vliet *et al.*, 2005; Wiersma *et al.*, 2005).

In order to assess the local contribution a location to societal risk, the studied area is generally divided into a number grid cells[13] with limited surface, e.g. 1 hectare or 1 km^2. The most straightforward and undisputed way to show the local contribution to societal risk is to calculate and plot the local contribution of one grid cell to the expected value of the number of fatalities. However, societal risks in the Netherlands are generally expressed in an FN curve, which is based on the cumulative distribution of the number of fatalities for the whole area. The possibility to depict the local contribution to the FN curve depends on whether the exposed area by an accident is smaller than the size of a grid cell or not, see figure 3-9.

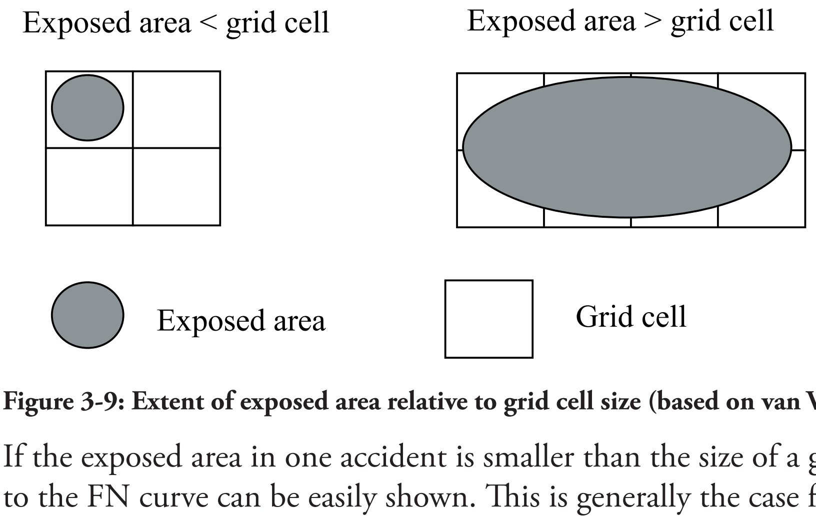


Figure 3-9: Extent of exposed area relative to grid cell size (based on van Vliet *et al.*, 2005)

If the exposed area in one accident is smaller than the size of a grid cell, the contribution to the FN curve can be easily shown. This is generally the case for accidents with a limited

13 Note that these grid cells thus represent (smaller) areas within the whole study area. It might thus be misleading to mention the contribution of one location, as a location basically consists of one smaller area. Here both terms are used as interchangeable.

accident footprint, such as airplane crashes. Each accident is assigned to one grid cell[14]. The contribution of one grid cell to the probability of exceedance of a certain number of fatalities can be determined directly and plotted in a graph. An example is given in figure 3-10 for the Dutch national airport Schiphol (Piers, 1998). Such a figure gives the spatial distribution of contributions of single gridcells. Summation of the probabilities of all grid cells in the area for the considered number of fatalities yields the corresponding probability (of exceedance) that is also shown in the FN curve.

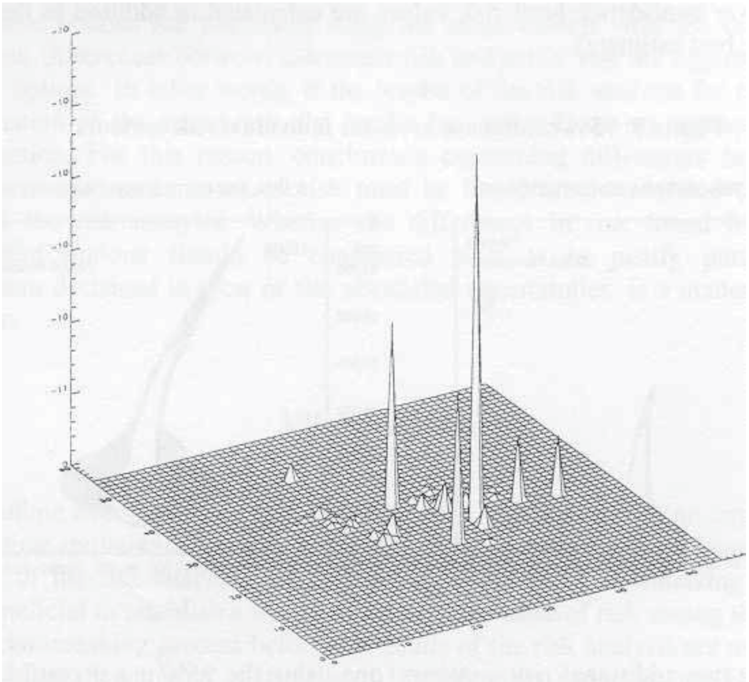


Figure 3-10: Contribution of grid cell of 1 km^2 to the FN curve of Schiphol for N=200 fatalities (situation 1990) (Piers, 1998)

If the exposed area in one accident is larger than the size of a grid cell, the local contribution to the FN curve is less straightforward to determine. This is generally the case for accident types that expose larger areas (and thus multiple grid cells) at once, such as floods and chemical gas plumes. In this case the fatalities for one accident scenario are distributed over multiple grid cells. This implies that the contribution of one grid cell to the FN curve cannot be depicted in a straightforward manner.

To overcome this issue it is proposed to assign a probability (of exceedance) to each grid cell that is proportional to its contribution to the total number of fatalities for the considered scenario, see also Jonkman and Vrijling (2005). This approach has the benefits that 1) the grid cell with the most fatalities has the highest contribution to the probability; 2) summation over the whole area of probabilities per grid cell for a certain number of fatalities N results in the probability shown in the FN curve.

Discussion

Above, the possibilities for presentation of local contributions to the societal risk in an area have been investigated. Especially for accidents where the exposed area is larger than the size of a grid cell, further investigation of methods for the quantification and presentation

14 Although an airplane crash could also expose multiple grid cells, their number will be relatively limited. Therefore it seems reasonable to assign the fatalities to one grid cell.

of the local contribution to societal risk is recommended. Also the relationship between local contributions to societal risk and the FN limit line for the whole area could be further investigated. Practical indicators could be developed to indicate how much housing developments at a location are still tolerable within the societal risk limit. However, societal risk is the summation of contributions to probabilities and consequences of all accidents in a certain area. This implies that it will not be easy to judge if additional housing is tolerable at a specific location, as this depends on (increases in) the presence of housing at other locations. Until these issues have been further explored and solved a more iterative approach is favourable. In this approach the effects of each new housing development on societal risks are assessed by means of a new calculation with a (numerical) risk analysis model.

3.5 Extension of the general formulations for risk quantification

Based on the general formulations for risk quantification, several extensions for specific situations are proposed, that allow a broader application of the approach. These extensions include alternative definitions for individual risk (3.5.1), the correction for reduction of actual presence of people e.g. due to evacuation (3.5.2); inclusion of the spatially distributed accidents (3.5.3) and direction dependent hazards (3.5.4).

3.5.1 Alternative definitions for individual risk

In literature several alternative definitions for individual risk are proposed, for which mathematical expressions can be formulated. The maximum individual risk (IR_{MAX}) in the exposed area is found as follows:

$$IR_{MAX} = \max_{A}\left(IR(x,y)\right) \qquad \textbf{(Eq. 3-24)}$$

The average individual risk (IR_{AV}) in an area becomes:

$$IR_{AV} = \frac{\iint\limits_{A} IR(x,y)m(x,y)dxdy}{\iint\limits_{A} m(x,y)dxdy} = \frac{E(N)}{N_{EXP}} \qquad \textbf{(Eq. 3-25)}$$

This clearly shows that this definition or IR does not give the actual risk for a specific individual or location, but that it in fact expresses a characteristic of societal risk. The average individual risk is often used to indicate the risks associated with certain activities, such as smoking, driving or mountain climbing.

For tunnels and other transport systems the individual risk becomes a characteristic of a specific or typical user, and it is necessary to define a number of travels per year for that user. Individual risk for tunnels (IR_T) is found as follows:

$$IR_T = \frac{E(N)R_P}{R_T} \qquad \textbf{(Eq. 3-26)}$$

Where: R_P– number of travels per year through the tunnel for the specific user; R_T– total number of travels per year through the tunnel

Generally, individual risk contours are drawn in two dimensions (x,y), as land use planning traditionally focused on building near or along transport routes and installations. Especially in densely populated areas, multiple use of space of infrastructure (buildings above roads and railways) has gained attention. Therefore, development of risk contours in three dimensions (x,y,z) has been proposed (Suddle, 2004; Suddle and Ale, 2006).

3.5.2 Correction for the actual presence of people

Permanent presence of persons has been assumed in elaborations in previous sections. However, some alternative definitions concern the actual presence of people in an area in order to determine the actual individual risk. Within the individual risk calculation an occupation factor (Carter and Hirst, 2000) or residence time fraction (Matthijsen, 2003) can be introduced that indicates the fraction of the time that people are present[15] at a certain location. Similarly, the effects of evacuation can be discounted in risk quantification. Especially for events that are predictable and for which the effects are developing relatively slow, evacuation might be possible (see section 2). The exposed population at a location can be reduced by evacuation, so that:

$$\gamma(x,y) = 1 - F_E(x,y) \qquad \textbf{(Eq. 3-27)}$$

Where: $\gamma(x,y)$ – occupation factor [-]; $F_E(x,y)$ – fraction of the population evacuated at location (x,y) [-]

This occupation factor can be included to correct for the actual exposure of the population and evacuation in the expressions for individual and societal risk:

$$N_{EXP} = \iint_A \gamma(x,y) m(x,y) dx dy \qquad \textbf{(Eq. 3-28)}$$

$$IR(x,y) = \int_0^\infty f_{C0}(c_0) F_D^*(c_0,x,y) \gamma(x,y) dc_0 = \int_0^\infty f_{C0}(c_0) F_D^*(c_0,x,y) \left(1 - F_E(x,y)\right) dc_0 \qquad \textbf{(Eq. 3-29)}$$

Inclusion of the effects of evacuation or the occupation factor in expressions for societal risk is straightforward.

Finally, the presence of buildings may offer some protection against the physical effects of the event and thus reduce mortality. In assessing the effects of protection it can be chosen to determine either the reduction of physical effects or the reduction of mortality via the dose response function. Van Leeuwen (1992) gives an example of the first type of application and assesses the reduction of toxic concentrations due to presence indoors. In the second type of application the effects of protection can be considered in an alternative version of the dose response function: $F_{DP}(c)$, where indicator *P* used to indicate effects of protection.

3.5.3 Risk quantification for spatially distributed accidents

The presented general formulations in the previous sections assumed one risk source at a fixed location, i.e. 'a point source'. This situation is representative for a stationary installation, where the physical effects develop as coming from one source. However, for many applications, for example transport of dangerous materials, flood protection or airport safety,

15 The complement of the factor: 1 - γ(x,y) indicates the time of the day that people are elsewhere, e.g. for school or work.

accidents can occur at different locations (e.g. sections of the road or dike, or all locations near an airport). Then it is necessary to take into account in risk quantification the spatial distribution of accident locations and the exposed area for an accident.

To show the conceptual approach for spatially distributed accidents the situation is elaborated for a one-dimensional example. Assume that an accident occurs at location *x'* ([16]). The effects occur within an exposed area with a "footprint" *A*. All locations within the accident footprint are exposed to the effects of the accident at *x'*, see figure 3-11.

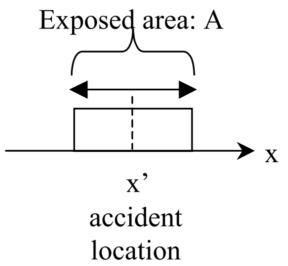


Figure 3-11: Schematic view of exposed area A in case of an accident at location x'

The probability of exposure at a certain location to the effects of spatially distributed accidents can be determined as follows. Assume that the probability of an accident equals p_f in one year. The (conditional) distribution of the accident location given an accident can be described with: $f_{x'|f}(x')$ for a one dimensional situation[17]. The probability of an accident in a certain area is found by integration of all accidents that can occur in that area. The probability of **exposure** at location *x* equals the probability that location *x* will be within the accident footprint. The probability of exposure at location *x* in one year becomes:

$$P(exposure\ at\ x) = P(x - A/2 < x' < x + A/2) = p_f \int_{x-A/2}^{x+A/2} f_{x'|f}(x')dx' \qquad \textbf{(Eq. 3-30)}$$

If the accident footprint *A* becomes larger this leads to an increase in the probability of exposure and consequently the level of individual risk. Exposure of a larger area can also lead to an increase of the number of fatalities in case of an accident.

For some applications, e.g. for transport routes, an alternative notation might be preferable, because the accident probability is a function of location. Then, a failure intensity $\lambda_f(x')$ per vehicle with unit [1/length] can be used, see also (JCSS, 2001) and below for an example. The dependency on length x expresses the variability in circumstances along the length, leading to variations in accident intensity (JCSS, 2001). For example, for a transport route the accident intensity might be larger in bends than on straight roads. The continuous function for the failure intensity $\lambda_f(x')$ can also be split into discrete probabilities indicating the probability of failure of a section of dike, or the accident probability at a road section, for example per kilometre.

16 Index (') is used to denote the difference between crash location (x') and location of exposure (x).

17 Of course the analysis can be extended into two dimensions (x,y).

Example: transport route

To illustrate the application of this approach a conceptual example is given for a transport route as representative for a line shaped risk source[18]. We assume a certain accident intensity $\lambda_f(x')$ per vehicle. We consider a location x at a distance y from the transport route. The location (x,y) can be exposed due to accidents occurring between locations x_1 and x_2, see figure 3-12.

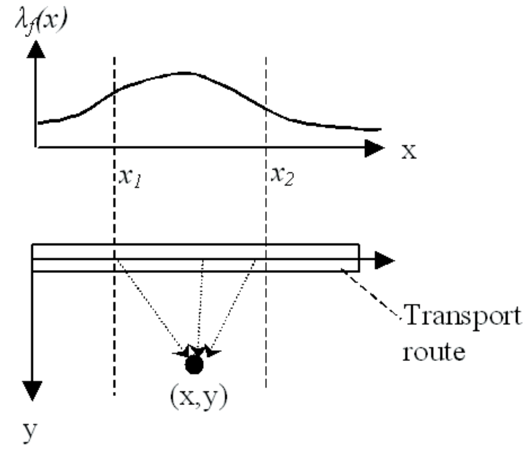


Figure 3-12: Example of transport route and accident intensity

The probability of an accident at that stretch of the route in one year and thus the probability of exposure at location (x,y) is found as follows[19]:

$$P_{accident[x1,x2]} = n_v \int_{x1}^{x2} \lambda_f(x')dx' \qquad \textbf{(Eq. 3-31)}$$

Where: $P_{accident[x1,x2]}$ – probability of an accident in one year between locations x_1 and x_2;
n_v – number of vehicles per year on transport route per year [yr^{-1}]

The individual risk at location (x,y) is now found by combining the probabilities of different accidents that expose (x,y) with the possible initial accident intensities and the dispersion and the dose response model. For a line shaped risk source the risk contours are obtained by summation over a large number of different accident locations. If the probability of an accident and the dispersion are constant along the considered stretch, risk contours will be located parallel[20] to the risk source, e.g. the road or dike.

The above analysis clearly shows that in the risk quantification for location (x,y) all accidents that can lead to exposure of the location have to be considered. This indicates that it is not sufficient to perform a risk analysis for one single section of a road nearest to the considered location, when accidents at other sections of the road can also contribute to exposure of the location. This implies that all accident locations within the maximum effect range have to be included in risk quantification. It is recommended to investigate this issue further, especially for transport safety in the Netherlands, where risks are generally assessed for arbitrary and separate sections of one kilometre.

18 A similar conceptual elaboration can be given for a line shaped flood defence structure.

19 If $\lambda_f(x')<<1$ we may assume that equation 3-31 results in a probability.

20 There is a similarity with a wave pattern, see also (Jonkman, 2001). While one single wave source gives a circular wave dispersion, a combination of many wave sources at one line give a wave front that disperses parallel relative to that line.

3.5.4 Meteorological conditions and direction dependent hazards

For some hazards meteorological conditions can influence the dispersion of physical effects and the extent of the exposed area, see also (Alp and Zelensky, 1994) for an extensive discussion. For example for the release of toxic gasses, the wind direction will determine the contour of the released gas plume and the exposed area (Vilchez *et al.*, 2004). For such situations the exposed area, consequences and risk levels are direction dependent.

The influence of meteorological conditions can be included in risk quantification. The occurrence of certain meteorological conditions, e.g. wind direction θ_W, can be described with a probability density function: $f_W(\theta_W)$. A polar coordinate system is generally used in which the angle and distance relative to the risk source are described with angle θ [rad] and radius R [m] respectively. The exposed area or "footprint" stretches out with radius B/2 on both sides of the occurring wind direction. It is assumed here that effects disperse over very large distance, so that R approaches infinity, see figure 3-13.

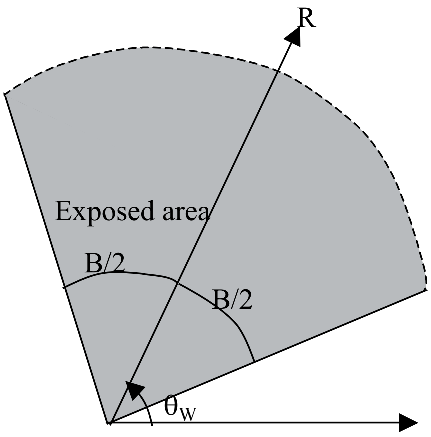


Figure 3-13: Area exposed to effects in case of wind direction θ_W in a polar coordinate system

Suppose that we analyse the risks for some location at radius θ. Similar to equation 3-30 the probability of exposure in this direction θ in one year is found by summing over all wind directions that result in exposure and combination with the probability of an accident[21]:

$$P(exposure\ at\ \vartheta) = p_f \int_{\vartheta - B/2}^{\vartheta + B/2} f_W(\vartheta_W)d\vartheta_W \qquad \textbf{(Eq. 3-32)}$$

Individual risk at location (R,θ) is assessed by combining the probability of exposure, with the dose response function and the dispersion model (formulated as $c(c_0,R,\theta)$ and substituted in the dose response function):

$$IR(R,\vartheta) = \int_{\theta - B/2}^{\theta + B/2} \int_{0}^{\infty} p_f f_W(\vartheta_W) f_{C0|f}(c_0) F_D^{*}(c_0, R, \vartheta) dc_0 d\vartheta_W \qquad \textbf{(Eq. 3-33)}$$

The direction dependent character of the hazards can also influence the societal risk. For example for toxic releases the consequences of the event will depend on the meteorological

21 It is assumed that the probability of an accident p_f and the wind direction are independent.

situation at the moment of occurrence of the event, and the dispersion of effects relative to population concentrations. Then, the number of fatalities for one initial release becomes conditional on the wind direction. This implies that the number of fatalities given one initial release (c_0) cannot be represented by a deterministic number. Instead it will have a certain conditional distribution. A schematic example is presented in figure 3-14, where a hazardous facility is located at the western side of the city. Consider one single initial release with a certain footprint. If the wind blows in the eastern direction the city will be maximally exposed (situation 1). For other wind directions the city will be partly exposed (situation 2) or not be exposed at all (situation 3). By combining information regarding the distribution of wind directions and the population density, the conditional pdf of fatalities given release is obtained.

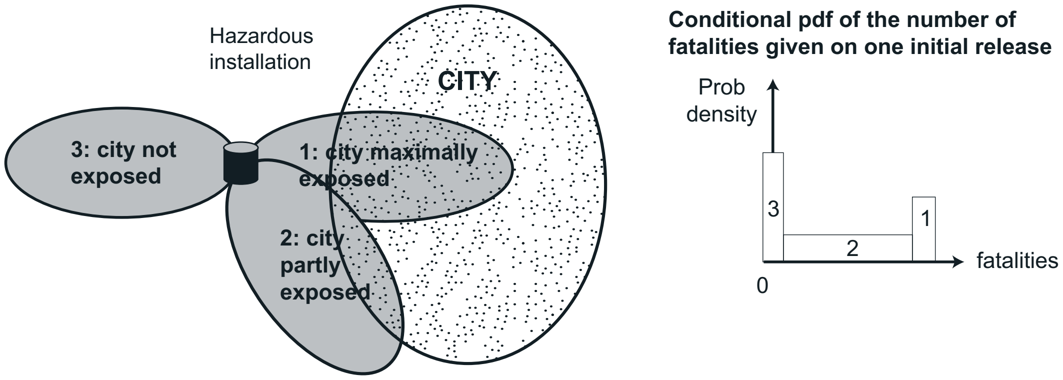


Figure 3-14: Schematic example for a facility: Conditional pdf of the number of fatalities for a given initial ease

For some applications, for example transport of dangerous gasses over transport routes or through pipelines, accidents will be spatially distributed and effects will be direction dependent. In this case the exposed area will depend on the accident location and the occurring wind direction. It is possible to combine both previously elaborated approaches by expressing the polar coordinates (R,θ) used for direction dependent hazards with the Cartesian (x,y) coordinates used for spatially distributed accidents.

3.6 Examples

To demonstrate the application of the general formulations and the proposed extensions to various sectors, different examples are elaborated in this section. The examples are conceptual and highly schematised, but characteristic for different applications. The examples and their main characteristics are summarized in table 3-2.

Table 3-2: Summary of elaborated examples and their main characteristics

Section	Example	Risk source	Dispersion of physical effects
3.6.1	Fictitious example	Point source	Point
3.6.2	Chemical installation	Point source	Spatial (radial)
3.6.3	Chemical installation	Point source	Spatial (radial) incl. Meteorological conditions
3.6.4	Airport	Plane source one- and two- dimensional	Spatial

For reasons of brevity and clarity individual and societal risk calculations are only fully elaborated for the first two examples. For the other examples the most characteristic and relevant results are presented.

3.6.1 Simple fictitious example

First, a simple and fictitious example is elaborated. It is assumed that effects and population density are uniformly distributed over a certain area. This situation can be schematised as a point source in a "point city", i.e. a city with an infinitely small surface.

The probability of failure of a risk source in one year equals p_f = 0,5.10^{-3} [yr^{-1}]. The conditional pdf of the intensity of initial effects given failure is described with an inverse quadratic Pareto pdf:

$$f_{C0|f}(c_0) = 0 \qquad 0 \le c_0 < 1$$

$$f_{C0|f}(c_0) = \frac{a}{c_0^{\,3}} \qquad c_0 \ge 1 \qquad \text{(Eq. 3-34)}$$

Where: a – constant with value 2 and a unit corresponding to one divided by the squared unit of c_0; c_0 – intensity of physical effects released at the risk source (in more practical examples this could for example be a concentration [mg/m^3]).

The (non-conditional) pdf of the intensity of initial effects in one year is then obtained as follows (see also figure 3-1a):

$$f_{C0}(c_0) = 1 - p_f = 1 - 0,5 \cdot 10^{-3} \qquad 0 \le c_0 < 1$$

$$f_{C0}(c_0) = p_f f_{C0|f}(c_0) = \frac{p_f a}{c_0^3} = \frac{10^{-3}}{c_0^3} \qquad c_0 \ge 1 \qquad \text{(Eq. 3-35)}$$

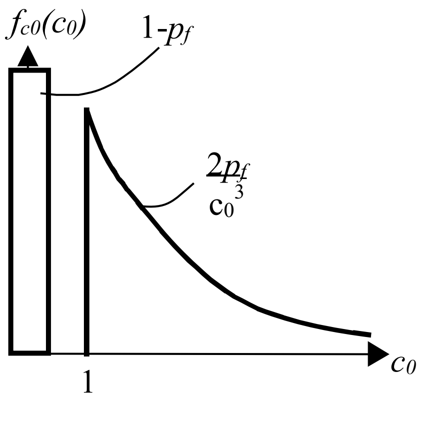


Figure 3-15: Probability density function of the intensity of initial effects

Given the chosen schematisation of a point city the dispersion of physical effects is not relevant, so c_0=c. The mortality for an event can now be directly estimated as a function of initial effects with a dose response function (figure 3-16):

$$F_D(c_0) = b\sqrt{c_0} \qquad 0 \le c_0 \le 1/b^2$$
$$F_D(c_0) = 1 \qquad c_0 > 1/b^2$$
(Eq. 3-36)

Where: b – constant with a unit corresponding to one divided by the square root of the unit of c_0.

In further elaboration it is assumed that b is very small and the second part of equation 3-36 is neglected in further analyses[22]. The number of people in the exposed area equals N_{EXP}.

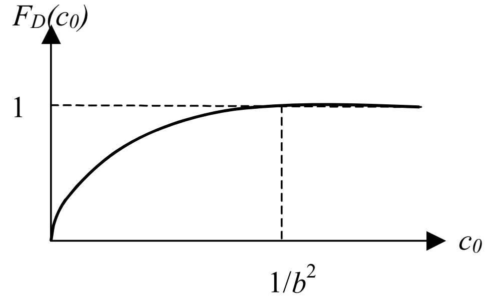


Figure 3-16: Dose response function

Derivation of individual risk

The individual risk is found by combining the pdf of initial effects with the dose response function (see also eq. 3-6):

$$IR = \int_0^{\infty} p_f f_{C0|f}(c_0) F_D(c_0) dc_0 = \int_1^{\infty} p_f \frac{a}{c_0^{\,3}} b c_0^{\,0,5} dc_0 = \left[-2/3abp_f c_0^{\,-3/2}\right]_1^{\infty} = 2/3abp_f$$

(Eq. 3-37)[23]

The expected value of the number of fatalities from individual risk is found by multiplication with the number of people exposed :

$$E(N) = \int_1^{\infty} p_f f_{C0|f}(c_0) F_D(c_0) N_{EXP} dc_0 = 2/3abp_f N_{EXP} \qquad \textbf{(Eq. 3-38)}$$

Derivation of societal risk

Following equation 3-8 the number of fatalities N is found as a function of initial effects and exposed population:

$$N = g(c_0) = F_D(c_0) N_{EXP} = bN_{EXP} c_0^{\,0.5} \qquad \textbf{(Eq. 3-39)}$$

The probability density function of the number of fatalities in one year can be derived as follows (note the transition of integration boundaries):

---

22 It is thereby assumed that $\int_{1/b^2}^{\infty} f_{C0}(c_0)$ is negligibly small relative to $\int_{1}^{1/b^2} f_{C0}(c_0)$

23 A check shows that IR has unit $[a][b][p_f]*c_0^{-3/2} = c_0^{\,2}\, c_0^{-1/2}\, yr^{-1} c_0^{-3/2}$ leading to a unit for IR of yr^{-1}

$$f_N(n) = 1 - p_f \qquad\qquad n = 0$$

$$f_N(n) = f_{C0}(c_0)\frac{dc_0}{dn} = f_{C0}(c_0)\frac{2c_0^{\,1/2}}{bN_{EXP}} = \frac{2ap_f(bN_{EXP})^4}{n^5} \qquad d \le n < \infty \qquad \textbf{(Eq. 3-40)}$$

$$d = n(c_0 = 1) = bN_{EXP}$$

Integration of this pdf yields the expected value of the number of fatalities in one year:

$$E(N) = \int_0^\infty nf_N(n)dn = \int_d^\infty \frac{2ap_f(bN_{EXP})^4}{n^4}dn = \left[-\frac{2/3ap_f(bN_{EXP})^4}{n^3}\right]_d^\infty = 2/3abp_fN_{EXP}$$

(Eq. 3-41)

Following the discussion in section 3.4.1 it is shown that expected values obtained from individual and societal risk (i.e. equations 3-38 and 3-41) are equivalent. The distribution function of the number of fatalities and the FN curve are found by integration of the pdf:

$$1 - F_N(n) = 1 - p_f \qquad\qquad n = 0$$

$$1 - F_N(n) = \int_n^\infty f_N(n)dn = \frac{2ap_f(bN_{EXP})^4}{4n^4} \qquad d \le n < \infty \qquad \textbf{(Eq. 3-42)}$$

Below, the corresponding FN curves are shown for a= 2; b=10^{-5}; p_f = $0{,}5.10^{-3}$ per year and N_{EXP}=10^5. Similarly, the pdf, distribution and FN curve[24] for the number of fatalities given failure can be derived. Note that the FN curves have a slope of -4. This can be derived from the combination of the pdf of effects, the Jacobian and the (square rooted) format of the dose response function. This shows that the steepness of the FN curve depends on the pdf of initial effects and the dose response function. Note that the (non-conditional) FN curve for the number of fatalities intersects the vertical axis at the value of the probability of failure p_f= $0{,}5.10^{-3}$ per year of killing at least one person. The conditional FN curve given failure is shifted by that same factor p_f.

24 number of fatalities given failure: pdf: $f_{N|f}(n)$; distribution $F_{N|f}(n)$; FN curve: 1- $F_{N|f}(n)$

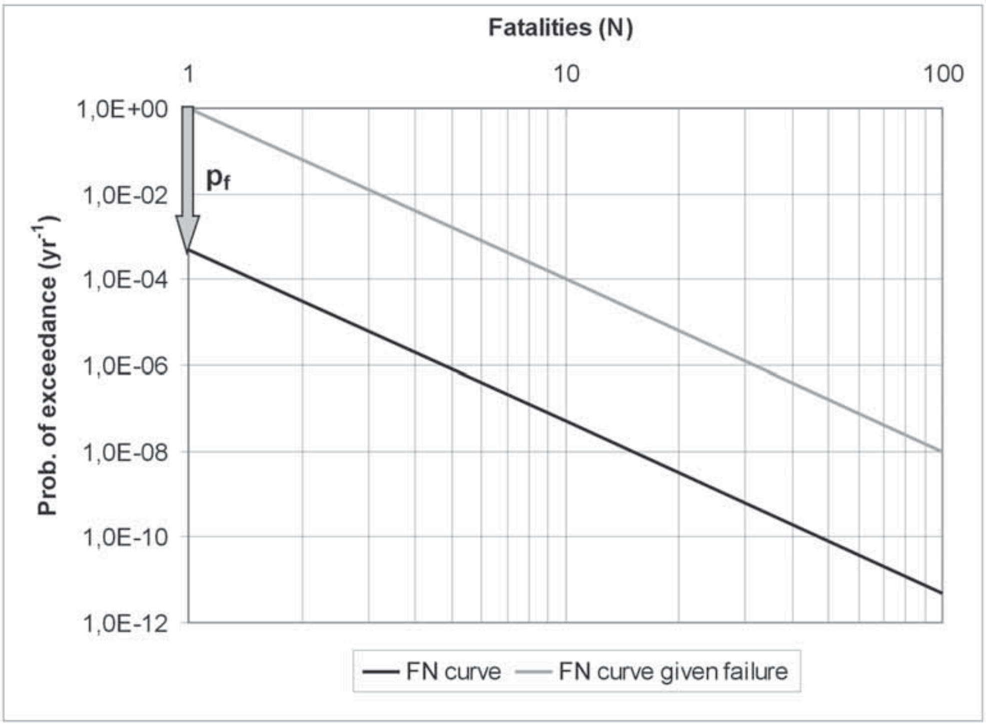


Figure 3-17: FN curve for the simplified example

Finally the standard deviation can be determined **(Eq. 3-43):**

$$\sigma^2(N) = E(N^2) - E^2(N)$$

$$E(N^2) = \int_0^\infty n^2 f_N(n)dn = \int_d^\infty \frac{ap_f(bN_{EXP})^4}{n^3}dn = \left[-\frac{ap_f(bN_{EXP})^4}{n^2}\right]_d^\infty = ap_f(bN_{EXP})^2$$

As it follows that $E^2(N)$ is small relative to $E(N^2)$ we find that $\sigma(N) \approx \sqrt{ap_f}\,bN_{EXP}$. Similarly, the expected value and standard deviation for the number of fatalities given failure can be derived analytically.

3.6.2 Point source with radial dispersion of effects

In the second example a point source is treated as representative for a chemical installation. The same pdf for intensity of initial effects and dose response function are used as in the previous section (3.6.1). It is assumed that effects disperse radially, which could for example correspond to dispersion of gas in a situation without wind. The intensity of effects decreases exponentially as a function of (radial) distance to the source:

$$c(c_0, R) = c_0 e^{-\alpha^* R}$$

$$F_D(c) = b\sqrt{c} \quad \Rightarrow \quad F_D^*(c_0, R) = bc_0^{0.5} e^{-0.5\alpha^* R} \qquad \textbf{(Eq. 3-44)}$$

Where: R – radial distance to source [m]; α^* – constant determining decrease of effects as a function of distance [m^{-1}].

Determination of effect distance

Based on the above functions an analytical expression for the so-called effect distance can be obtained. This concept is used for risk mapping and communication in the external safety policy in the Netherlands (SAVE, 2002) and gives the distance from the risk source within which fatalities are expected for a certain initial release. As a boundary for this area generally the 1% mortality fraction is used. An analytical expression for effect distance is obtained by combining the dispersion and mortality functions. For the above example this results in:

$$R_{1\%} = -\frac{2}{\alpha *}\ln\left(\frac{0,01}{bc_0^{0,5}}\right) \quad \textbf{(Eq. 3-45)}$$

Where: $R_{1\%}$ - effect distance: distance from risk source to a location where a intensity value is reached that corresponds to 1% mortality [m]

The above equation shows that the effect distance depends on the chosen value of the initial intensity of physical effects c_0 and that it is thus a deterministic concept, i.e. the distribution of initial releases is not accounted for. Using the above concept analytical expressions for effect distances for lethal and non-lethal injury can be developed if the response function and dispersion model are given.

Individual risk

The individual risk is now determined as a function of radial distance to the source:

$$IR(R) = P(Z(R) < 0) = \int_1^\infty p_f f_{C0|f}(c_0) F_D^*(c_0, R) dc_0 = \int_1^\infty p_f \frac{a}{c_0^{\,3}} bc_0^{\,0,5} e^{-0,5aR} dc_0$$

$$= \left[-2/3abp_f e^{-0,5aR} c_0^{-3/2}\right]_1^\infty = 2/3abp_f e^{-0,5aR}$$

(Eq. 3-46)[25]

As an example, individual risk levels are shown in figure 3-18 (left figure) as a function of distance to the risk source for a=1,5; b=10^{-4}; p_f = 10^{-2}; α=0.015. Based on the previous equation the distance to an individual risk contour is determined as follows:

$$R(IR) = -\frac{2}{\alpha *}\ln\left(\frac{3IR}{2abp_f}\right) \quad \textbf{(Eq. 3-47)}$$

The above formulation shows that for this case (exponential decay of physical effects) the distances between successive individual risk contours is identical. Distances to individual risk contours are shown in figure 3-18 (right figure). At the location of the installation (R=0) IR=10^{-6} per year. Because radial dispersion and no influence of wind are assumed, the risk contours have a radial shape. This shows that individual risk contours are two-dimensional projection on a map of the three dimensional distribution of individual risk.

25 For this example it is shown in appendix 3. I that the same result is obtained when the dispersion model and initial effects are combined (see also figure 3-3).

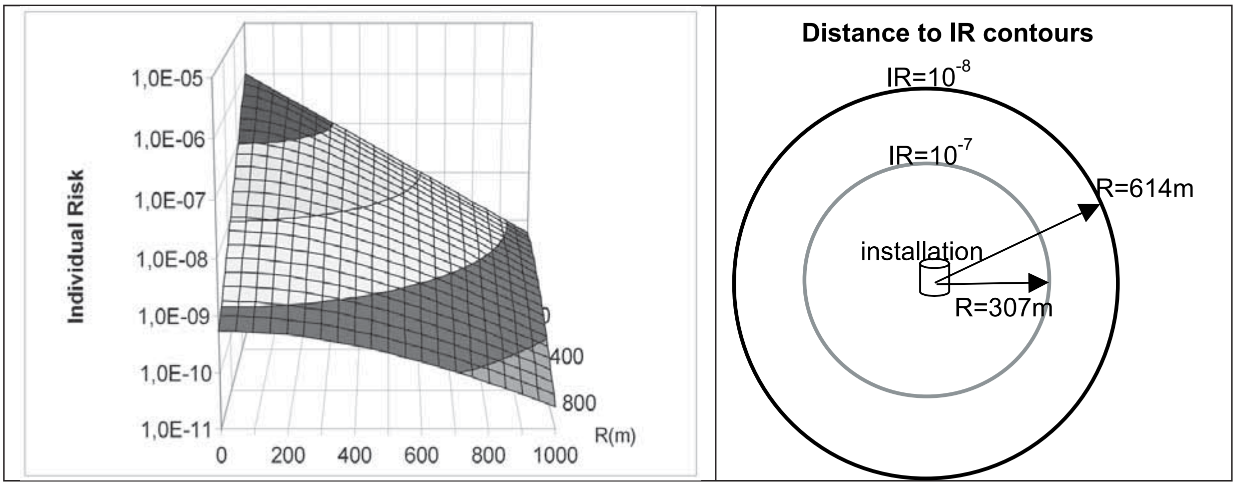


Figure 3-18: Individual risk levels as a function of location (left) and distance to individual risk contours (right)

Societal risk

In order to determine societal risk a circular city is assumed with an infinite surface and with a homogeneous uniform population density, so that $m(R)=m_0$ for all values of R. The number of fatalities is expressed as a function of the initial release term:

$$N = g(c_0) = \int_0^\infty F_D^*(c_0, R)m(R)dR = \int_0^\infty b\sqrt{c_0}e^{-1/2\alpha R}m_0 dR$$

$$= \left[\frac{-4b\pi\, m_0\sqrt{c_0}}{\alpha}e^{-1/2aR}\right]_0^\infty = \frac{4b\pi\, m_0\sqrt{c_0}}{\alpha} \qquad \textbf{(Eq. 3-48)}$$

The pdf of the number of fatalities is obtained from the Jacobian and by substitution of equation 3-48 ([26]) in equation 3-10:

$$f_N(n) = 1 - p_f \qquad n = 0$$

$$f_N(n) = f_{C0}(c_0)dc_0 / dn = \frac{ap_f}{c_0^{\;3}}\frac{\alpha\sqrt{c_0}}{2b\pi\, m_0} = \frac{512ap_f}{n^5}\left(\frac{b\pi\, m_0}{a}\right)^4 \qquad i \le n < \infty$$

(Eq. 3-49)

Note that the domain of the pdf of initial effects (eq. 3-35) has to be taken into account. If $c_0=1 \rightarrow n=i=4F_D\pi m_0/\alpha$. Integration of all values of n yields the expected value::

$$E(N) = \int_0^\infty nf_N(n)dn = \left[\frac{-512ap_f}{3n^3}\left(\frac{b\pi\, m_0}{\alpha}\right)^4\right]_i^\infty = 8/3ap_f\,\frac{b\pi\, m_0}{\alpha} \qquad \textbf{(Eq. 3-50)}$$

For confirmation the expected value is also determined from the expression obtained for individual risk (see eq. 3-46):

26 It follows that: $c_0 = \left(\frac{n\alpha}{4b\pi\, m_0}\right)^2$ and $dn / dc_0 = \frac{2b\pi\, m_0}{\alpha\sqrt{c_0}}$

$$E(N)=\int_0^{\infty} IR(R)m(R)dR=\left[-\frac{8ap_f b\pi m_0 e^{-0.5aR}}{3\alpha}\right]_0^{\infty}=8/3ap_f\frac{b\pi m_0}{\alpha} \quad \text{(Eq. 3-51)}$$

This again shows that individual and societal risk approaches are consistent. Following from the pdf of fatalities the distribution function and the FN curve can be derived. Given the format of the pdf of the number of fatalities, the FN curve has a steepness of –4, which is the same as in figure 3-17. As $E^2(N)$ is small relative to $E(N^2)$ we approximate the standard deviation with $€^2(N)\approx E(N^2)$, where:

$$E(N^2)=\int_0^{\infty} n^2 f_N(n)dn=\left[\frac{-256ap_f}{n^2}\left(\frac{b\pi m_0}{\alpha}\right)^4\right]_i^{\infty}=16ap_f\left(\frac{b\pi m_0}{\alpha}\right)^2 \quad \text{(Eq. 3-52)}$$

3.6.3 Point source with direction dependent dispersion of effects

The above example concerns the (hypothetical) situation of radial dispersion without the influence of wind. Released (toxic) substances will be dispersed by the wind and consequence- and risk levels depend on the wind direction. Following the proposals in section 3.5.4, the inclusion of direction dependent hazards is illustrated in the following example. In this example the already introduced schematisations are used for the occurrence of initial effects ($f_{C0}(c_0)$), dispersion of effects ($c(c_0,R)$) and the dose response function ($F_D(c)$). We assume that the pdf of the occurring wind direction (θ_W [rad]) can be described by:

$$f_W(\theta_W)=\frac{1}{\pi}\cos^2\frac{1}{2}\vartheta_W \qquad 0\le\vartheta_W\le 2\pi \quad \text{(Eq. 3-53)}$$

The dominating wind direction is the western wind (θ_W=0) and integration of the pdf over all wind directions yields 1. The probability of occurrence of a certain wind direction for each rounded degree[27] is obtained as follows (see figure 3-19a):

$$P(\vartheta_W)=\int_{\vartheta_W-0,5/180\pi}^{\vartheta_W+0,5/180\pi} f_W(\vartheta_W)d\vartheta_W=\left[\frac{1}{\pi}\left(\frac{\vartheta_W}{2}+\frac{\sin(\vartheta_W)}{2}\right)\right]_{\vartheta_W-0,5/180\pi}^{\vartheta_W+0,5/180\pi} \quad \text{(Eq. 3-54)}^{28}$$

The actually exposed area or "footprint" stretches along 45° (or $\pi/4$ in radians) on both sides of the occurring wind direction (see figure 3-9). Thus the probability of exposure in a direction θ in case of a failure is found as follows, results are shown in figure 3-19b. It is assumed that the occurrence of an initial release and the wind direction are independent.

$$P(exposure\ in\ dir.\vartheta\mid f)=\int_{\vartheta-\pi/4}^{\vartheta+\pi/4} f_W(\vartheta_W)d\vartheta_W=\left[\frac{1}{\pi}\left(\frac{\vartheta_W}{2}+\frac{\sin(\vartheta_W)}{2}\right)\right]_{\vartheta-\pi/4}^{\vartheta+\pi/4} \quad \text{(Eq. 3-55)}$$

Based on this equation the probability of a certain wind direction (θ_W) can be compared with the probability of exposure at direction (θ). Note that the probability of exposure is higher than the probability of a certain wind direction due to the add-on effects associated with the width of the exposed area.

27 The probability of occurrence of a wind direction θ_W within a rounded degree is determined by taking into account all wind directions within $\theta_W - 0{,}5^\circ \le \theta_W < \theta_W + 0{,}5^\circ$

28 Scaling of degrees leads to the formulation in the equation, because $1/360*2\pi=1/180\pi$

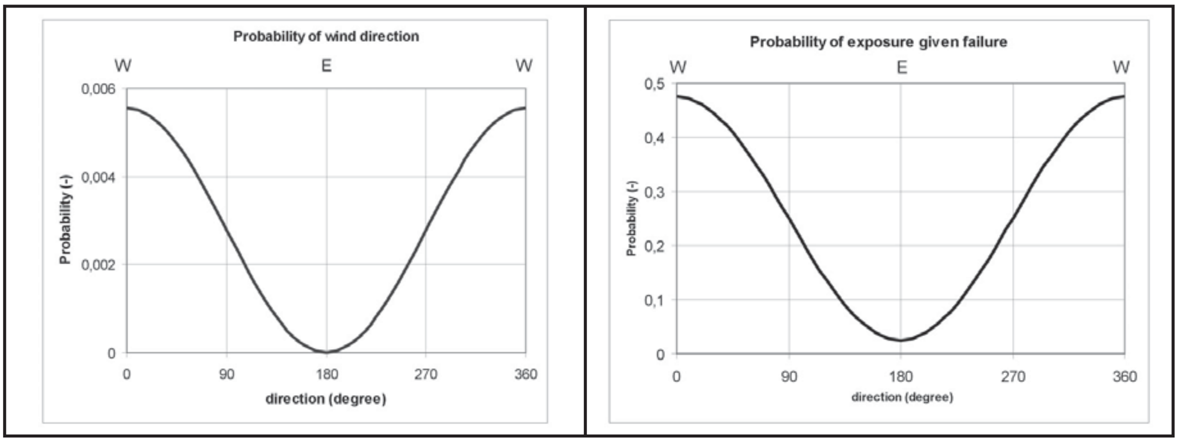


Figure 3-19: a) Probability of a occurrence of a certain wind direction; b) probability of exposure given failure in a certain direction.

The individual risk at radius R in direction θ can be assessed by combining the probability of an initial release, the probability of exposure, the dispersion model and the dose response function. By combination with equation 3-46 we obtain **(Eq. 3-56):**

$$IR(R,\vartheta) = \int_{\vartheta-\pi/4}^{\vartheta+\pi/4} \int_{0}^{\infty} p_f f_{C0|f}(c_0) f_W(\vartheta_W) F_D^{*}(c_0,R)\, dc_0 d\vartheta_W = 2/3 abp_f e^{-0,5aR} \int_{\vartheta-\pi/4}^{\vartheta+\pi/4} f_W(\vartheta_W) d\vartheta_W$$

Based on the above equation the individual risk contours can be plotted as is shown in figure 3-20 for values used in the previous section. It shows the 10^{-6} and 10^{-7} risk contours for the parameter values that have been given in earlier examples. The figure clearly shows the effects of the dominating western wind direction. This causes the IR contours to reach much further at the eastern side of the facility, as the wind direction is often west. There is a bend in the 10^{-8} contour at the western side of the origin. This is due to the fact that the eastern wind direction does not occur. Wind directions that are nearly east can still expose the western side of the installation (see also figure 3-19 – right).

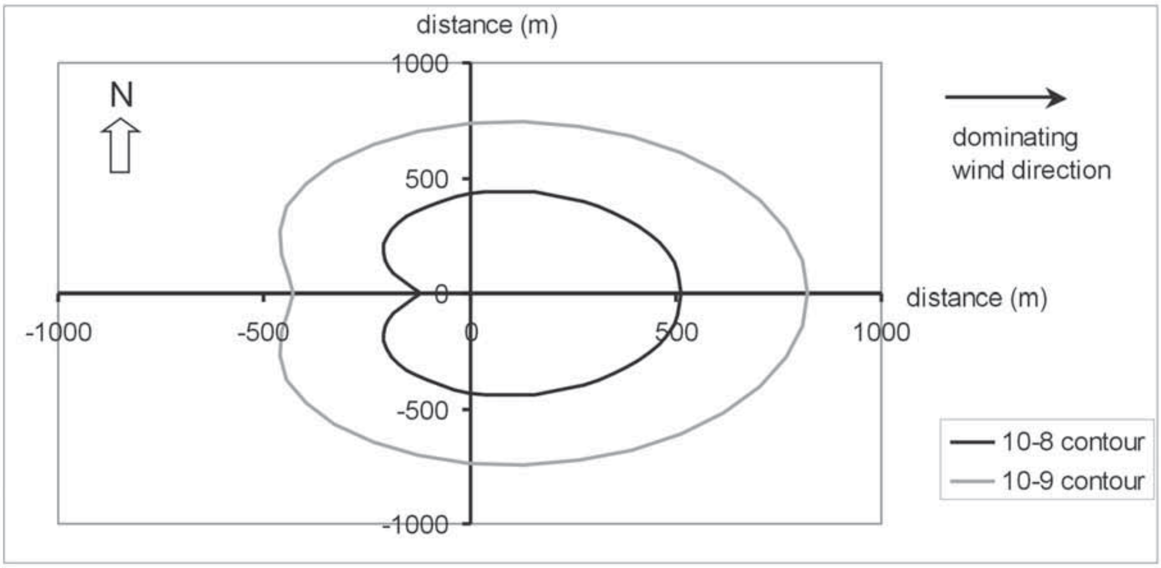


Figure 3-20: Individual risk contours for a hazardous facility taking into account the dominating wind direction.

Societal risk is not elaborated in further detail here. In more practical situations the societal risk will depend on the situation of population concentrations in areas that have a high probability of being exposed, see also section 3.5.4.

The above elaboration is mainly conceptual. In the Netherlands standardized guidelines have been developed with more advanced methods for quantification of probabilities, dispersion of effects (e.g. for explosion, fire, toxic gas) and consequences (CPR, 1999). In practical applications advanced numerical models are generally used for the risk analysis of hazardous installations in the Netherlands, such as SAFETI, Riskcalc and SAVEII (Ale *et al.*, 2001).

3.6.4 Spatially distributed accidents: Airport risk analysis

In previous applications the hazard source could be schematised as a point source. For some applications the accident location can be spatially distributed, for example the occurrence of airplane crashes in the vicinity of an airport. To demonstrate the approach for a spatially distributed risk source, the individual and societal risks are estimated in an example for a schematised airport "Schippolder". A mainly one-dimensional elaboration is given to improve understanding of the basic concepts[29].

The hypothetical airport "Schippolder" consists of one runway. Based on the number of airplane movements and accident frequencies, a crash is expected once in 20 years on average (p_f=0,05 yr^{-1}). In the one-dimensional elaboration only the distribution of the crash location relative to the flightpath centre line is considered, see also figure 3-22. The location of the crash (*x*') given an accident is normally distributed relative to the flightpath centre line with a standard deviation σ_C=300m. The pdf of a crash at location *x*' given an accident equals:

$$f_{x'|f}(x') = \frac{1}{\sqrt{2\pi}\sigma_C} \exp\left(-\frac{(x')^2}{2\sigma_C{}^2}\right) = \phi(x';0;\sigma_C) \qquad \textbf{(Eq. 3-57)}$$

The probability of a crash within a stretch of a metre in one year is thus found as follows:

$$P(crash\ at\ x') = p_f \int_{x'-0,5m}^{x'+0,5m} f_{x'|f}(x')dx'$$

The probability of exposure in one year is determined as follows. A person at location *x* will be exposed to crash effects of a crash at location *x*' if he is present within the crash area (see also section 3.5.3 and figure 3-11), leading to:

$$P(exposure\ at\ x) = P(x - A/2 < x' < x + A/2) = p_f \int_{x-A/2}^{x+A/2} f_{x'|f}(x')dx' \qquad \textbf{(Eq. 3-58)}$$

The probability of exposure at a location and the probability of a crash are depicted in figure 3-21. The width of the crash area A equals 50 metres and it represents the footprint of the crash. The probability of exposure at a location is higher than the crash probability due to the "add-on" effects associated with the crash area. The probability of being killed when present in the crash area is assumed constant (Piers *et al.*, 1992), leading to a dose response

29 The elaborations in this section are based on notes by prof. J.K. Vrijling

function: F_D=0,5. The individual risk is also shown in figure 3-21 and follows from the combination of the accident probability, the probability of exposure and the dose response function:

$$IR(x) = p_f F_D \int_{x-A/2}^{x+A/2} \varphi(x',0,\sigma)dx' \qquad \textbf{(Eq. 3-59)}$$

Results in figure 3-21 show that the curves for accident probability, exposure and individual risk all have the same shape as that of the normal pdf of the crash location given an accident (note that the vertical axis has a logarithmic scale). It is also remarked that the individual risk will be equal to the probability of exposure if mortality F_D=1.

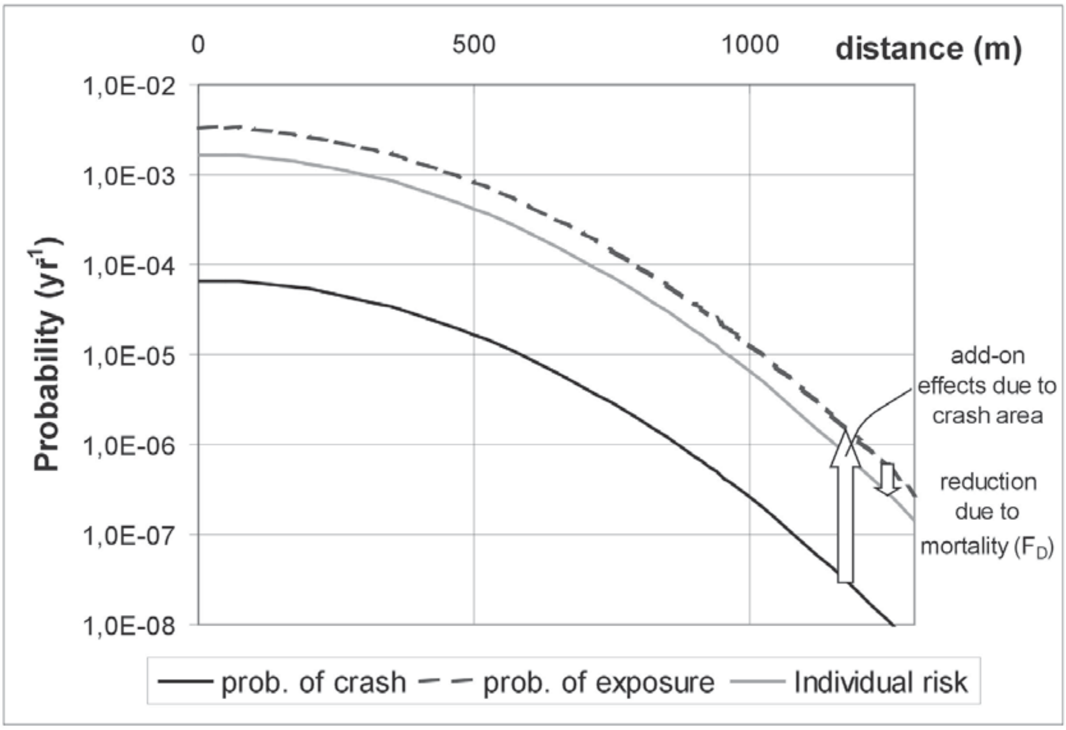


Figure 3-21: Probabilities of airplane crash and exposure and individual risk as a function of distance to the flightpath centre line.

Societal risk

Societal risk is determined for Schippolder airport. For this airport the individual risk limit is set at 10^{-5} (at 960m) and no new housing developments are tolerated within this contour. A residential area is present just outside the IR=10^{-5} contour. It has a width in *x* direction of 1000m and an infinite length in *y* direction, see figure 3-22. The population density in the area equals 200 people/ha. or 0,02 person / m^2. The population density in can thus be expressed as follows (see also figure 3-23a):

$$m(x) = 0\,pers/m^2 \qquad 0 \le x < 960 \quad and \quad 1960 < x < \infty$$
$$m(x) = m_0 = 0,02\,pers/m^2 \quad 960 \le x \le 1960 \qquad \textbf{(Eq. 3-60)}$$

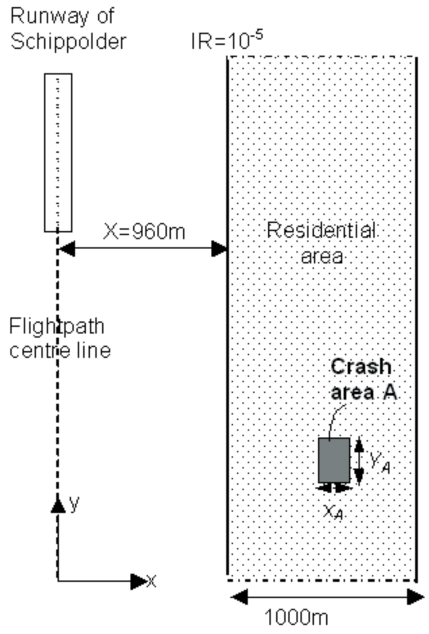


Figure 3-22: Situation of Schippolder airport showing location of residential area and the crash area

The airplane crash affects an area A with dimensions y_A=100m in y direction and x_A=50m in x direction. The number of fatalities due to a crash at location x' is found by multiplying the mortality with the number of people present inside the crash area:

$$N(x') = F_D y_A \int_{x'-x_A/2}^{x'+x_A/2} m(x)dx \qquad \textbf{(Eq. 3-61)}$$

If the airplane crashes in the centre of the area residential the number of fatalities equals: N=$F_D m_0 A$. If the crash occurs at the boundaries of (or just outside) the area, the number of fatalities is smaller when the crash area partially covers the populated area is exposed, see figure 3-23b.

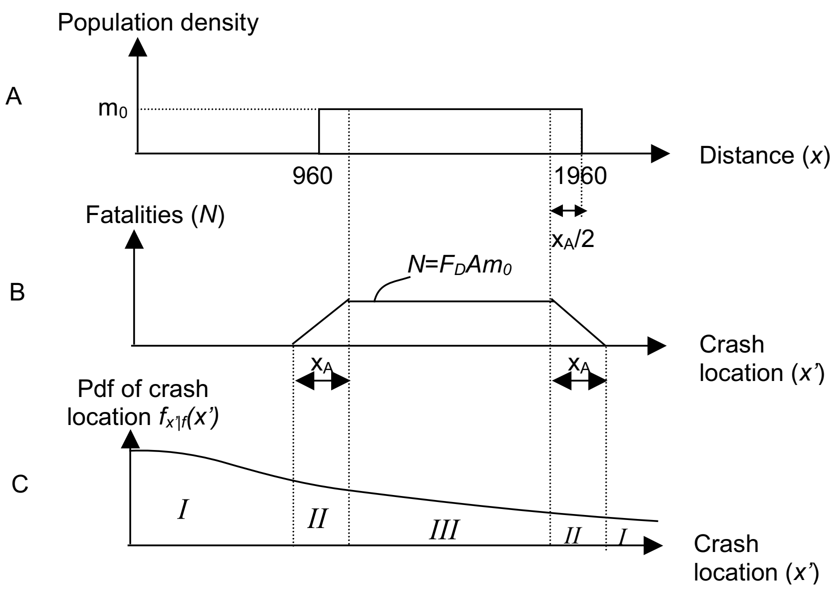


Figure 3-23: A): Population density; B): Number of fatalities in case of a crash at location x'; C): probability density function of crash at location x'

The probability of a certain number of fatalities is obtained by taking into account the pdf of a crash at location x' (see figure 3-23c). By combining the pdf of the crash location and the resulting number of fatalities, the probability density function of the number of fatalities is obtained (figure 3-24). The regions of probability density in figure 3-24 can be derived from the spatial pdf of the crash location. The probability density of 0 fatalities equals the probability of no crash ($1-p_f$) with the probability of a crash outside the populated areas (area I) added to it. The density of the maximum number of fatalities corresponds with a crash of which the effects are fully within the populated area (III). Area II represents situations where the crash area is partly within a populated area. The FN curve is derived from the probability density function and shown in figure 3-24. This implies that the probability at the intersection with the vertical axis of the FN curve corresponds to a probability of a crash which hits the residential area.

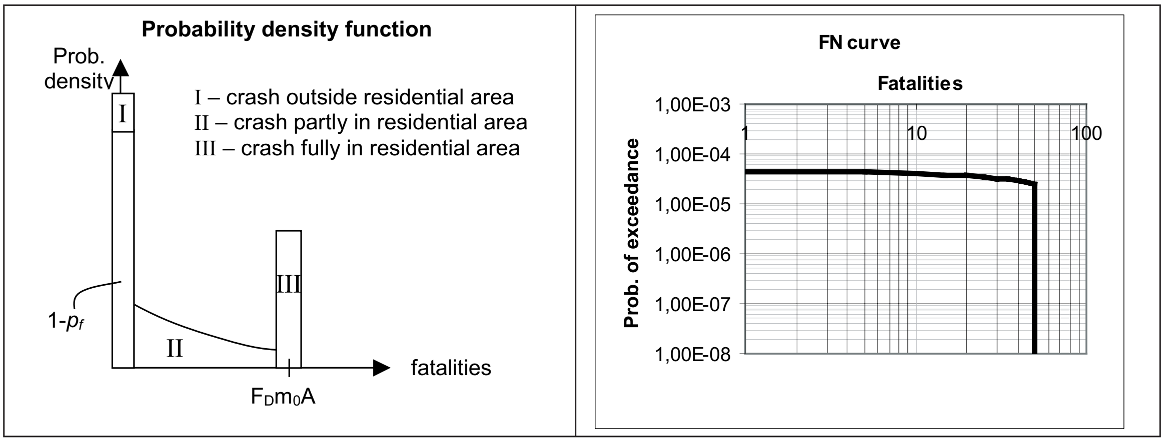


Figure 3-24: Probability density function of the number of fatalities due to a crash (left) and FN curve (right)

Integration of all possible crash locations and the consequently exposed areas yields the expected value of the number of fatalities:

$$E(N) = p_f \int_{-\infty}^{\infty} f_{x'|f}(x')n(x')dx' = p_f F_D y_A \int_{-\infty}^{\infty} f_{x'|f}(x') \int_{x'-x_A/2}^{x'+x_A/2} m(x)dxdx'$$

$$= p_f F_D y_A \int_{-\infty}^{\infty} \varphi(x',0,\sigma_C) \int_{x'-x_A/2}^{x'+x_A/2} m(x)dxdx' = 1{,}7 \cdot 10^{-3}\ fat/yr \qquad \text{(Eq. 3-62)}$$

From numerical approximation it follows that $\sigma(N) \approx 0{,}34$ *fat./yr* . The standard deviation is large relative to the expected value, due to the small probability of an event with a large number of fatalities.

The above shows how IR contours and the FN curve are related to the spatial distribution of accident locations and the population density. From this information insight can be gained in the relationship between individual and societal risk. For the example, increase of the population density near the IR=10^{-5} contour would significantly increase the societal risk because the accident probability is relatively high. However, it can also be shown that crashes at larger distances (> 2000m) from the flight path centre line do hardly contribute to the societal risk due to their low probability of occurrence. Thus, in this example, building additional houses east of the existing residential area would not substantially increase societal risk.

Discussion

The above text discussed simplified concepts related to risk quantification for external risk from airports. The example treated the problem in one dimension, but it can be easily extended to two dimensions. For more realistic modelling of airport risks reference is made to (Ale and Piers, 2000; Piers *et al.*, 1992; Piers, 1998). In more advanced calculations other distributions can be used to model the crash probability (e.g. Binomial) and the (conditional) spatial distribution of crash locations (e.g. Gamma and Pareto). The spatial distribution of the crash location is dependent on the airplane's flight path. As a result, the individual risk contours will generally follow the spatial runway and flightpath patterns. In risk quantification, multiple aircraft types and corresponding variation in crash areas should be accounted for. For realistic results the population density around the airport has to be included. In ongoing research the possibilities for causal risk modelling for Schiphol airport are explored, aiming to take into account the influence of other factors on accident probabilities in more detail. Examples of investigated issues are the effects of human factors (e.g. crew alertness) and weather conditions on crash probabilities (Roelen *et al.*, 2003).

Although the risk measures that are used for airports in the Netherlands are constantly changing, IR contours and the FN curve remain important indicators for representation of the risk of an airport. Currently the FN curve is only determined for external fatalities, i.e. those present on the ground. In this context it is also recommended to draw an FN curve for the internal risk (i.e. for passengers and crew). The FN curves for both the internal and external risk can be presented separately in the same FN curve to provide a more complete overview of the risks for different parties.

3.7 Concluding remarks

In this section a general approach for the quantification of individual and societal risk has been proposed. Analytical formulations for individual and societal risk have been derived based on the principles of reliability theory. Such a general set of formulations was not available in literature and thereby the foundation of risk quantification has been improved.

Risks to people can be quantified by combining four general elements: the probability of occurrence of physical effects at a risk source, the dispersion of effects, the number of people exposed, and the mortality amongst the exposed population. This subdivision also makes it possible to analyse the effects of risk reduction measures in a systematic way. It has also been shown how additional factors such as evacuation, meteorological conditions and spatially distributed accidents can be taken into account in risk quantification. The framework proofs applicable to different terrains and provides insight in the factors that influence the individual and societal risk levels.

It has been shown how the shape of individual risk contours is determined by the spatial dispersion of physical effects and / or the spatial distribution of accident locations. Individual risk can be plotted as a function of a location in a three dimensional graph and individual risk contours are obtained by projection of individual risk levels on a map[30]. It has also been shown in an example (section 3.6.2) how the general formulations can be used to derive analytical expressions for related indicators such as the effect distance and the distance to individual risk contours, which are currently mainly determined numerically. The individual risk for a system can never become larger than the probability of failure of the system.

Societal risk concerns the probability of a multiple fatality accident. Societal risk is often shown in the FN curve. It has been shown how the FN curve can be analytically derived. In theory, the steepness of the FN curve depends on the shape of the pdf of initial effects, the dispersion function and the dose response function. In practice an FN curve is often generated based on information regarding probabilities and consequences for various accident scenarios. The shape of the FN curve depends on the probability that accident scenarios will expose populated areas. Figure 3-25 shows an exemplar FN curve. The intersection with the vertical axis equals the cumulative probability of lethal accidents (this is often equal to the overall probability of failure of a system). The curve remains horizontal up to the fatality number that corresponds to the scenario with smallest consequences. The intersection of the curve with the horizontal axis corresponds to the accident scenario with the largest number of fatalities.

30 It is noted that this is similar to the concept of a joint probability density function of two variables. The joint probability density can be displayed in a three-dimensional graph as a function of both variables or it can be by projected in a two dimensional figure.

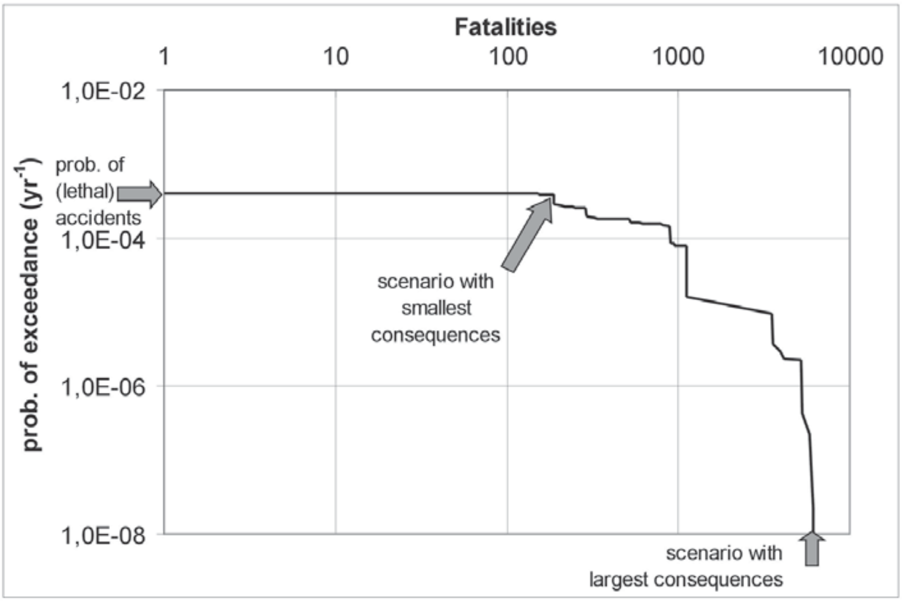


Figure 3-25: FN curve for flooding of South Holland (see also section 9)

For spatially distributed accidents (e.g. airplane crashes) and direction dependent hazards (e.g. toxic releases) the influence of the extent of the exposed area (or accident footprint) *A* has been investigated. If *A* becomes larger this leads to an increase of the probability of exposure and consequently the individual risk. Exposure of a larger area can also lead to an increase in the number of fatalities given an accident and thus to an increase of societal risk.

The proposed formulations have been used to give a theoretical confirmation of the relationship between individual and societal risk. The expected values obtained from individual and societal risk must be identical. It is noted that in risk calculations in practice the expected values calculated from individual and societal risk are sometimes not the same, because different assumptions are used for the calculations of individual and societal risk. More specifically the relationship between individual risk contours, which are generally used for zoning, and the FN curve has been clarified. For a fixed installation, zoning measures affect the consequences of an accident and lead to a horizontal shift of the FN curve. For situations where the probability of an accident is spatially distributed, zoning leads to a change in the probability of exposure and lead to a vertical shift of the FN curve.
The above insights in the properties of the FN curve and individual risk contours and their mutual relationship can be used to verify the consistency of individual and societal risk calculations obtained from numerical models.

This section focused on the quantification of individual and societal risk. Eventually the acceptability of these risks has to be evaluated. The results of individual and societal risk calculations can be used as input for decision-making. Several of the proposed evaluation methods are directly based on the expected value of loss of life, such as the Life Quality Method (Nathwani *et al.*, 1997; Rackwitz, 2002). In other approaches specific risk limits for individual and societal risk are proposed, see e.g. (Vrijling *et al.*, 1998; Bottelberghs, 2000; Jonkman *et al.*, 2003; Trbojevic, 2004). An example of the analysis and evaluation of flood risks in the Netherlands with the latter type of limits is presented in section 9.

4 Uncertainties in loss of life estimates

Research question: How will uncertainties in loss of life estimates affect the outcomes of risk quantification?

Keywords: uncertainty, dose response function, loss of life, quantitative risk analysis

4.1 Introduction

This section investigates the effects of uncertainties in loss of life estimates on the outcomes of risk quantification. Dose response functions are generally used to estimate loss of life caused by a critical event. They give a relationship between the intensity of physical effects and the mortality in the exposed population. In most applications it is assumed that the dose response function returns a deterministic response fraction for every intensity level of physical effects, see e.g. (CPR, 1990; AIChE, 2000; PGS, 2005). Such a schematisation neglects the potential uncertainties in loss of life estimates. In this section two types of uncertainty are considered: 1) uncertainty due to the randomness in the outcome of the exposure of people to physical effects and 2) model uncertainty in the dose response function. Within the proposed classification for uncertainties (see section 1.2.3) the first type is an inherent uncertainty, the second a knowledge uncertainty. Both types of uncertainties are described in more detail below.

Randomness in the outcome of the exposure of a group of people

The possible randomness in the outcome of the exposure of people can be illustrated with a simple example. Suppose that we have a population of 100 objects and that the dose response function for these objects is known. The objects (e.g. concrete cubes) are exposed to a load that is expected to lead to a probability of failure for each object of 0,2. The experiment (exposure of all 100 objects) is repeated for 100 populations. Different distributions of the number of failures could result as outcome of the series of experiments. These distributions all give the same number of total failures. A few examples of the many possible outcomes are:

- All 100 experiments result in 20 failures;
- 50 experiments result in 10 failures, 50 experiments result in 30 failures;
- 80 experiments result in 0 failures, 20 experiments result in 100 failures.

The example above shows that there can be variation in the outcomes of individual experiments. The same concept applies to the use of dose response function for the estimation of the number of fatalities within an exposed population. If the dose response function is applied to an exposed **group** (or population) as a whole, it is used to determine the expected number of people in that group that does not survive. This type of application has been used in the previous section. It is indicated as a deterministic application as it is assumed that there is no variation in the consequences. Alternatively, the dose response function can be used to estimate the **individual** probability of death[1]. The total number of fatalities in a group is found by summing up the individual outcomes. The consequence will be a ran-

1 Thereby this differs somewhat from the mortality definition that has been used in sections 2 and 3. There it has been defined as the fraction of fatalities amongst the exposed population.

dom number due to variation in individual responses to exposure. The resulting distribution of the number of fatalities is determined by dependencies between individual failures, as will be discussed in more detail in sections 4.3. The two above types of applications are schematically depicted in figure 4-1.

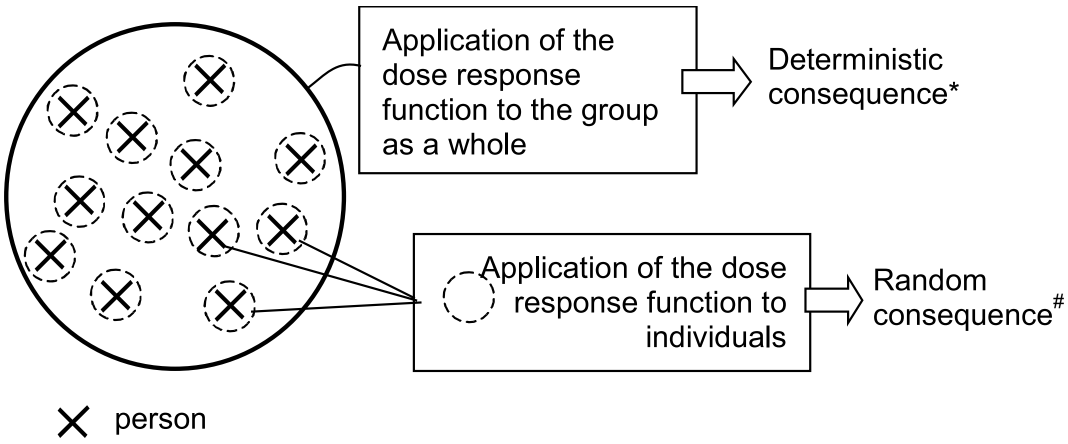


Figure 4-1: Schematic difference between the application of a dose response function to an exposed group of people or to individuals

Figure notes: * - A deterministic consequence is only obtained if the model uncertainty in the dose response function is not considered, see below. # - It will be shown in section 4.4 that the result of the application of the dose response function to individuals approximates the deterministic outcome for independent resistances and a large number of people exposed.

Model uncertainty in the dose response function

A dose response function is conceptually similar to a so-called fragility curve. Such a curve is used to model the probability of structural failure of structures as a function of the load, e.g. for earthquakes. A fragility curve can be derived from field observations after disasters or from experimental data. In a similar way a dose response function can be derived from observations on human mortality from past disasters or from (scaled) data from animal tests (see also section 2). Available observations will generally be scattered around the bestfit function that is derived from the observations. This results in model uncertainty in the dose response function. Due to the effects of model uncertainties in the dose response function, the consequences of exposure of a group could also be uncertain (see figure 4-1). Model uncertainty can arise due to the fact that the observations that are used to derive the dose response function represent different circumstances (that are not captured as variables in the dose response function) and /or populations with different vulnerabilities (see further discussion in section 4.5). The model uncertainty in the dose response function can be represented by means of a conditional distribution of the response fraction for a given intensity of physical effects, see figure 4-2. Over the whole range of intensities, the uncertainty can be displayed with confidence intervals around the average[2] dose response function. Thereby the uncertainty is quantified and displayed by means of a family of distribution curves, where each curve represents a confidence level (see also section 1.2.4). Bayesian probability theory offers the possibility to integrate these uncertainties in the dose response function, as will be explained in more detail in section 4.5.

2 In the further elaborations in this thesis a symmetrical conditional distribution for model uncertainty is assumed. In that case the average and median dose response functions are the same. However, for other cases the average and median curve do not need to be the same, see also (Paté Cornell, 2002).

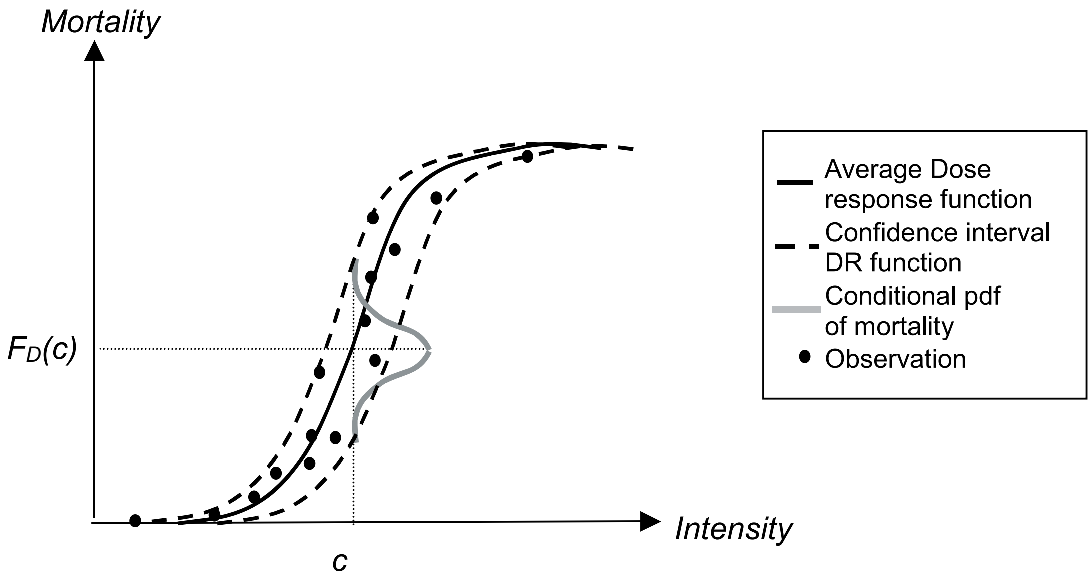


Figure 4-2: Model uncertainty in the dose response function

Outline of this section
Above, general concepts related to uncertainty in loss of life estimates have been introduced. In the following sections these are further elaborated. For completeness, first the application of the deterministic dose response function is elaborated in section 4.2. Consequently, the effects of **randomness** in individual responses are investigated for the application of the dose response function to individuals in section 4.3. In this section different situations related to dependencies between failures are elaborated. The practical interpretation of these dependencies is explored in section 4.4. **Model uncertainties** and possibilities for their integration in the dose response function are discussed in section 4.5. Section 4.6 gives an overview of different distributions that can be used to represent uncertainty in loss of life estimates and investigates the influence of uncertainties on compliance to risk limits. A closing discussion is provided in section 4.7.

4.2 Deterministic application of the dose response function

In this approach it is assumed that application of the dose response function to a group of people exposed returns one deterministic number of fatalities for each load. Outcomes are shown for a deterministic and probabilistic load situation.

Deterministic load situation
We first assume the occurrence of one single event *(f)* and a deterministic load case. The number of fatalities given failure $(N|f)$ is found by multiplying the mortality fraction (F_D) with the number of people exposed (N_{EXP}). The corresponding probability density function[3] (pdf) of the number of fatalities is depicted in figure 4-3. Note that in this section the probability mass at n is presented as a density over the range n-½ to n+½ .

3 For situations with discrete stochastic variables (variables that can have discrete value) formally a probability mass function should be used. For continuous stochastic variables a probability density function (pdf) is used. To avoid confusion in terminology, the general term of probability density function is used for both situations in this thesis.

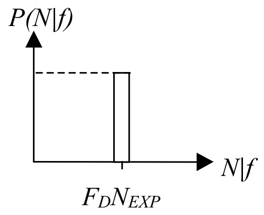


Figure 4-3: Probability density function of the number of fatalities given an event for a deterministic load

$$\begin{aligned} &P(N = F_D N_{EXP} \mid f) = 1 \\ &P(N \neq F_D N_{EXP} \mid f) = 0 \\ &E(N \mid f) = F_D N_{EXP} \\ &\sigma(N \mid f) = 0 \end{aligned} \qquad \textbf{(Eq. 4-1)}$$

Probabilistic load situation

In a probabilistic calculation both the randomness of load situations and human resistances have to be considered. For this schematisation the application of dose response function in risk quantification, has been extensively discussed in section 3. For clarity, the concept is briefly repeated in figure 4-4. The load consists of physical effects with a certain intensity, and the dose response function represents the human resistance. For each given load intensity, a response fraction follows from the dose response function. The number of fatalities is determined by multiplying the mortality (F_D) by the magnitude of the exposed group (N_{EXP})([4]). The pdf of the number of fatalities ($f_N(n)$) is obtained by combining the pdf of intensity of physical effects, the dose response function, and the magnitude of the exposed population, see figure 4-4 and section 3 for formulas.

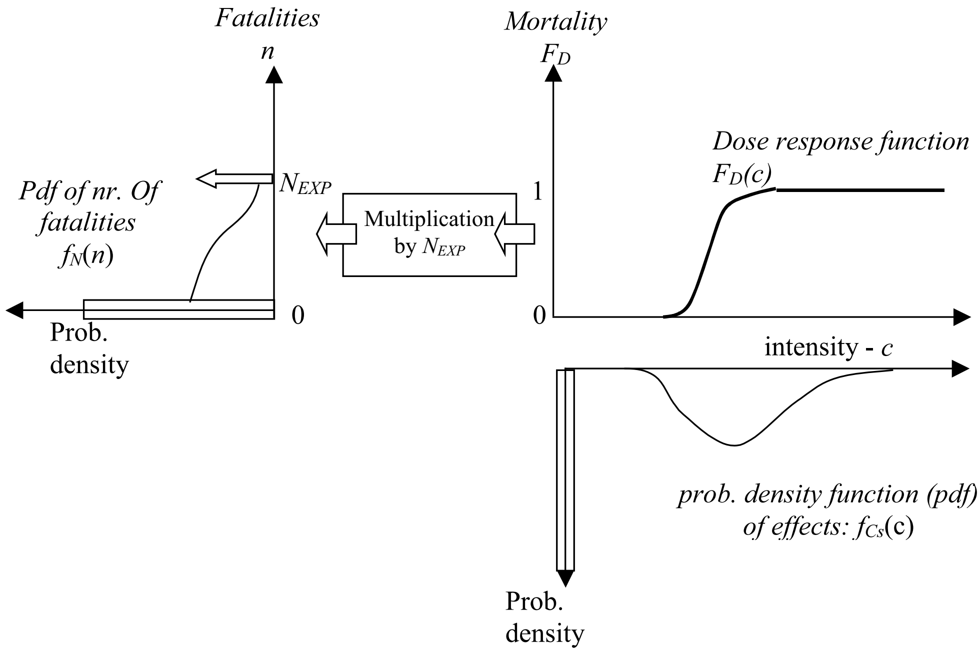


Figure 4-4: Determination of the pdf of the number of fatalities by combing load (physical effects) and resistance (the dose response function), for a constant exposed population N_{EXP}.

4 It is assumed that the magnitude of the exposed group is constant, independent of the load and that no evacuation occurs.

4.3 Application of the dose response function to individuals

4.3.1 General

The dose response function can also be applied to estimate the probability of death of an individual person. This can be appropriate when there is a large variation between the intensities of physical effects to which individuals are exposed. An analysis at the individual level can also be carried out to consider the variation in responses that is associated with variability between persons. Application of the dose response function to an individual implies that it is assumed that the considered individual has the resistance (properties) of an arbitrary person from the population for which the dose response function has been derived[5].

When the dose response function is applied to individuals, the total number of fatalities in the group may be random, even if the load is deterministic. The key issue is that the distribution of the number of fatalities will be determined by dependencies in load intensities and human resistances.

Correlation is used as a measure for dependency. In general, correlation expresses the degree to which one phenomenon or random variable is associated with or can be predicted from another. Here, linear correlation is used to express the dependency. It refers to the degree to which a linear predictive relationship exists between random variables, as measured by a (linear) correlation coefficient ρ. The terms dependency and linear correlation are not fully equivalent. If two stochastic variables are independent the value of the linear correlation coefficient is 0. However, examples can be given where stochastic variables are dependent but not correlated, e.g. when there is a quadratic relationship between them. In the following elaborations the term dependent is used to denote situations that are linearly dependent and (linearly) correlated. The effects of dependencies on the distribution of failures are investigated in the following sections. This is first illustrated in an example for a deterministic load scenario. After that, a probabilistic load situation is elaborated.

Deterministic load situation
In a first example it is assumed that all the people in a group are exposed to the same deterministic load. The schematic experiment (exposure of a person to physical effects) is repeated for every person[6]. We assume a non- deterministic resistance function, i.e. with standard deviation larger than 0. For each individual (i) there are two possible outcomes, namely death (with probability $F_{D,i}$) or survival (with probability 1-$F_{D,i}$). Summation of individual "failure probabilities" for the whole exposed group yields the expected number of fatalities:

$$E(N \mid f) = \sum_{i=1}^{N_{EXP}} F_{D,i} \qquad \textbf{(Eq. 4-2)}$$

5 Note that it is possible to develop a dose response function that takes account of an individual's or a subgroup's specific resistance characteristics, see also appendix 2.III.

6 In analogy: the experiment can be considered as repeated loadings of single elements, which all have a probability of failure.

Application of the dose response functions to a group as a whole or to individuals leads to the same **expected value,** for given values of mortality (F_D) and the magnitude of the exposed population (N_{EXP}). However, the distribution of consequences is determined by dependencies between failures of elements, as is shown below.

We consider a situation where people have independent resistances[7] and are exposed to the same deterministic load. Then the **Binomial** distribution can be applied to describe the overall distribution of consequences (see figure 4-5). The probability density function, expected value and standard deviation of the Binomial distribution are as follows:

$$P(N=n\,|\,f)=\frac{N_{EXP}!}{n!(N_{EXP}-n)!}F_D{}^n(1-F_D)^{N_{EXP}-n}$$
$$E(N\,|\,f)=F_D N_{EXP} \qquad \textbf{(Eq. 4-3)}$$
$$\sigma(N\,|\,f)=\sqrt{N_{EXP}F_D(1-F_D)}$$

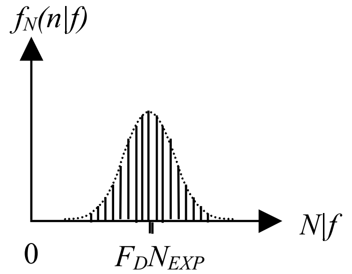


Figure 4-5: probability mass function for the Binomial distribution

Note that the standard deviation is small relative to the expected value for large values of N_{EXP} and / or large values of F_D. For large values of N_{EXP} the Poisson distribution[8] is a good approximation. The normal distribution gives a good approximation for the binomial for larger values of N_{EXP} and values of F_D close to 0,5.

Alternatively, one may consider full dependence[9] between the outcomes of the individual experiments, i.e. between persons' resistances. In the present case this means that the death of one person also implies the death of the whole population. As a result, exposure of the population has two possible discrete outcomes: all persons die with probability F_D or all persons survive with probability (1-F_D). This situation can be modelled with the **Bernoulli** distribution (figure 4-6):

$$P(N=0\,|\,f)=1-F_D$$
$$P(N=N_{EXP}\,|\,f)=F_D$$
$$E(N\,|\,f)=F_D N_{EXP} \qquad \textbf{(Eq. 4-4)}$$
$$\sigma(N\,|\,f)=N_{EXP}\sqrt{F_D-F_D{}^2}$$

7 This example also concerns a non-deterministic resistance function, with standard deviation larger than 0.

8 Poisson distribution: $P(N=n\,|\,f)=\frac{(F_D N_{EXP})^n}{n!}e^{-F_D N_{EXP}}$; $E(N|f)=F_D N_{EXP}=VAR(N|f)$:

9 A and B are fully dependent when: P(A|B)=1, thus P(A ∩ B)=P(A)=P(B)

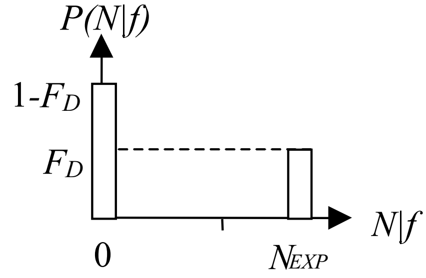


Figure 4-6: Probability density function of the Bernoulli distribution

The above results show that the distributions obtained when the dose response function is applied to individuals differs from the distribution that is obtained when the dose response function is applied to a group of people. The expected values of the two approaches are identical.

Probabilistic load situation
In another situation both load and resistance are both stochastic variables. In this case the distribution of consequences depends on the dependency between failures of two elements.

Therefore, it is relevant to understand which factors determine the dependency between the failures of two elements. Let us now consider the most general case, in which loads and resistances are stochastic variables. Let us introduce a formal approach by defining:

$$Z = R - S \qquad \textbf{(Eq. 4-5)}$$

Here, R is the resistance and S the load. The variable Z is called the limit state function of the element or object. Such a type of approach is generally followed in (structural) reliability analysis. The general formulation to determine the correlation between the Z-values of two elements is:

$$\rho_{ZZ} = \frac{COV(ZZ)}{\sigma_Z{}^2} = \frac{\rho_{RR}\sigma_R^2 - 2\rho_{RS}\sigma_R\sigma_S + \rho_{SS}\sigma_S^2}{\sigma_R^2 + \sigma_S^2 + 2\rho_{RS}\sigma_R\sigma_S} \qquad \textbf{(Eq. 4-6)}$$

Where:
COV(ZZ) – Covariance between the Z values of elements
σ_R - standard deviation of the resistance
σ_S - standard deviation of the load
σ_Z - standard deviation of the Z value of the element
ρ_{RR} - correlation between the resistances of elements
ρ_{RS} - correlation between the loads on and resistances of elements
ρ_{SS} - correlation between loads on elements

For most applications it is realistic to assume that load and resistance are independent, so ρ_{RS}=0. This reduces the equation to:

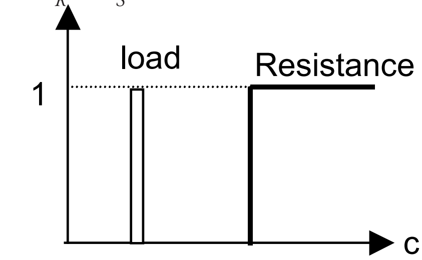
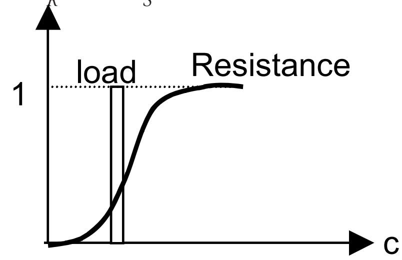
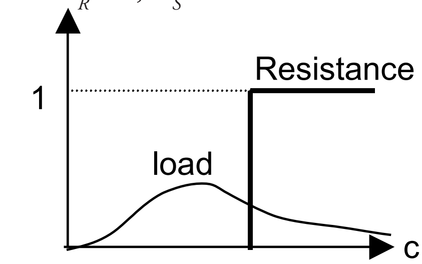
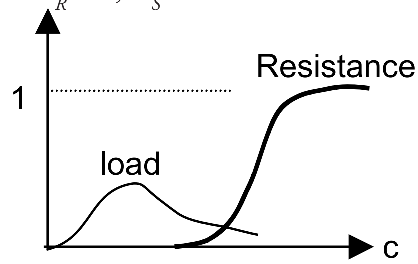
$$\rho_{ZZ} = \frac{\rho_{RR}\sigma_R^2 + \rho_{SS}\sigma_S^2}{\sigma_R^2 + \sigma_S^2} \qquad \textbf{(Eq. 4-7)}$$

Based on equation 4-7 we can conclude that two variables determine the dependency between the failure of two (or more) elements or persons, and thus the distribution of failures:

1. The standard deviations of load (σ_S) and resistance (σ_R);
2. The mutual correlations between loads (ρ_{SS}) and resistances (ρ_{RR}) of the elements.

1) Standard deviations of load and resistance: Load and resistance can either be expressed deterministically ($\sigma=0$) or with a distribution ($\sigma>0$). Four situations are distinguished, based on variations in load and resistance. Table 4-1 shows the pdf of load and the distribution of resistance for these situations.

Table 4-1: Combinations of load (S) and resistance (R)

	Deterministic resistance	**Variable resistance**
Deterministic Load	*I:* $\sigma_R = \sigma_S = 0$ 	*II:* $\sigma_R > 0; \sigma_S = 0$ 
Variable Load	*III:* $\sigma_R = 0; \sigma_S > 0$ 	*IV:* $\sigma_R > 0; \sigma_S > 0$ 

2) Mutual correlations between loads and resistances

Possible combinations of mutual correlations between loads and resistances are shown in table 4-2 for positive correlation values. Negative correlation values ($\rho<0$) are not considered in table 4-2 and the remainder of this section. A negative correlation value implies a negative relationship between loads or resistances respectively. For exposure of humans such negative correlations are considered less realistic. Note that there are situations in other applications where negative correlations are more relevant. Consider for example a system consisting of two elements, where one element absorbs the load in the system and reduces the load on the other element[10].

10 A related example of negative correlation between failures could be given for dike ring areas in the Netherlands. Flooding of one dike ring could imply a reduction of loads on the other dike ring, and thereby reduce the probability of flooding of that dike ring. In that case, the failures of the two dike rings will have a negative correlation.

Table 4-2: Possible combinations of (positive) correlations between load and resistance

	ρ_{SS}=0	ρ_{SS} =1
ρ_{RR}=0	Loads and resistances independent	Loads dependent resistances independent
ρ_{RR}=1	Loads independent resistances dependent	Loads and resistances dependent

Next sections

The next sections will further outline the application of dose response functions to individuals. The situations distinguished in table 4-1 are used as a framework. Quadrants II, III en IV[11] are elaborated in section 4.3.2 to 4.3.4. For each situation it will be shown how the distribution of consequences depends on the mutual correlations between loads and resistances (table 4-2). For completeness and comparison, the outcomes of the deterministic application of the dose response function are also presented.

4.3.2 Deterministic load and variable resistance

As the combination of deterministic load and variable resistance has already been discussed in the previous section, an example of this situation is given here. Suppose that an explosion occurs in a tunnel with 100 people present (N_{EXP}=100). The explosion has a peak pressure of 400 kPa. The corresponding mortality is found from the probit function derived from (CPR, 1990) and shown in figure 4-7. The corresponding mortality equals F_D=0,4. For the different situations that have been discussed previously, the resulting distribution of the number of fatalities given an accident is determined.

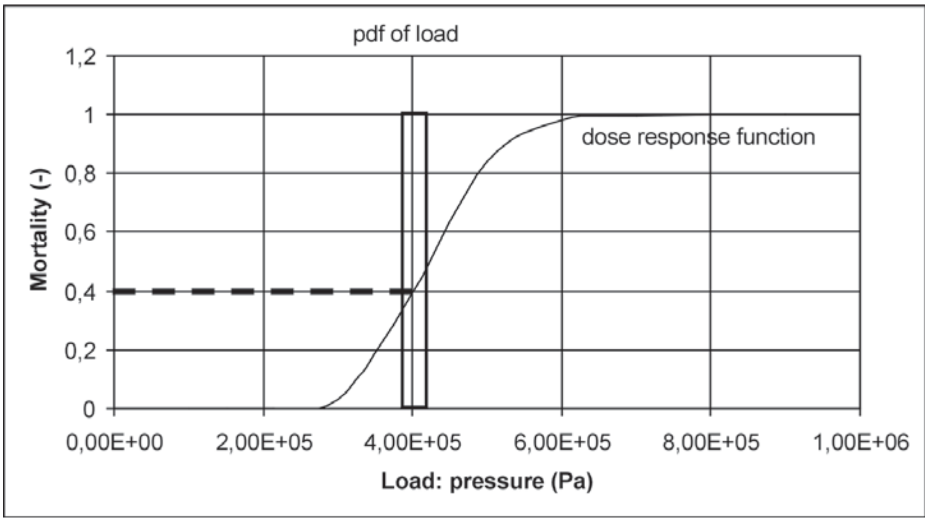


Figure 4-7: Dose response function used for estimation of mortality due to explosion pressures (CPR, 1990) and deterministic load.

When the dose response function is applied to the **group** as a whole (section 4.2),_this leads to the following expected outcome: $E(N|f)=F_D N_{EXP}$ with probability 1; and $\sigma(N|f)=0$, see figure 4-8.

11 As the combination of a deterministic load and resistance gives a known outcome, this situation is not treated.

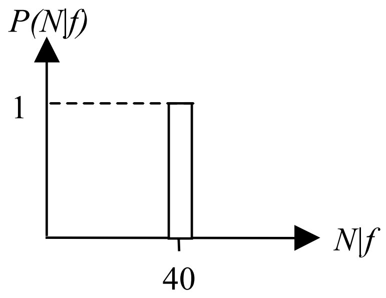


Figure 4-8: Probability density function of the number of fatalities for application of the dose response function to a group (deterministic load, variable resistance)

Application of the dose response function to **individuals** with fully **dependent resistances** (ρ_{RR}=1) results in a Bernoulli distribution. The possible outcomes are 0 fatalities with probability 0,6 or 100 fatalities with probability 0,4, see figure 4-9.

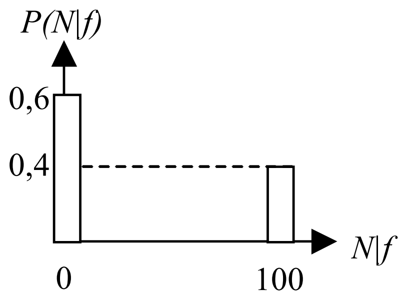


Figure 4-9: Probability density function of the number of fatalities for application of the dose response function to individuals with fully dependent resistances (deterministic load, variable resistance)

In case of repeated **individual** experiments and **independent resistances** (ρ_{RR}=0) the Binomial distribution can be applied. In the case of the application to independent individuals the same experiment (i.e. exposure to the explosion) is repeated for every person present. The individual experiment has two possible outcomes: the person either survives or dies. The probability of failure of each individual thus equals F_D=0,4 and the number of experiments equals N_{EXP}=100. The resulting Binomial probability density function of the number of fatalities is shown in figure 4-10.

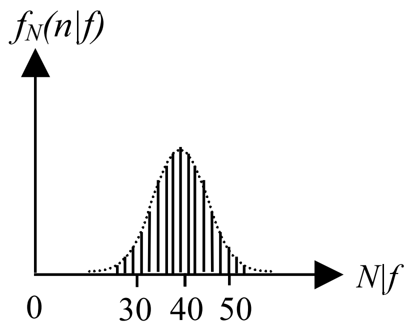


Figure 4-10: Probability density function of the number of fatalities for application of the dose response function to individuals with independent resistances (deterministic load, variable resistance)

The expected values for the Binomial and Bernoulli distributions are equal:

$E(N \mid f) = F_D N_{EXP} = 40$

The standard deviations become:

Binomial distribution: $\sigma(N \mid f) = \sqrt{N_{EXP} F_D (1 - F_D)} = 4{,}89$

Bernoulli distribution: $\sigma(N \mid f) = N_{EXP} \sqrt{F_D - F_D^{\ 2}} = 48{,}9$

4.3.3 Variable load and deterministic resistance

This case represents a deterministic resistance and a variable load (Figure 4-11). The dose response function is modelled the deterministically, i.e. F_D=1 when a critical dose or concentration threshold of effects (c_{cr}) is exceeded.

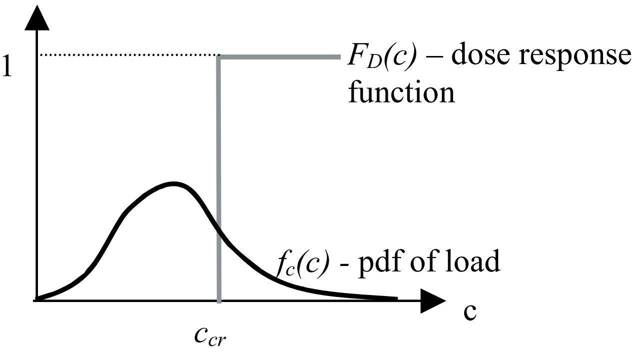


Figure 4-11: Variable load and deterministic dose response function

For this situation application of the pdf of load and dose response function to a **group** results in the Bernoulli distribution, see see figure 4-12. The event 'death of the whole exposed population' occurs with a probability that is equal to the probability of exceedance of c_{cr}

$$P(N = 0 \mid f) = P(c \le c_{cr}) = \int_0^{c_{cr}} f_C(c)dc = F_c(c_{cr})$$

$$P(N = N_{EXP} \mid f) = P(c > c_{cr}) = \int_{c_{cr}}^{\infty} f_C(c)dc = 1 - F_c(c_{cr}) \qquad \textbf{(Eq. 4-8)}$$

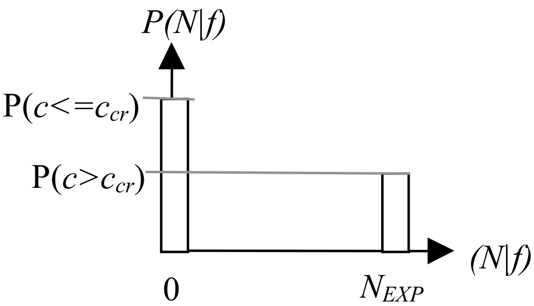


Figure 4-12: Probability density function of the number of fatalities for application of the dose response function to a group (variable load, deterministic resistance)

When the dose response function is applied to **individuals** with deterministic resistances, who are exposed to fully **dependent loads** (ρ_{SS}=1), that same Bernoulli distribution results. When **individuals** are exposed to **independent loads** (ρ_{SS}=0) from the pdf $f_c(c)$, each exposure leads to probability of failure $P(c>c_{cr})$. Then, a Binomial distribution for the number of fatalities in the population is obtained, see e.g. figure 4-5.

4.3.4 Variable load and variable resistance

This section discusses a situation with variable load and resistance distributions. The elaboration for the deterministic application of the dose response function to a group has been discussed in section 4.2.

When dose response functions are applied to individuals, the distribution of consequences (i.e. the number of fatalities) will be determined by dependence between failures of different elements. Figure 4-13 shows correlation between failures (ρ_{ZZ}), as a function of correlations between loads (ρ_{SS}) and resistances (ρ_{RR}) for positive correlation values. ρ_{ZZ} is determined according to formula 4-7 and it is assumed that load and resistance have the same standard deviation.

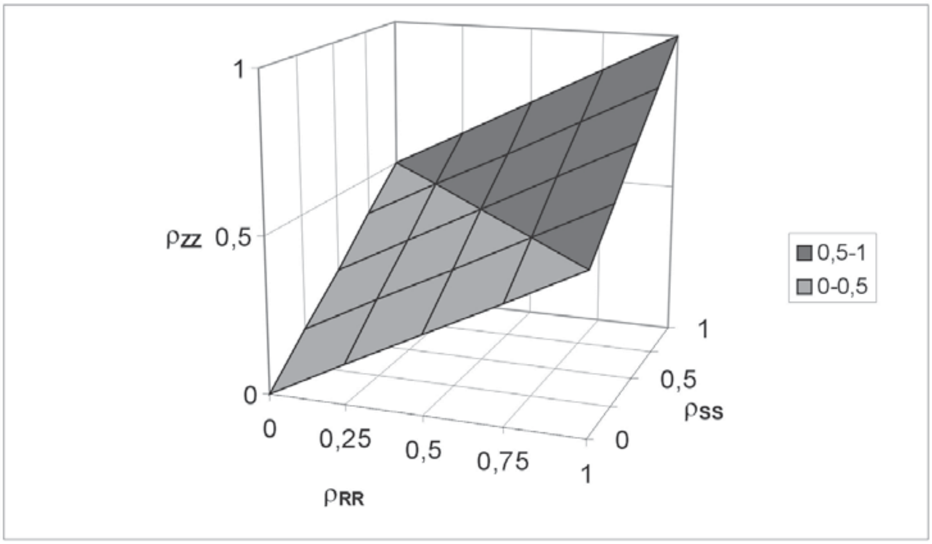


Figure 4-13: Correlation between failure of elements as a function of mutual correlations between loads and resistances, for $0 \leq \rho_{SS} \leq 1$ and $0 \leq \rho_{RR} \leq 1$ and $\sigma_R = \sigma_S$.

The effect of correlation on the distribution of consequences is examined by considering the probability of mutual failure of two elements. A standard situation is elaborated with two identical elements representing two persons. The probability of failure of each element is denoted by $P(Z1<0) = P(Z2<0)$. Failure of an element represents the death of a person and the corresponding probability represents mortality. In order to determine the distribution of consequences, the probability that both elements fail simultaneously ($P(Z1<0$ and $Z2<0)$ is of interest. This probability, derived from the standard solution for the failure of a series system, is depicted in figure 4-14 as a function of the correlation between failures of elements ρ_{ZZ}.

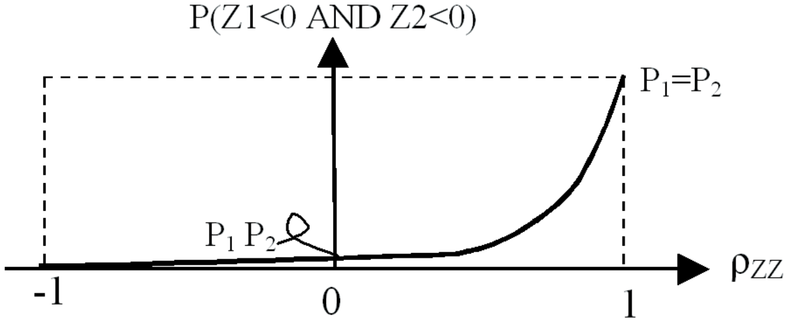


Figure 4-14: Failure probability of a series system of two elements as a function of correlation coefficient (schematic display) modified after (Vrouwenvelder and Vrijling, 1996)

A few standard situations are recognisable in figures 4-14. If two elements are mutually exclusive (ρ_{ZZ}= -1) simultaneous failure is impossible. If elements are independent (ρ_{ZZ}= 0) the resulting distribution of failures is binomial. If failure of the elements is fully dependent (ρ_{ZZ} = 1) the Bernoulli distribution can be applied. Figure 4-14 shows that only for values of ρ_{ZZ} near 1, the probability of mutual failure of elements becomes significant. Situations with correlations values $0<\rho_{ZZ}<1$ cannot be described with standard distribution types.

Table 4-3: Distribution of outcomes for different correlation values

	ρ_{SS}=**0**	ρ_{SS} =**1**
ρ_{RR}=0	Binomial	
ρ_{RR}=1		Bernoulli

For other values of correlation ($0<\rho_{ZZ}<1$) the probability of mutual failure of elements and the corresponding distribution of failures can be determined numerically or approximated[12]. Ditlevsen (1977) developed a method to approximate the bounds of probability of mutual failure of two elements (see also e.g. CUR, 1997). For two identical elements, this probability can be approximated as follows:

$$\Phi(-\beta)\Phi(-\beta^*) \leq P(Z1 < 0 \cap Z2 < 0) \leq 2\Phi(-\beta)\Phi(-\beta^*)$$

$$\beta^* = \frac{\beta - \rho_{ZZ}\beta}{\sqrt{1-\rho_{zz}^2}} \qquad \textbf{(Eq. 4-9)}$$

For smaller correlation values, the lower Ditlevsen bound gives a good approximation. For larger correlations the upper bound can be used[13]. The effects of mutual correlations between loads and resistances on the distribution of the number of failures are examined in a simplified example.

12 It is thus possible to combine figures 4-13 and 4-14. It is then possible to show the probability of mutual failure of two elements in a three dimensional graph as a function of correlations between loads and resistances.

13 If ρ_{ZZ} approaches 1, β* approaches 0, and Φ(-β*) becomes 0,5, the upper bound becomes approximately Φ(-β), which equals the failure probability of an element, see also figure 4-14.

Example

An example is elaborated as an illustration of a situation with variable load and resistance, for different values of the correlations. Exposure of two persons is considered schematically. For both persons identical normal distributions for load and resistance are applied:

$$\mu_R = 196 \qquad \sigma_R = 20$$

$$\mu_S = 160 \qquad \sigma_S = 20$$

The probability of death of a single person (i.e. the probability of failure of one element) is found as follows:

$$\mu_Z = \mu_R - \mu_S = 36 \qquad \sigma_Z = \sqrt{\sigma_R^2 + \sigma_S^2} = 28,28$$

$$\Rightarrow \beta = 1,27 \qquad P(Z < 0) = 0,101$$

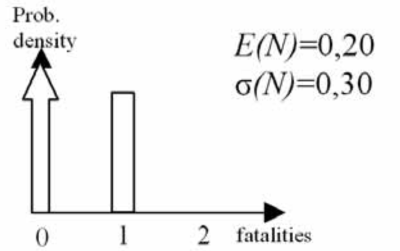
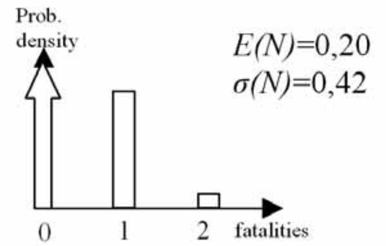
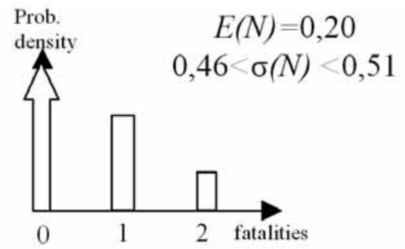
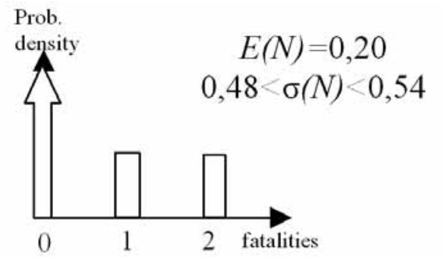
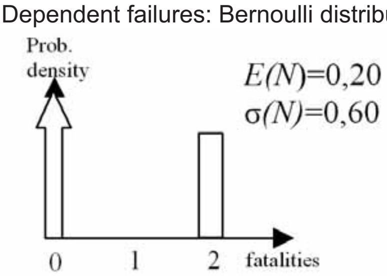
For different dependence situations and corresponding correlation values the following items are shown in table 4-4:

- Correlations between loads on (ρ_{SS}) and resistances of (ρ_{RR}) the two elements
- Correlation between mutual failure (ρ_{ZZ})
- The probability of mutual failure of the two persons: $P(Z1<0 \cap Z2<0)$[14]
- A sketch of the probability density function of consequences, and the expected number of fatalities and standard deviation.

In all cases the same expected value is found. It is shown that the probability of mutual failure of elements and standard deviation increase with correlation. The standard deviation of the number of fatalities is maximal for the fully dependent case, which results in the Bernoulli distribution. The results confirm an observation that has also been done in other studies, e.g. (Egorova, 2004); the distribution becomes wider when dependency between failures increases.

14 This probability is given exactly for the fully dependent (ρ_{ZZ} =1) or independent (ρ_{ZZ} =0) cases when possible, and approximated with the Ditlevsen bounds for other correlation values ($0<\rho_{ZZ}<1$).

Table 4-4: Effects of correlation on the distribution of failures for variable load and variable resistance. Table summarizes correlations between loads, resistances and failures. Last column shows the mutual probability of failure of two elements and pdf of the number of fatalities (μ_R=196; μ_S=160; σ_R= σ_S=20)

ρ_{SS}	ρ_{RR}	ρ_{ZZ}	**Failure probability P(Z1∩Z2<0)**	**Probability density function of fatalities**
-1	-1	-1	0	Mutually exclusive 
0	0	0	0,0103	Independent failures: Binomial distribution 
1	0	0,5	0,023≤ P(Z1∩ Z2<0) ≤ 0,046	
1	0,5	0,75	0,032≤ P(Z1∩ Z2<0) ≤ 0,064	
1	1	1	0,101	Dependent failures: Bernoulli distribution 

4.4 Practical interpretation of dependencies between failures

In this section the practical interpretation of dependencies between failures in the context of loss of life estimation is discussed. These dependencies can concern the load conditions (e.g. the concentration to which people are exposed) or the resistance properties (human response to exposure) and are discussed below. This issue is somewhat similar to the consideration of dependencies in engineering applications. For example in the probabilistic assessment of flood protection, mutual correlations between loads (wave height) and resistances (soil parameters) have to be considered over different individual dike sections, see e.g. (Vrouwenvelder and Vrijling, 1996; Vrijling, 1996; Vrijling and van Gelder, 1998). In these applications the effects of uncertainties on the failure probability of a system are investigated. Here, the influence of dependencies on the distribution of the number of failures (i.e. fatalities) is examined.

Dependencies between resistances
Smaller groups of people may show dependencies between individual resistances, which could be related to age, condition or heredity. For example during a tunnel fire the exposed population could concern a bus with elderly or disabled people, or a twin in one car. In general, resistances for people in special facilities, such as schools, hospitals or elderly homes, might be dependent due to similarities in physical condition[15]. If the people exposed are part of a larger arbitrary population it is reasonable to assume that persons' resistances are independent and not correlated, so ρ_{RR}=0.

Dependencies between loads
Dependencies between loads to which individuals are exposed can concern spatial and temporal correlations. These describe how certain loads are correlated at two locations or moments in time respectively. For the description of **spatial correlation** a so-called correlation function can be used which describes the correlation between loads at two locations as a function of their mutual distance, see figure 4-15. When the distance Δx between locations is small, ρ_{SS} approximately equals 1. For larger distances it decreases to 0. A correlation length can be defined indicating the distance from an origin to a location to reduce the correlation to a certain predefined value, e.g. 0. For specific event types, it might be interesting to determine typical correlation lengths for loads, for example for floods, tunnel fires, etc..

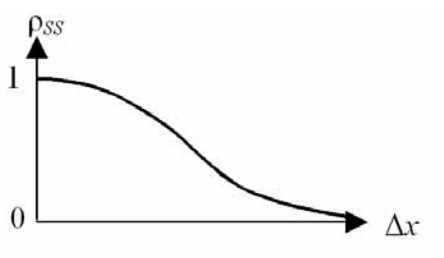


Figure 4-15: Correlation as a function of distance between two locations (Vanmarcke, 1983)

15 Dose response functions that have been derived based on a limited number of observations from past disasters could reflect such correlations.

The concept of spatial correlation is further illustrated in figure 4-16. Assume a certain probability density function of load at the origin. The figures show the load as a function of distance to the origin. In figure 4-16a the loads at locations 1 and 2 are (almost) identical and fully correlated. Here the correlation length is larger than the distance between the two locations. In figure 4-16b fluctuations in loadings are so high that loads at locations 1 and 2 are considered (linearly) independent. Correlation length is smaller than distance between persons. For completeness it is noted that loads at two locations can be fully correlated, e.g. via the dispersion model or terrain topography, but they need not be identical. An example is given in Appendix 4.I for a flood prone area.

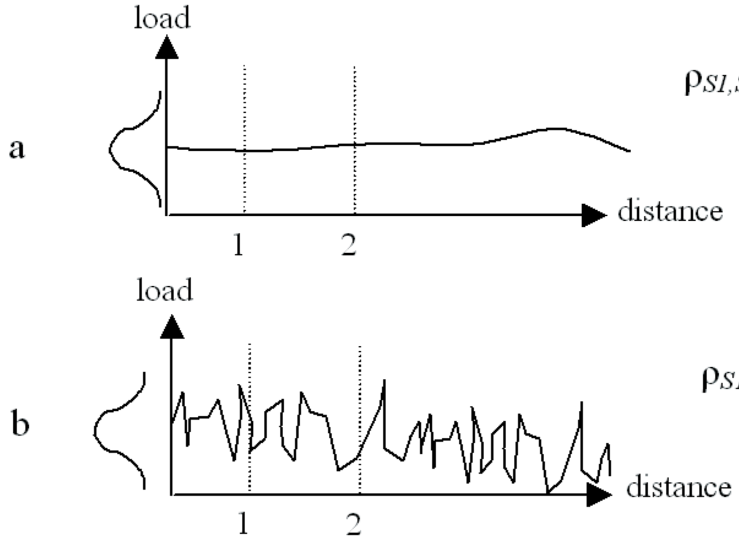


Figure 4-16: Fluctuation in load as a function of distance

Applications considered in this study generally concern one risk source. Loads at different locations will be fully correlated via the dispersion model. As the correlation length is generally larger than the size of the exposed area, it is often reasonable to assume that $\rho_{SS} \approx 1$.

With respect to **temporal correlation**, especially the moment of exposure of different locations is relevant. This determines the available time for evacuation. For some events the effects occur (nearly) simultaneously at different locations, for example for an explosion or earthquake. Thus, for such sudden disasters with rapidly evolving events it seems reasonable to assume temporal correlation between loads. Also when the arrival time at two locations is fully linearly dependent via the dispersion model, full correlation is applicable.

Implications for modelling of uncertainties in loss of life estimates

Below, it will be discussed for which situations dependency between death of different people needs to be taken into account in loss of life estimation. Except for very rare occasions it seems reasonable to assume that people's resistances are not correlated, so ρ_{RR}=0. Therefore equation 4-7 simplifies further to:

$$\rho_{ZZ} = \frac{\rho_{SS}\sigma_S^2}{\sigma_R^2 + \sigma_S^2} \qquad \textbf{(Eq. 4-10)}$$

The occurrence of fatalities (or failure of elements) will be fully dependent if:

1) The loads to which the people are exposed are fully correlated ($\rho_{SS} \approx 1$)

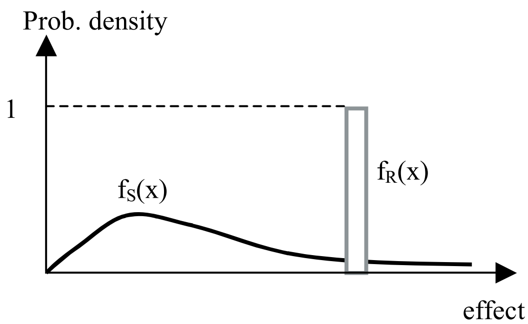
AND

2) The variation in resistance is small relative to the variation in load ($\sigma_R << \sigma_S$)

Ad 1) $\rho_{SS} \approx 1$ when the correlation length is larger than the exposed area. This seems to be a reasonable assumption for most cases because elements are exposed by the same event (see also discussion above). Also, in most practical risk analyses a limited number of (deterministic) event scenarios is considered, e.g. various fire magnitudes or dike breaches. For a given release of effects (i.e. for one scenario) exposure loads can be assumed to be fully correlated.

Ad 2) If the first condition is fulfilled, the variations in load and resistance become important. An illustration is shown in figure 4-17, where it is assumed loads are fully correlated. It follows that when $\sigma_R << \sigma_S$ the correlation between failure of two elements is $\rho_{ZZ} \approx 1$.This is also true for a deterministic resistance function, so if $\sigma_R = 0$. If the variation in resistance is large relative to variation in load: $\sigma_R >> \sigma_S$, then the failures are independent. So also for a deterministic load scenario ($\sigma_S = 0$), deaths of different people can be considered as independent. The Binomial distribution is appropriate to model variation in consequences for the independent failures.

$$\sigma_R < \sigma_S \qquad \rho_Z = \frac{\sigma_S^2}{\sigma_R^2 + \sigma_S^2} \approx 1$$



$$\sigma_R > \sigma_S \qquad \rho_Z = \frac{\sigma_S^2}{\sigma_R^2 + \sigma_S^2} \approx 0$$

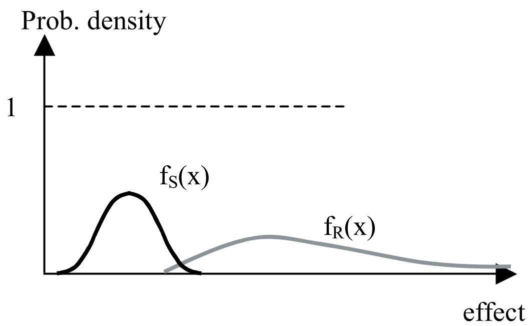


Figure 4-17: two cases illustrating the influence of variations on correlation, resulting in dependent failure (upper figure) and independent failure (bottom figure). Pdf's of load $f_S(x)$ and resistance $f_R(x)$ are shown.

Discussion

Full dependence between loads seems to be a reasonable assumption in various cases (see above). Therefore the variations in load and resistance need to be examined case-by-case to determine whether fully dependent modelling is appropriate, and whether the corresponding Bernoulli pdf can be used. If the failures are independent, e.g. when there is a deterministic load (σ_S=0), the Binomial distribution can be used for the modelling of variation in consequences and application to loss of life estimation. Using equation 4-3 it can be shown for the Binomial distribution that:

$$\frac{\sigma(N|f)}{E(N|f)} = \frac{\sqrt{F_D(1-F_D)N_{EXP}}}{F_D N_{EXP}} = \sqrt{\frac{(1-F_D)}{F_D N_{EXP}}} \quad \text{(Eq. 4-11)}$$

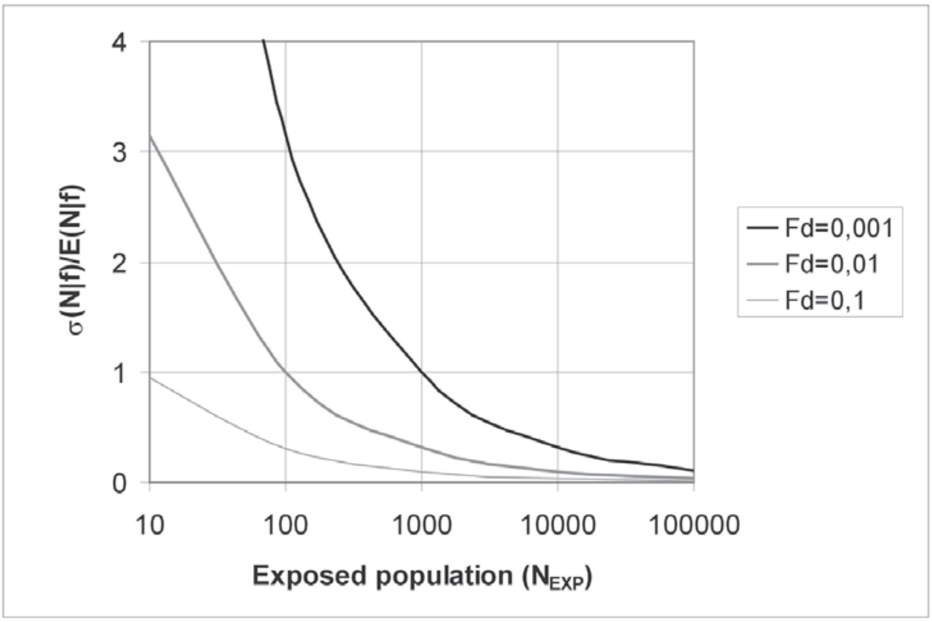


Figure 4-18: Ratio between standard deviation and expected value as a function of exposed population for the Binomial distribution

Figure 4-18 shows the ratio between standard deviation and expected value for different values of mortality (F_D) and exposed population (N_{EXP}). For small mortality values and relatively small exposed populations (N_{EXP}) standard deviation is large relative to the expected value. In this case the effect of individual variation in response is substantial. For larger exposed populations the standard deviation becomes very small relative to the expected value. For example for a flood we assume a typical mortality of $F_D=10^{-2}$ and a large exposed population of N_{EXP}=10.000 people, leading to $\sigma(N|f)/E(N|f)$=0,31. For these cases the Binomial distribution can be approximated with a deterministic outcome. This corresponds to the deterministic outcome that is associated with the application of the dose response function to a group.

Many practical situations will be partly dependent ($0<\rho_{ZZ}<1$). Above, it has been shown that the distribution of failures becomes wider when correlation increases. Therefore it is suggested to use a normal distribution for partly dependent cases, with a standard deviation that is larger than that of the Binomial distribution.

4.5 Model uncertainties in dose response functions

4.5.1 General

This section discusses model uncertainty in the dose response function. Model uncertainty is caused by the fact that not all physical phenomena are known, or because some variables of lesser importance are omitted in the model for reasons of efficiency (van Gelder, 2000).

Model uncertainty could originate because data from different populations is used to derive a dose response function. Theoretically, a dose response function could be derived by testing the response of a population to exposure to physical effects in controlled settings, see also section 2.3.3. In theory this type of experiment could be repeated multiple times with other populations. If populations and test circumstances are exactly identical the previously obtained dose response function will be reproduced exactly in every experiment. However, in practice it is unlikely that the outcomes of all experiments will be exactly the same because exposed populations or test circumstances (e.g. temperature, humidity) will differ between experiments. Therefore the resulting dose response function from each experiment will be different.

Figure 4-19 (upper figure) gives an example for measurements and derived dose response functions for two fictitious populations A and B. It assumed that both populations consist of 40 people exposed. Each dot represents the death of one person and a 0,025 response fraction. When measurements from both populations are used for derivation of dose response function, model uncertainty arises. An example is given in the lower part of figure 4-19. Various observations are sampled from populations A and B. The resulting dataset contains 12 observations and the derived best-fit dose response function is shown in figure 4-19 (lower). It is clear that the observations are somewhat scattered around the derived average dose response function. This shows how mixing data from different populations and different circumstances can introduce model uncertainty in the dose response function.

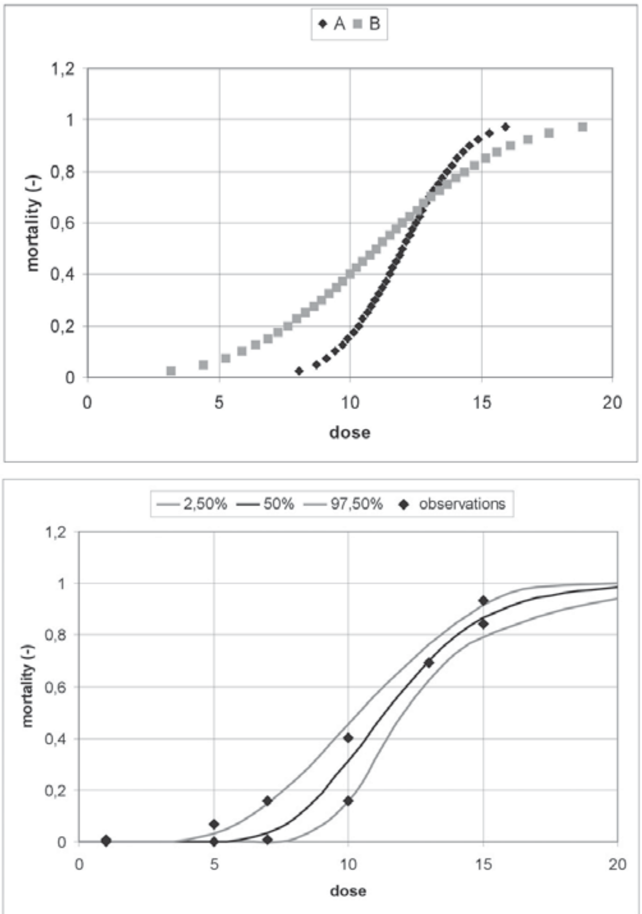


Figure 4-19: Dose response functions for populations A and B (upper figure). Resulting average dose response by taking samples from the populations is shown in the lower figure.

In practice a limited number of measurements from animal tests or observations from disasters are generally available to derive a dose response function. As a consequence, the measurements used are expected to represent different situations and populations. In addition, variables that affect mortality could be omitted in the dose response function. For example, dose response functions for floods are mainly based on water depth. In reality, other potentially important factors, such as water temperature and the effects of waves, are not included in the functions. Due to the above factors, observations will not be situated exactly at the average dose response function. In that case there is model uncertainty associated with the average dose response function, see also figure 4-2.

4.5.2 Integration of model uncertainties in the dose response function

In this section it is investigated how model uncertainties can be included in the dose response function by using Bayesian probability theory. Van Gelder (2000) gives an extensive discussion of the underlying methods and additional possibilities for inclusion of statistical uncertainties.

First, we assume that a distinction can be made between inherent uncertainties in load (S) and resistance (R), and model uncertainties. As an implication the model uncertainty can be represented by a separate term I , which schematically represents the confidence intervals of the dose response function that are shown in figure 4-2. The limit state function can be formulated as follows (see also Vrouwenvelder and Vrijling, 2000):

$$Z = R - S - I \qquad \textbf{(Eq. 4-12)}$$

Where: I - variable in the limit state function that represents the knowledge uncertainty, $\mu(I)=0$, $var(I)>0$

Following section 3 the limit state function can be rewritten with the inclusion of a resistance concentration c_R and the load: the random exposure concentration c_S:

$$Z = c_R - c_S - I \qquad \textbf{(Eq. 4-13)}$$

The dose response function now gives the probability that the exposure concentration is larger than the resistance concentration (i.e. $F_D(c)=P(c_R<c)$). First, we consider a situation where a dose response function is used, which gives the bestfit trendline through a series of measurements regarding exposure dose and response. This type of dose response function is called the average dose response function and it represents the response given an average level of information or knowledge I:

$$F_D\left(c \mid I = \mu_I\right) = P\left(c_R < c \mid I = \mu_I\right) \qquad \textbf{(Eq. 4-14)}$$

The average value of model uncertainty is $\mu_I=0$. The above dose response function does not account for uncertainty in the response. Application of this type of average dose response function for loss of life estimation implies that the effects of knowledge uncertainty are neglected. It is possible to take into account the effects of knowledge uncertainty in the dose response function. Using a Bayesian approach, a predictive dose response function can be derived, in which the knowledge uncertainty is integrated (van Gelder, 2000):

$$F_{DP}(c) = \int F_D(c \mid I = i)\, f_I(i)\, di \qquad \textbf{(Eq. 4-15)}$$

Where:

$F_{DP}(c)$ Predictive dose response function with uncertainty integrated
$F_D(c|I=i)$ Dose response function, which gives response for a given level of uncertainty i
$f_I(i)$ pdf representing knowledge uncertainty

Example
As an example exposure of an object to a deterministic load is assumed. Three shapes of average dose response functions are considered: normal, lognormal and exponential, see table 4-5. The model uncertainty is modeled with a normal distribution[16].

16 In this example model uncertainty I is modelled here in the horizontal the direction, so in the load. It could for example indicate the measurement error in concentration. It can be shown that uncertainty in horizontal direction is equivalent to uncertainty in the vertical direction (i.e. In the response fraction) and vice versa, see appendix 4.III. Thus, the (conditional) distribution of responses for a given load can be derived based on the (conditional) distribution of load and the dose response function. The advantage of modelling the uncertainty term in the horizontal direction is that the response fraction will always be . $0 \leq F_{DP}(c) \leq 1$

Table 4-5: Distributions used in simplified example

	μ	σ
Average dose response functions		
Normal	5	1
Lognormal*	4,36	1,13
Exponential (λ=0,25)	4	4
Knowledge uncertainty I		
Normal**	0	1

*: So that Y=ln(x) has a normal distribution, with μ_Y=1,44 and σ_Y=0,2566

**: It is noted that the model uncertainty is assumed to be independent of the load value. In reality the uncertainty (standard deviation) could be dependent on the value of the load.

Consequently, the predictive dose response function, in which uncertainty is integrated, is determined with formula 4-15. It gives P(Z<0) and it includes the effects of uncertainty *I*. For the normal distribution the following formula for reliability index β is obtained (Vrouwenvelder and Vrijling, 2000):

$$\beta = \frac{\mu_R - \mu_S - \mu_I}{\sqrt{\sigma_S^{\,2} + \sigma_R^{\,2} + \sigma_I^{\,2}}} \qquad \textbf{(Eq. 4-16)}$$

As μ_I=0 and the load is deterministic (μ_S=*S*; σ_S=0), the equation simplifies to:

$$\beta = \frac{\mu_R - S}{\sqrt{\sigma_R^{\,2} + \sigma_I^{\,2}}} \qquad \textbf{(Eq. 4-17)}$$

For the lognormal and exponential distributions of the average dose response functions the predictive dose response functions are found by numerical integration[17]. Results are presented in figure 4-20.

17 Analytical approximation methods for the predictive function of several distributions are presented by van Gelder (2000)

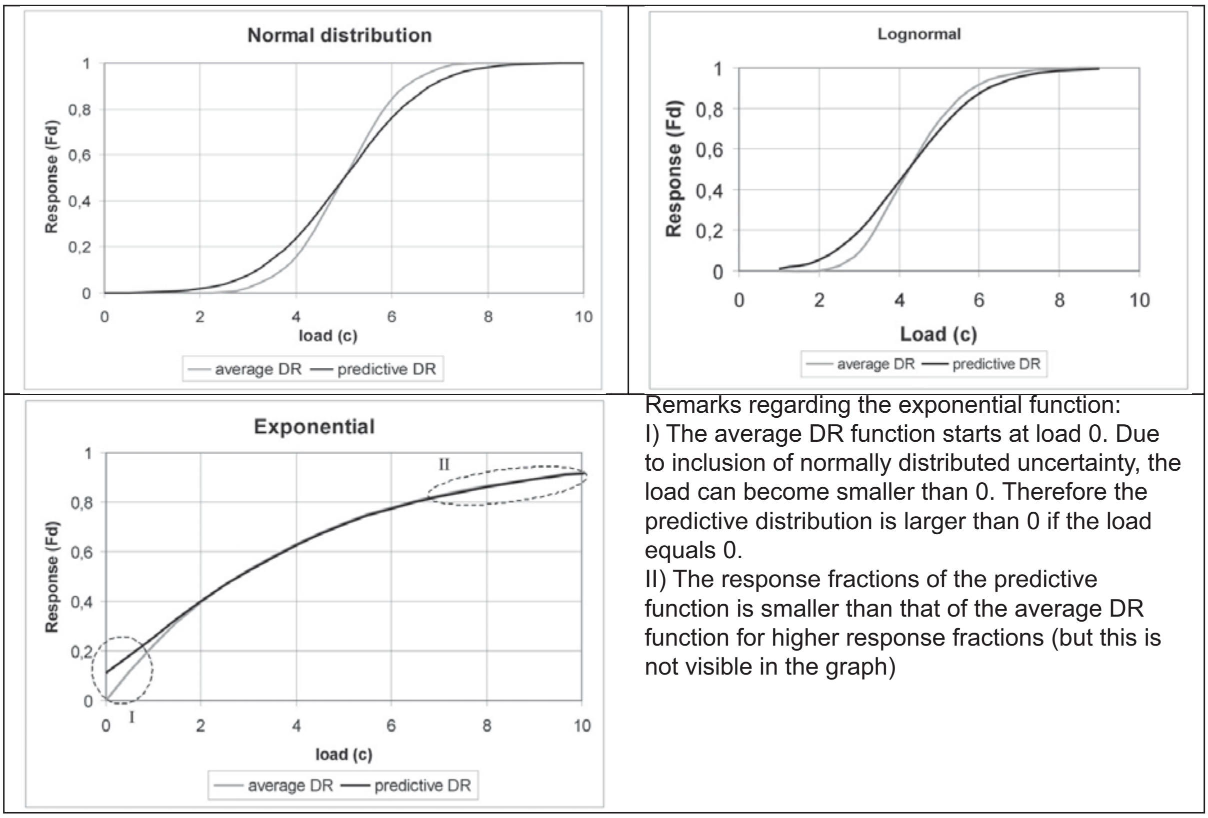


Figure 4-20: Integrating uncertainties in dose response functions with the Bayesian approach

All cases show a similar pattern: the predictive dose response function is widened compared to the average dose response. When model uncertainties are included, the response fraction becomes higher than the average for smaller loads and lower for higher loads. In general, the effects of the inclusion of uncertainty on the failure probability of a given system depend on the specific distributions of load and resistance. For most practical cases the failure probability of a system will increase due to inclusion of uncertainty (see e.g. Vrijling *et al.*, 2005), but examples can be found where the system's failure probability decreases, as is shown in appendix 4.II.

Remarks regarding the inclusion of model uncertainty in the dose response function

At this moment, most consequence and risk analyses use the average dose response function and they do not explicitly account for uncertainties. It can be questioned whether the effects of model uncertainties should be included in the dose response function and the resulting loss of life and risk estimates. This depends on the chosen treatment of uncertainties in risk analysis (see also section 1.2.4 and Paté Cornell, 1996, 2002):

- Assessment of inherent uncertainties (or randomness) only: If one chooses to present best estimates for probabilities and consequences, the average dose response function can be used. This results in one single risk curve, implying that model uncertainties in the dose response function are neglected.
- Separated assessment of inherent and knowledge uncertainties: It can be chosen to display knowledge uncertainties in probability and consequence estimates, by a family of risk curves. In this case, uncertainty in the dose response curve can be modeled with a conditional distribution.

- Integrated assessment of inherent and knowledge uncertainties: Using a Bayesian approach the model uncertainties can be integrated in the consequence estimate.

4.6 Uncertainty in loss of life estimates and compliance to risk criteria

The previous sections have investigated the backgrounds of uncertainty in loss of life estimates. It has been shown how certain distribution types (Bernoulli, Binomial) can be used to model randomness in consequences for specific cases. Several (other) distribution types can be used to model the uncertainty in the number of fatalities given an accident. Based on earlier work by Vrouwenvelder and Vrijling (1995) and Vrijling *et al.* (1998), some distribution types for the number of fatalities given failure *(N|f)* are summarized in table 4-6. All these distributions have the same (conditional) expected value of the number of fatalities.

Table 4-6: Probability density functions for the conditional number of fatalities for some distribution types (based on Vrouwenvelder and Vrijling (1995))

Distribution type	**Pdf or distribution of number of fatalities given failure**	**Exp. value *E(N|f)***	**Standard deviation *σ(N|f)***
Deterministic	$P(N = F_D N_{EXP} \mid f) = 1$ $P(N \neq F_D N_{EXP} \mid f) = 0$	$F_D N_{EXP}$	0
Binomial	$P(N = n \mid f) = \frac{N_{EXP}!}{n!(N_{EXP} - n)!} F_D{}^n (1 - F_D)^{N_{EXP} - n}$	$F_D N_{EXP}$	$\sqrt{F_D (1 - F_D) N_{EXP}}$
Exponential	$f_N(n \mid f) = \frac{1}{F_D N_{EXP}} \exp\left(-\frac{n}{F_D N_{EXP}}\right)$	$F_D N_{EXP}$	$F_D N_{EXP}$
Inverse quadratic Pareto	$P(N > n \mid f) = \frac{1}{4}\left(\frac{F_D N_{EXP}}{n}\right)^2 \quad for\ n \geq \frac{1}{2} F_D N_{EXP}$ $P(N > n \mid f) = 1 \quad for\ n < \frac{1}{2} F_D N_{EXP}$	$F_D N_{EXP}$	∞
Normal ($with$ $\sigma(n \mid f)/E(n \mid f) = 1$)	$f_N(n \mid f) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{(n-\mu)^2}{2\sigma^2}\right)$	$F_D N_{EXP}$	$F_D N_{EXP}$
Lognormal ($with$ $\sigma(n \mid f)/E(n \mid f) = 1$)	$F_N(n \mid f) = \Phi\left(\frac{\ln(n) - a}{b}\right)$ $a = \ln(F_D N_{EXP}) - 0{,}5b^2 \quad b = \sqrt{\ln(1 + (\sigma_N / \mu_N)^2)}$	$F_D N_{EXP}$	$F_D N_{EXP}$
Bernoulli	$P(N = 0 \mid f) = 1 - F_D$ $p(N = N_{EXP} \mid f) = F_D$	$F_D N_{EXP}$	$\sqrt{F_D (1 - F_D) N_{EXP}}$

Application of a conditional distribution for the number of fatalities will logically affect the distribution of fatalities and thus the calculated FN curve. The shape of the calculated FN curve can affect compliance to an FN limit line, which limits the tolerable probability of exceedance of a certain number of fatalities. This is illustrated in an example.

Assume an installation with a certain accident with probability of occurrence of p_f=10^{-3} per year. The accident exposes N_{EXP}=1000 people and mortality is F_D=0,1, leading to $E(N|f)$=100 people. FN curves are drawn for the distributions types of table 4-6, see figure 4-21. Some of the previously discussed situations are recognizable, i.e. a deterministic[18] number of fatalities given failure, the Binomial distribution for independent failures and the Bernoulli distribution for dependent fatalities.

In the FN curve a limit line with a quadratic steepness is drawn, by which the deterministic situation is just acceptable. As has also been concluded by Vrouwenvelder and Vrijling (1995) the situation complies to the limit line for the first six distributions in table 4-6 (i.e. deterministic, binomial, exponential, inverse quadratic Pareto, normal and lognormal). The FN limit line can be exceeded especially for normal and lognormal distributions with standard deviations that are large compared to the average[19]. In this considered example, the limit line in the FN curve will be exceeded if $\sigma(N|f)\approx 1,45\ \mu(N|f)$ for the normal distribution and for the lognormal distribution if $\sigma(N|f)\approx 2\ \mu(N|f)$. For the Bernoulli distribution, the number of fatalities equals N_{EXP} and the corresponding probability of occurrence equals $p_f F_D$. As a result, the limit line in the FN curve will be exceeded for this distribution.

All distributions shown in table 4-6 and figure 4-21 have identical expected values. However, different distributions of consequences might be valued differently in decision-making. Some proposed risk criteria, such as the total risk, risk integral, and the quadratic limit line in the FN curve, include the standard deviation of the number of fatalities (see section 3.3.4). In these cases the acceptable probability of failure depends on the conditional distribution of the number of fatalities given failure and thus on the uncertainty in the number of fatalities given failure[20]. Overall, this shows that the inclusion of uncertainty and the choice of the conditional distribution type could influence compliance to risk criteria.

18 If the number of fatalities given failure is deterministic, the (unconditional) distribution of the number of fatalities corresponds to a Bernoulli distribution (Vrouwenvelder and Vrijling, 1995).

19 Large standard deviations could be chosen e.g. if the loss of the mortality estimate is based on a large sample of statistical data with much variation. For example statistical analyses of global data for floods (section 5 of this thesis) showed that standard deviation of event mortality is large for data for one type of flood.

20 It is noted that for the inverse quadratic distribution type the standard deviation approaches infinity and this can give problems in combination with certain risk limits that include the value of the standard deviation.

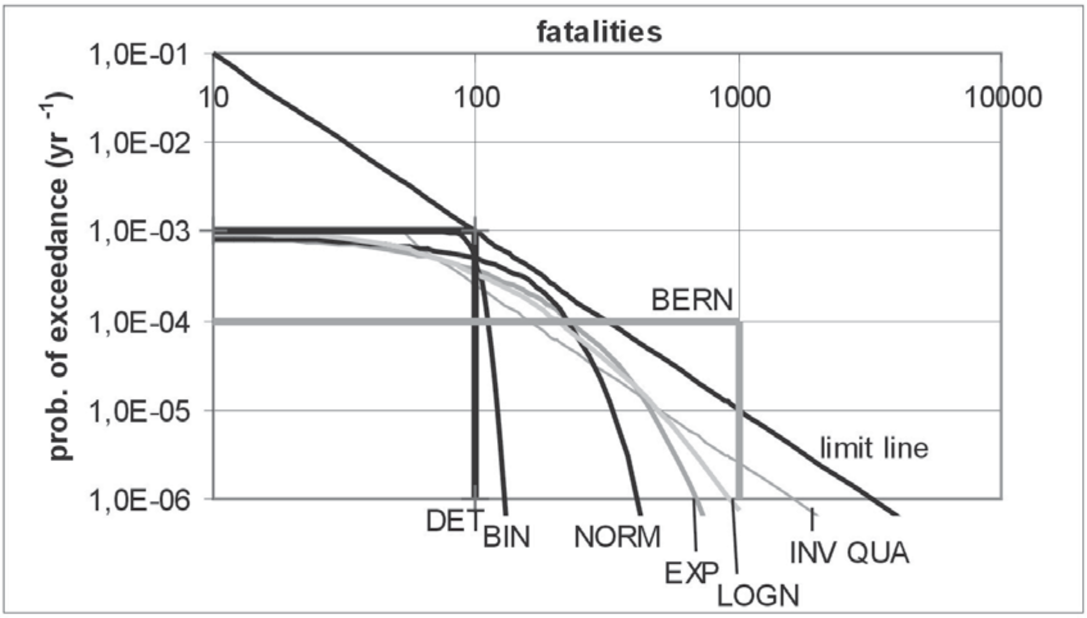


Figure 4-21: FN curves for several conditional distribution types for the number of fatalities (DET – deterministic; BIN – Binomial; NORM – normal; EXP – exponential; LOGN – lognormal; BERN – Bernoulli; INV QUA – Inverse quadratic Pareto).

4.7 Concluding remarks

In this section issues related to uncertainties in loss of life estimates have been discussed. Firstly, uncertainty in the consequences of the exposure of a group of people to physical effects can arise due to the variation in individual responses. Secondly, model uncertainty can exist in the dose response function.

Application of a dose response function to a group as a whole results in a deterministic outcome. Application of a dose response function to individuals could lead to uncertainty in the consequences due to variation (or randomness) in individual responses. This has no effect on the expected number of fatalities. However, the uncertainty affects the distribution of the number of fatalities and thereby the value of the standard deviation. The resulting distribution of the number of fatalities is determined by dependencies between individual failures. More specifically it has been shown how the conditional distribution of consequences (i.e. of the number of fatalities given failure) depends on a) the standard deviations of load and resistance; b) dependencies between loads and resistances. Results for different combinations are summarized in table 4-7.

Table 4-7: Overview of resulting distributions for different combinations of load and resistance; and levels of dependency between loads and resistance

		$\sigma_R=0$	$\sigma_R>0$	
			$\rho_{RR}=0$	$\rho_{RR}=1$
$\sigma_S=0$		Known outcome	Binomial	Bernoulli
$\sigma_S>0$	$\rho_{SS}=0$	Binomial	Binomial	*
	$\rho_{SS}=1$	Bernoulli	*	Bernoulli

* - These situations cannot be described with standard distribution types.

If failures of elements are independent, this results in a Binomial distribution. For large exposed populations the Binomial distribution approximates the deterministic outcome. In case of complete dependence between failures, the resulting distribution is a Bernoulli type. It is shown that the distribution of failures becomes wider and the standard deviation becomes higher, when dependencies between failures increase.

Model uncertainty can originate because the number of available measurements is limited or because the available measurements represent different conditions and population vulnerabilities. Model uncertainty can be integrated in the dose response function by means of a Bayesian approach. It has been shown that this results in a widened dose response function (i.e. lower response fractions increase, higher response fractions decrease).

The effects of randomness and model uncertainty could occur jointly. Randomness indicates that the outcome of each individual exposure is uncertain, i.e. each single exposure results in a certain probability of death. Model uncertainty refers to the fact that the exact value of this probability is uncertain. The analogy of a dice can be used: the outcome of one throw is uncertain due to randomness. The value of the probability of a certain outcome can be uncertain due to model uncertainty, e.g. because the dice is imperfect. Even when all knowledge uncertainties have been eliminated, the outcome of one throw remains uncertain due to randomness.
Uncertainties in estimates of the number of fatalities given failure could affect compliance to risk averse risk limits, such as the limit line in the FN curve with a quadratic steepness. In general, the chosen treatment of uncertainties in risk calculation could affect the acceptability of a situation according to risk limits. For example, a flood defence could be safe according to the safety standard when knowledge uncertainties are neglected. When knowledge uncertainties are included in the probability estimate the flood defence could be judged as unsafe according to the standard because the failure probability has increased. Then, it would be required to reduce the knowledge uncertainties or carry out (expensive) physical measures, see also section 1.2.4 and Vrouwenvelder and Vrijling (2000) for further discussion and examples. The above implies that it would be good if guidelines for risk analysis, such as (CPR, 1999), would also prescribe whether and how uncertainties should be accounted for in the risk calculation.

At this moment, most consequence and risk analyses use the average dose response function and they do not explicitly account for uncertainties in loss of life estimates. It is recommended to assess and present these uncertainties in consequence and risk estimates. Different approaches can be chosen for the treatment of uncertainties in risk estimates (see section 1.2.4). Goldman (1997) and Egorova (2004) provide a discussion on the inclusion of uncertainty in flood damage estimates.

The issues discussed in this section might have a wider relevance than loss of life estimation only. For example, in the assessment of hurricane damage, dependencies in wind loads (e.g. due to location) and structural resistances (e.g. due to similarities in the design and construction) could influence the distribution of the number of buildings collapsed. These dependencies are referred to as loss interactions (RMS, 2005). Therefore, further investigation of the proposed concepts is recommended for other domains of reliability analysis where dose response functions, damage models and fragility curves are used.

Part two:
Loss of life estimation and flood risk assessment

5 Loss of human life in floods: Overview and analysis of the available information

Research question: Which information is available regarding loss of life caused by floods? Which factors have to be taken into account in a model for the estimation of loss of life for floods?

Keywords: loss of life, floods, flood disasters, damage

This section presents an overview and analysis of the available information regarding loss of life caused by floods. The aim is to determine the factors that are most relevant for the estimation of loss of life, and to discuss the applicability of different types of information for the development of a method for the estimation of loss of life for floods.

After a general discussion of floods, types of floods and flood damage in section 5.1, different aggregation levels of available information are reviewed. Global information regarding the loss of life in floods is discussed in section 5.2. An overview of historical flood events in the Netherlands is provided in section 5.3. Section 5.4 discusses available information from international flood events. At a more detailed level, the causes and circumstances of individual flood disaster deaths are discussed in section 5.5. These types of information are evaluated in section 5.6, and the major determinants of loss of life are summarised.

5.1 General introduction: floods and flood damage

5.1.1 Defining floods and flood types

OED (2003) defines a flood as “the presence of water where water does not normally appear”. Two other examples of flood definitions are:

- “A temporary covering of land by water as a result of surface waters (still or flowing) escaping from their normal confines or as a result of heavy precipitation” (Munich Re, 1997).
- “Significant rise of water level in a stream, lake, reservoir or a coastal region.” (UN DHA, 1992).

Given the complex interrelated processes that can cause and influence floods, defining and classifying them is not simple. It is not surprising that no standardised definitions of “flood”, “flood disaster”, or “flood fatality” exist. Working definitions are proposed below, based on an intuitive understanding and the generally accepted vocabulary. These definitions are imperfect, but provide a useful and necessary starting point for analysis of flood fatalities.

- Flood: The presence of water on land which is usually dry, as a result of surface waters escaping from their normal confines.
- Flood disaster: A flood which significantly disrupts or interferes with normal human and societal activity.

- Flood fatality or flood-related fatality: A fatality which would not have occurred without a specific flood event. Synonyms for the plural form include “flood deaths”, “loss of life in floods”.

Types of floods

Flood type definitions often reflect both the source of the event (coast, river) and the flood characteristics (water depth, rise rate, e.g. in the case of flash floods). (Berz *et al.*, 2001) and (French and Holt, 1989) distinguish three types: coastal, river and flash floods. Tsunamis and tidal waves are generally treated as separate hazards, although they also result in flooding. Also dam breaks are often considered as distinct hazards, as they are considered “manmade” events and floods as “natural” disasters[1]. An attempt to provide a categorisation and a set of descriptions for the different types of floods is given below:

- Coastal floods or storm surges: These occur along the coasts of seas and big lakes. Wind storms (for example hurricanes or cyclones) and low atmospheric pressure cause set-up of water levels at the coast. When this situation coincides with an astronomical high tide at the coast, this can lead to (extremely) high water levels and flooding of coastal areas.
- Flash floods: These occur after local rainfall with a high intensity, often in mountainous areas. They are characterised by a quick rise of water levels causing a threat to the lives of those exposed. The time available to predict flash floods is limited.
- River floods: These are characterised by the flooding of a river outside its regular boundaries, sometimes due to breaching of flood defences. River floods can be associated with various causes: high precipitation levels, not necessarily in the flooded area, or other causes (melting snow, blockage of the flow).
- Tsunamis (or seismic sea waves): Series of large waves generated by sudden displacement of seawater (caused by earthquake, volcanic eruption or submarine landslide); capable of propagating over large distances and causing a destructive surge when reaching land (EMDAT, 2004).
- Tidal wave / bore[2]: Abrupt rise of tidal water caused by atmospheric activities rapidly moving inland from the mouth of an estuary or from the coast (EMDAT, 2004).
- Dam break / failure: Breach of a (large) human-built dam, resulting in the rapid propagation of a flood wave through the exposed area.

The general flood definition implies that drainage problems are considered as a distinct category:

- Drainage problems: caused by high precipitation levels that cannot be handled by regular drainage systems.

Low-lying areas, such as the Netherlands, are sometimes threatened by multiple types of floods, e.g. coastal and river floods and drainage problems. Finally, it is noted that floods can be related to other types of disasters. For example, coastal floods are often caused by storms, and flash floods might trigger landslides and mudflows. The broader scope of water-related disasters also includes other types of events, such as avalanches and droughts.

1 It has been discussed in section 1.1 that this distinction between manmade and natural disasters is inappropriate.

2 Note the distinction between a tidal wave and a tsunami. A tidal wave is caused by the natural tide, a tsunami is caused by an extreme event, e.g. a landslide or earthquake.

5.1.2 Categorisation of damage caused by floods

The consequences of a flood encompass multiple types of damage, i.e. they are multi-dimensional. An overview of different types of consequences is given in table 5-1. All these different types of consequences can be observed after large flood disasters, for example after the flooding of New Orleans due to hurricane Katrina in 2005. The damage is divided into tangible and intangible damage, depending on whether or not the losses can be assessed in monetary values. Another distinction is made between the direct damage, caused by physical contact with floodwaters, and damage indirectly following from the flood. Indirect damage can be defined as damage that occurs outside the flooded area[3] (Merz *et al.*, 2004; Morselt and Evenhuis, 2006). For example companies can lose supply and demand from the flooded area.

Table 5-1: General classification of flood damage, based on (Morselt and Evenhuis, 2006) and (Vrouwenvelder and Vrijling, 1996)

	Tangible	Intangible
Direct	• Residences • Structure inventory • Vehicles • Agriculture • Infrastructure and other public facilities • Business interruption (inside flooded area) • Evacuation and rescue operations • Reconstruction of flood defences • Clean up costs	• Fatalities[4] • Injuries • Animals • Utilities and communication • Historical and cultural losses • Environmental losses
Indirect	• Damage for companies outside flooded area • Substitution of production outside flooded area • Temporary housing of evacuees	• Societal disruption • Damage to government

Methods for the estimation of direct economic damage to physical objects (such as structures, houses) are well established, and the use of so-called stage damage curves is widespread, see e.g. (Penning-Rowsell and Chatterton, 1977; Dutta *et al.*, 2003; Kok *et al.*, 2005). In addition, losses due to business interruption can be very significant, for example in the case of long-term closure of a national airport. Van der Veen *et al.* (2003) propose a method for the analysis of indirect economic damage. The methods for the estimation of intangible damage are less well developed. Recent research has focused on different types of intangible flood damage in the Netherlands, such as environmental damage (Stuyt *et al.*, 2003). Hajat *et al.* (2004) and Ahern *et al.* (2005) give comprehensive overviews of the available information regarding the general health impacts of floods. Some evidence exists regarding connections between psychological health effects and post flood mortality, see e.g. (Bennet, 1970).

Table 5-1 does not account for the damage caused by secondary events or so-called chain reactions. Floods can damage industrial installations or disrupt critical industrial processes.

3 Alternative definitions of indirect consequences exist. Parker *et al.* (1987) define indirect losses as those that are caused trough interruption of and disruption of economic and social activities. Some authors, e.g. (Kelman, 2004), argue that the distinction between direct and indirect consequences is inappropriate. They mention that irrespective of how the damage occurred, it occurred directly as a result of the flood disaster.

4 Fatalities may also occur indirectly due to the flood. These are fatalities outside the flooded areas, for example deaths from traffic accidents during evacuation and those due to post flood stress. As most fatalities will be due to direct causes (i.e. physical contact with flood waters), it is categorised as direct damage in table 5-1.

Stored substances can be released, and potentially undergo chemical reactions with water or air. Such effects can harm ecological systems, pollute drinking waters and even lead to additional fatalities (Reinders and Ham, 2003).

5.2 Global perspectives of loss of life caused by floods

5.2.1 Introduction

Every year floods cause enormous damage and loss of life on a global scale. Berz *et al.* (2001) have documented general statistics of various natural disasters on a worldwide scale, but a comprehensive analysis of global statistics on loss of human life caused by floods is not yet found in literature. As floods can occur in different forms, sizes and at various locations with different vulnerabilities, their impacts will differ strongly. Although every flood can be considered a unique event with unique characteristics, patterns may be observed when a large number of floods is studied on a global scale. This provides insight in 1) the magnitude of loss of life in floods on a global scale; 2) the mortality caused by flood events with respect to their type and location.

Information from the OFDA / CRED International Disaster Database (EM-DAT[5]) has been used for a large number of flood events that occurred worldwide. EM-DAT only included information regarding the number of affected people per event. It has been assumed that the number of affected equals the number of exposed[6], leading to mortality = number of killed / number of affected.

5.2.2 Inland floods[7]

Introduction
The statistical analysis presented in this section is limited to three types of inland (or freshwater) flood events: drainage problems[8], flash floods and river floods. No representative sample of coastal flood events could be retrieved from EM-DAT as many significant coastal flood events are classified as windstorms in the database. Coastal floods are analysed separately in section 5.2.3.

The data have thus been evaluated with respect to flood type and location. Overall, information regarding 1883 flood events, which occurred between January 1975 and June 2002, has been considered. Over this period the inland flood events in the database are reported to have killed 176.864 people and affected 2,27 billion people. The event with most fatalities occurred in 1999 in Venezuela: about 30.000 people died during flash floods and extensive land and mudslides.

5 EM-DAT contains data on international disasters and is maintained by the Centre for Research on the Epidemiology of Disasters in Brussels (CRED) in cooperation with United States Office for Foreign Disaster Assistance (OFDA). A disaster is included in the database when at least one of the following four criteria is fulfilled: 10 or more people are killed, 100 or more people are affected, there is a declaration of a state of emergency, or there is a call for international assistance.

6 Due to evacuation the actual number of people exposed could be smaller than the reported number of affected people. The presented mortality statistics could be underestimations.

7 This section is a summary of (Jonkman, 2005).

8 Given the proposed definition in section 4.1 drainage problems are formally not considered as floods.

Analysis by region

Flood impacts can depend on the characteristics of the flooded area. Relevant factors include population magnitude and density, warning and emergency systems and potentially other socio-economic factors (Haque, 2003). However, no significant differences in average mortality per flood event could be observed between different continents, as average event mortality ranges between 0,011 (Americas) and 0,014 (Europe). The impacts in terms of the number of people killed and affected differ by continent. European floods are often relatively small-scale, Asian floods affect and kill more people than events in other continents as they affect substantially larger areas with large populations. The first 45 floods with the highest number of people affected all occurred in China, India, Bangladesh and Pakistan. Larger differences are obtained when the average flood mortality per event is assessed for the 17 world-regions defined in EM-DAT. The differences are mainly caused by the dominance of some high mortality events in the regional datasets. These results do not indicate a relationship between mortality and the underlying determinants, such as socio-economic development of the region. For example, the dataset for the European Union has a high average mortality (0,02), due to the inclusion of some high mortality flash flood events.

Analysis by flood type

The impact of a flood will be strongly influenced by the characteristics of the flood itself. On a general level, typical flood characteristics will differ between event types. For example, rapidly rising flash floods can cause more devastation than small-scale floods due to drainage problems. Figure 5-1 indicates the impacts by flood type, for the events with one or more fatalities. The total number of people exposed is shown on the x-axis and the number of fatalities on the y-axis. The dashed lines indicate different mortality levels.

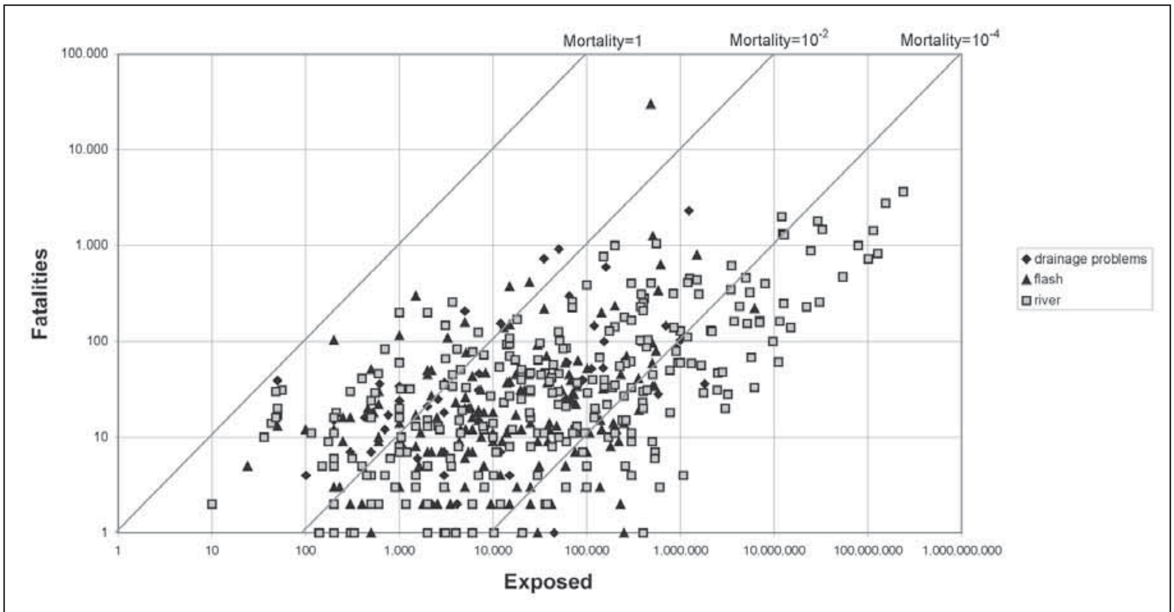


Figure 5-1: Number of fatalities and people exposed for floods with more than 0 fatalities by flood type.

Figure 5-1 shows that floods with large numbers of exposed people are river floods, mainly occurring in Asia. Flash floods form a majority of the floods with lower numbers of affected people. Event mortality is in the order of magnitude of 10^{-3} to 10^{-4} for events with 100.000 people affected, while mortality is in the order of magnitude of 10^{-5} for events with 100 million affected. With the population affected, the size of the affected area also increases. This will therefore include areas where the flood effects will be less lethal (Graham, 1999). Secondly, more time for warning and evacuation will be available when a large area is affected, since the flood will need considerable time to progress through the area.

For the three flood types the (cumulative) probability distribution of event mortality is plotted in figure 5-2. The intersection at the left side of the figure equates the probability mass of the events with F_D=0 (due to the logarithmic scale F_D=0 cannot be displayed in the figure).

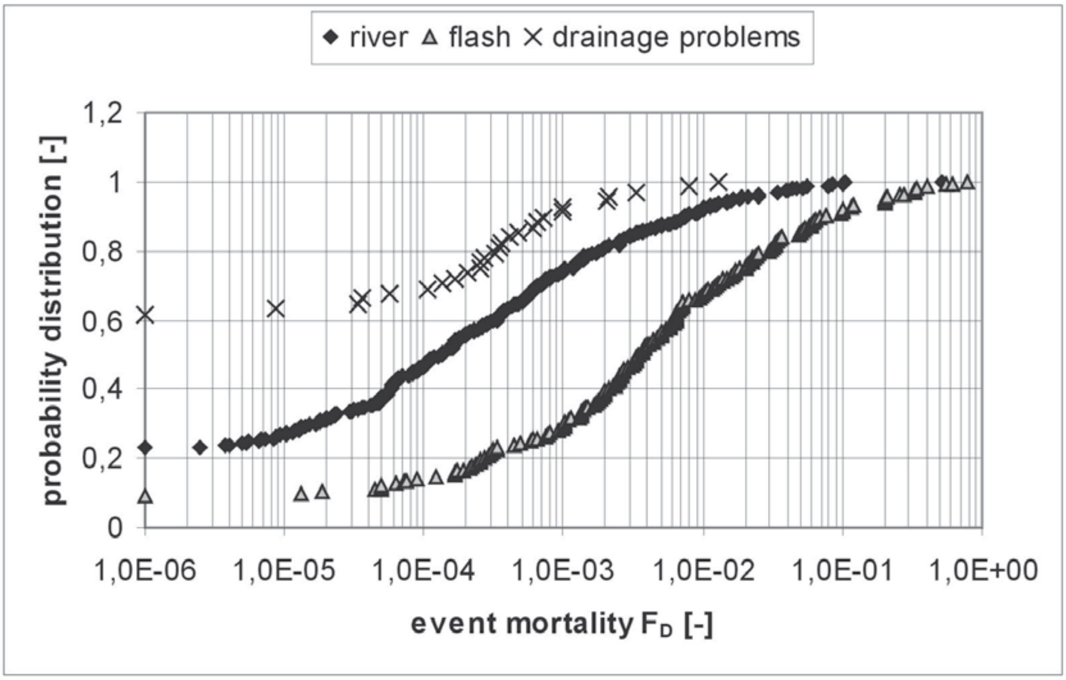


Figure 5-2: Distribution of event mortality for different flood types

For all three flood types the distribution of mortality can be approximated with a (modified) lognormal distribution, which has the following general expression:

$$F = a + (1-a)LOGN(F_D, \mu, \sigma) \qquad \textbf{(Eq. 5-1)}$$

a a constant representing the probability mass of F_D=0
μ, σ the average and standard deviation of the lognormal distribution

Average event mortalities and the derived constants for the distribution function are shown in table 5-2. Average mortality from dataset can be compared with average mortality approximated from the lognormal distribution. The latter equals: $(1-A)exp(\mu+0{,}5\sigma^2)$. Results correspond relatively well. These derived lognormal distributions or their corresponding pdf's can be used as a very general description of conditional mortality for a certain type of event. However, the variation in such an approximation is large due to the variation in mortality between events for one flood type.

Table 5-2: Dataset statistics, and the derived lognormal bestfit trendlines for three event types.

	Dataset		Lognormal bestfit trendline		
Event type	**Events**	**Average event mortality (F_D)**	***A***	**μ**	**σ**
Drainage problems	70	$5{,}3.10^{-4}$	0,62	-7,92	2,46
River floods	392	$4{,}9.10^{-3}$	0,23	-7,95	1,41
Flash floods	234	$3{,}6.10^{-2}$	0,091	-5,23	2,23

Table 5-2 shows that average mortality is highest for flash floods, as these generally occur unexpectedly and are often rapidly developing events, which severely affect smaller areas. River floods affect larger areas and more people, but result in relatively low values for numbers of fatalities and mortality per event. In general they are better predictable and have less severe effects. Average mortality is low for drainage problems. More than half of the drainage events in the dataset causes one or zero fatalities. It is interesting to note that average mortality approximately varies one order of magnitude (a factor ten) between event types.

Cross analysis by region and flood type

A cross analysis of the combination of region and flood type shows that event mortality is relatively constant by flood type considered over the different continents. For example, flash floods result in the following average mortality values for the different regions: Africa (0,042), Americas (0,027), Asia (0,032) and Europe (0,056). These results do not indicate a relationship between mortality and the underlying determinants, such as socio-economic development of the region. The impact in terms of absolute numbers killed differs by continent due to differences in the extent of the populations affected. These differences depend on the number of people present in the exposed areas and the local protection level. The cross analysis shows that river floods in Asia are the most significant in terms of absolute impact, as they caused 40% of the deaths in the considered dataset and 96% of the total people affected.

5.2.3 Coastal floods

Coastal floods are generally caused by windstorms, including hurricanes, cyclones and typhoons. Strong winds and low atmospheric pressure cause set-up of water at the coast. Most of the fatalities due to these storms are caused by the flood effects (Rappaport, 2000). Some available statistics regarding the impacts of some large coastal floods in the 20th century are summarised in table 5-3. Rappaport (2000) and Schultz *et al.* (2005) provide more comprehensive discussions on the impacts of coastal floods.

Table 5-3: Overview of coastal floods (sources: EM-DAT and sources listed in section 5.4).

Date	Location	Cause	Fatalities[9]	People exposed[10]	Event mortality
1-2-1953	Netherlands, Southwest	Storm surge	1836	250.000	0,0073
1-2-1953	United Kingdom, East coast	Storm surge	315	32.000	0,0098
26-9-1959	Japan, Ise Bay	Typhoon	5101	430.000	0,012
12-11-1970	Bangladesh	Tropical cyclone	300.000		
18-9-1974	Honduras	Tropical cyclone	8.000		
12-11-1977	India, southern	Tropical cyclone	14.000	9.000.000([4])	0,0016
25-5-1985	Bangladesh	Tropical cyclone	10.000	1.800.000	0,0056
30-4-1991	Bangladesh	Tropical cyclone	139.000	4.500.000	0,031
End of October 1998	Central America	Tropical cyclone	19.000		
29-10-1999	India, Orissa	Tropical cyclone	9800	12.600.000([11])	0,008

Although this dataset only includes a small sample of coastal floods, the total number of killed far exceeds the accumulated number of killed for inland floods. Coastal floods are capable of causing large numbers of fatalities, as they are often characterised by severe flood effects (large depths and velocities) when low-lying coastal areas are flooded. In addition, in the past they often occurred unexpectedly without substantial warning. This allowed little or no time for warning and preventive evacuation and resulted in large exposed populations. Especially developing countries have been severely affected by coastal floods. It is noted that temporal trends might be reflected in the data, as improvements are made on a global scale in the prediction of storms and typhoons and warning and evacuation of the population (Schultz *et al.*, 2005). For example, Chowdhury *et al.* (1993) relate the reduction over the years in the numbers of flood deaths in Bangladesh to the development of better warning systems.

Figure 5-3 shows the number of killed people versus the number of exposed people for the events from table 5-4. Results show that the average event mortality for the considered events is in the order of magnitude of about 1% (average mortality F_D= 0,0097) for the considered events. For the events in the Netherlands, United Kingdom and Japan the deviation from the observed mortality is less than 40%. For events in India and Bangladesh the estimates of the exposed population and thereby mortality are considered as less reliable[11]. The 1% mortality value can be used as a first rule of thumb to estimate the number of fatalities for large-scale coastal flood events.

9 The reported numbers of fatalities may include considerable uncertainty, especially for the developing countries. For example, for the 1991 floods in Bangladesh the estimated death toll ranges between 67.000 and 139.000 (Chowdhury *et al.*, 1993), resulting in a mortality between 1,5% and 3,1%.

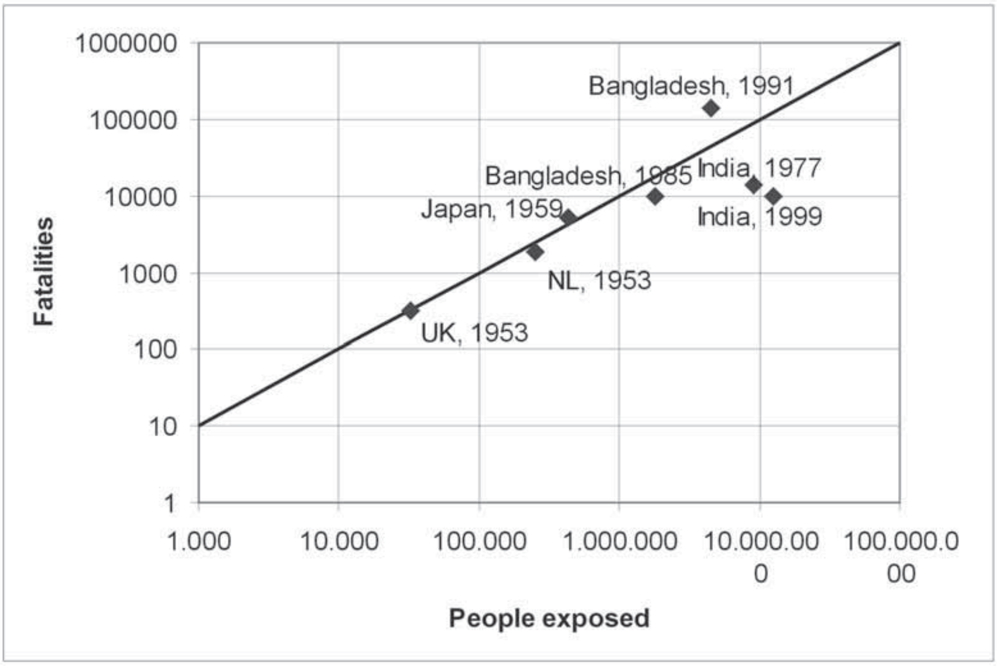


Figure 5-3: Number of fatalities and people exposed for coastal floods from table 5-4. Events are indicated in the figure.

5.2.4 Discussion: comparison of mortality for different flood types

In this section event mortalities for different flood types are compared. Figure 5-4 gives a schematic presentation of the probability density functions of mortality given the occurrence of an event by flood type. Results are based on information presented in the previous sections and Graham's (1999) data for dam breaks. Average mortality is indicated with a dot and the 10% and 90% confidence boundaries are shown with horizontal lines. The spikes at the bottom represent the probability mass of an event with F_D=0.

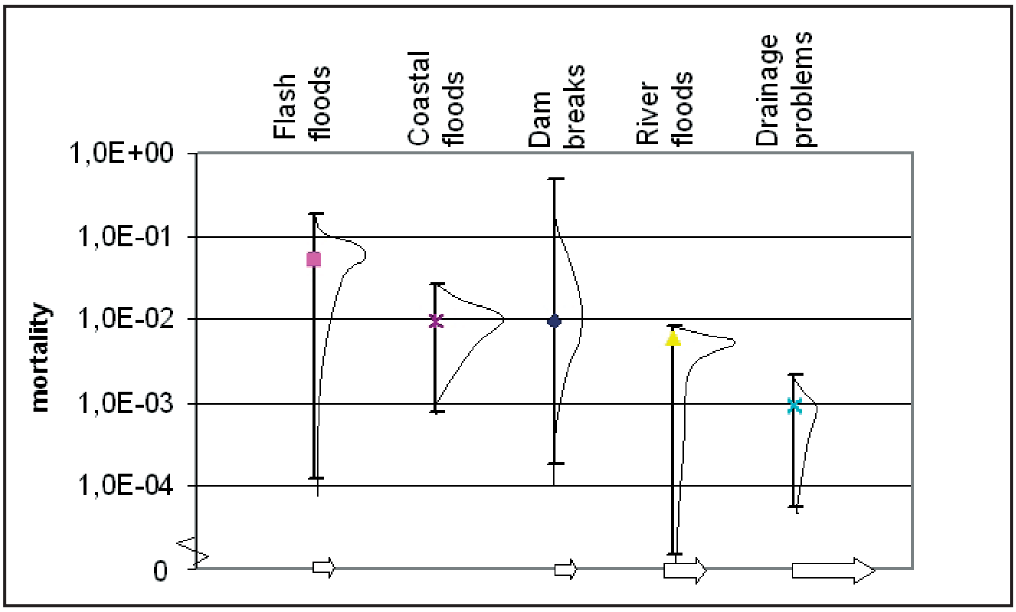


Figure 5-4: Probability density functions of event mortality for different flood types (pdf's are indicated schematically)

The (average) mortalities can be related to 1) the possibility of warning and evacuation and 2) the severity of flood effects. Severity refers to the intensity of the physical flood effects (e.g. depth, velocity and rise rate) and their potential to cause damage and harm (injury, mortality) to the exposed population. Qualitative comparison of the event types shows that those with the most severe physical effects, and limited possibilities for evacuation, result in the highest (average) mortality[10]. Examples are dam breaks and flash floods. Although tsunamis are not included in the figure above, recent investigations of the consequences of the Indian Ocean tsunami of 2005 (Rofi *et al.*, 2006; Guha Sapir *et al.*, 2006) show that mortality locally could exceed F_D=0,1 (or 10%). These high mortality values could be related to the unexpected occurrence of the event and the deadly flood effects associated with the tsunami wave. Average mortality for coastal floods is approximately 0,01. Mortality for river floods shows large variation. It can be in the order of 10^{-2} for sudden and unexpected flooding, larger and more predictable events generally result in much lower mortality. Examples of the latter events are the 2002 Germany floods (mortality in the order of magnitude: 10^{-4}), or large-scale floods in China (10^{-5}). Drainage problems are well predictable and the severity of their effects (e.g. flood depth) is mostly limited. Although large areas can be exposed mortality is often low or even zero.

The extent of consequences is also related to the type of area that is affected. The consequences of flooding can be particularly large when low-lying areas protected by flood defences are flooded. Such low-lying areas protected by flood defences are often indicated as so-called polders[11]. In these areas the land level is below the (high) water levels. In case of a breach in the flood defences extensive areas will be flooded up to large flood depths. These low-lying areas are mainly found in delta areas, such as the Netherlands. It is expected that the consequences of floods in such delta areas will be larger than those in non-delta areas (e.g. upper catchment of a river), both in absolute (fatalities, damage, exposed population) and relative (mortality, damage fraction) terms The difference between flooding potential of delta and non-delta areas is schematically illustrated in figure 5-5.

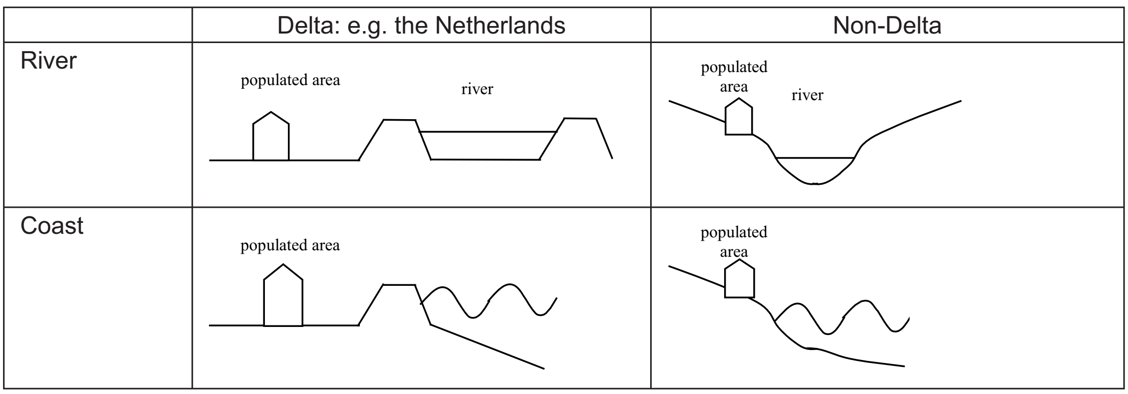


Figure 5-5: Schematic difference between Delta and non-Delta areas with respect to topography and potentially flooded areas

10 It is interesting that differences in average mortality between events may also be reflected in protection standards of flood defences. For example, in the Netherlands safety standards for coastal flood defences are more stringent than the standards for river dikes.

11 Polder: low-lying area protected from flooding by flood defences such as dikes. In addition, drainage systems are needed to discharge rainwater from the polder and to prevent rise of the groundwater table.

Overall, the averages and distributions indicated in figure 5-4 can be used to give first-order estimates of the overall event mortality and loss of life for different event types without detailed input needed. For coastal floods the assumption of 1% mortality seems to give a good first order estimate (see previous section). Such general indicators could provide a rough but useful first estimate for mortality for an event type. However, variation in event mortality remains large. To estimate mortality and loss of life more accurately for one event, case-specific circumstances (flood characteristics; possibility of warning and evacuation) have to be taken into account[12].

5.3 Loss of life in historical floods in the Netherlands

The Netherlands is situated in the deltas of the rivers Rhine and Meuse. Large parts of the Netherlands have been reclaimed from rivers and sea. Without the protection of dikes, dunes and hydraulic structures large parts of the country would be frequently or even permanently flooded. Due to its situation, parts of the country have been regularly exposed to floods from the rivers and the coast throughout history. Several sources provide mainly anecdotal insight in the occurrence of floods in the history of the Netherlands. One of the first reported floods dates from the 3rd century before Christ (SNSD, 1956). The most comprehensive source is the study by Gottschalk (1971). This shows that the number of river floods in the 14th, 15th and 16th century amounted to 40,50 and 65 respectively. Since then, the number of river floods has been reduced due to river regulation. Table 5-4 gives an overview of some characteristic floods in history, for which estimates of the numbers of fatalities are available.

12 For example for dam breaks this is clearly demonstrated by the analysis of Graham (1999). He shows that severe dam breaks without possibilities for evacuation will result in event mortalities between 0,3 and 1. However, for dam breaks with lower severity and no warning mortality is around 0,01

Table 5-4: Overview of some historical floods in the Netherlands with respect to their loss of life.

Year	Name	Flooded area	Type / origin	Fatalities[13]	Source
838		Coast, Frisia	Storm surge		*
1228			Storm surge	100.000	Mitchell, 2003
1287	St. Luciavloed	Waddensea	Storm surge	50.000	Mitchell, 2003
1404	1st St. Elisabethsvloed	Vlaanderen en Zeeland	Storm surge		*
1421	2nd St. Elisabethsvloed	Southwest Nederland	Storm surge	>10.000	Slager, 1992
1530	St. Felixvloed	Zeeland	Storm surge	More than 100.000	Slager, 1992
1570	Allerheiligenvloed	Whole coast: Zeeland, Friesland	Storm surge	20.000	Van der Heijden, 2003
1686	St. Maartensvloed	North- Netherlands	Storm surge	1558	Mulder, 1954
1717		Western coast	Storm surge	11.000	Mitchell, 2003
1784		Betuwe, Tielerwaard, Maas en Waal	River	10 tot 20	Van der Ven, 1995
1809		River area: Ooijpolder to Ablasserwaard	River	275	Van der Ven, 1995
1825		Noord Holland, Overijssel	Storm surge	305	Mulder, 1954
1855		Betuwe en Land van Maas en Waal	River	13	Commissie Rivierdijken, 1977
1861		Bommelerwaard, Land van Maas en Waal	River	37	Van der Ven, 1995
1880		Land van Heusden en Altena	River	2	Commissie Rivierdijken, 1977
1916		Zuiderzee	Storm surge	15	*
1926		Maas	River	?	Commissie Rivierdijken, 1977
1953	Watersnoodramp	Southwest Netherlands	Storm surge	1835	Slager, 1992

*: source http://proto.thinkquest.nl/~jrb144/stormvloedrampen.htm, accessed December 2005.

The table shows that especially storm surges from sea resulted in a large number of fatalities. The number of fatalities for historical river floods is much lower. Due to their relatively frequent occurrence people in river areas were relatively well prepared for these floods. Furthermore, deeper parts of the polder were generally not inhabited before the 18th century and most people lived on higher grounds.

It is difficult to derive directly applicable indicators for the estimation of loss of life for floods in the current situation from the historical figures presented. Several developments have influenced the flood hazards. These include: improvements of prediction and warning systems, evacuation routes and transport systems and quality of buildings. However, also disadvantageous developments can be indicated such as the intensive habitation of the deepest polders[14], limited awareness of calamities in the populations and the vulnerability of modern communication systems during crises. The committee on improvement of the river dikes (Commissie Rivierdijken, 1977) states that “experiences from the past indicate that in the past floods have never occurred without loss of human life”. Based on the available data the committee estimates that the number of fatalities caused by a river flood will

13 The available sources show large variations in the number of reported fatalities per event. For example for the first St. Elisabeths flood in 1421 the reported number of fatalities varies between 10.000 and 100.000

14 van den Hengel (2006) analysed the consequences of the 1953 storm surge disaster that flooded large parts of the Southwest of the Netherlands. He found that, if that same flood would occur nowadays, the number of fatalities would increased more than the population has increased since 1953. This is due to the fact that most new housing developments took place in deeper (and more vulnerable) parts of the area.

vary between one and decades. However, (according to the author of this thesis) it would be incorrect to assume that a limited number of fatalities will occur for river floods by definition. If a deep river polder is flooded unexpectedly and without warning, the death toll could be very high. This has also been confirmed by recent case studies (Asselman and Jonkman, 2003; Jonkman and Cappendijk, 2006). These showed that, depending on the area, extreme floods from the river could lead to hundreds or even thousands of fatalities if no evacuation is performed.

5.4 Historical flood events and the determinants of loss of life

Specific flood events for which documentation is available are discussed below. This provides more insight in the determinants of loss of life. Given the scope of this study the examined cases concern floods in low-lying areas protected by flood defences.

5.4.1 North Sea floods 1953

From 31 January to 1 February 1953, a North Sea storm surge devastated coastal areas of the United Kingdom, Belgium and the Netherlands. Apart from enormous economic damage and severe societal disruptions, this event claimed over 2000 lives in the three countries. The event is relatively well documented, and relevant findings and data concerning fatalities in the three countries are outlined below.

Netherlands
Large parts of the Southwestern part of the Netherlands were flooded (figure 5-6). The disaster caused enormous economic damage and 1835 fatalities. About 250.000 people were affected, more than 47.000 cattle en 140.000 poultry were killed in the floodwaters. 3000 Residences and 300 farms were destroyed, and more than 40.000 houses and 3000 farms were damaged. Approximately 200.000 hectares were flooded and the total material damage was estimated at 1,5 billion guilders (1953 prices - Source: www.delta2003.nl).

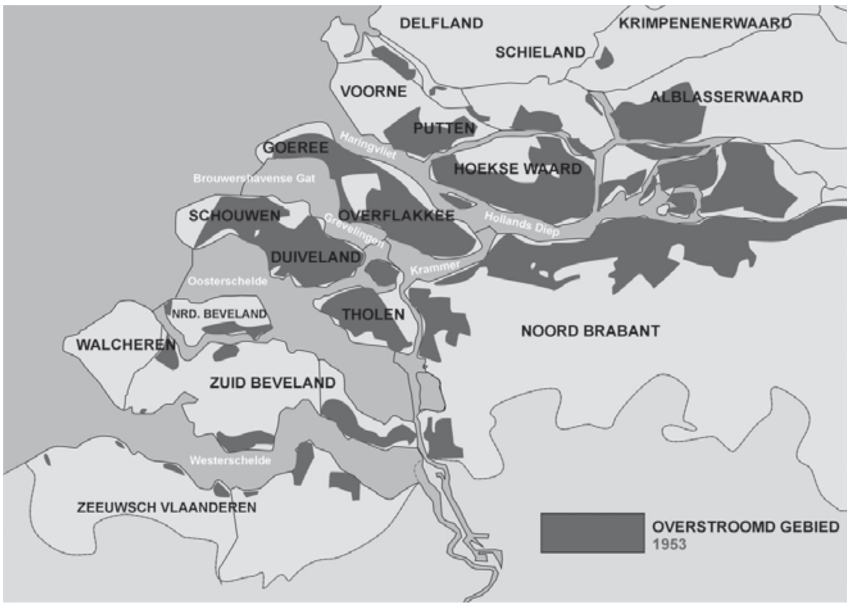


Figure 5-6: Flooded areas (indicated in dark) during the 1953 storm surge in the Netherlands (Source: Rijkswaterstaat)

Mainly due to individual initiative, some villages were adequately warned and suffered a limited number of fatalities. However, at many locations very little or no warnings were given in advance. No preventive evacuation could be executed, but people took refuge in higher buildings and grounds locally. Most fatalities occurred at locations where there was insufficient warning and where the water rose rapidly to form a deep flood. Descriptions of the 1953 floods in the Netherlands by Slager (1992) show that at high-mortality locations, large numbers of buildings collapsed due to the severe conditions and the poor quality of buildings. As a consequence the poorest communities suffered most fatalities.

Duiser (1989) and Waarts (1992) collected data regarding the loss of life in the Netherlands due to this disaster from memorial volumes and official reports. Both reports give loss of life and hydraulic circumstances by municipality. Official death tolls have been listed in the dataset published by the Delta 2003 project[15]. By combining available sources a dataset has been obtained that includes 91 locations and 1795 fatalities. The difference between the totals 1835 and 1795 is accounted for by a number of people that died in a period after the disaster because of the illness and suffering they experienced during the first hours or days. Based on the descriptions from memorial volumes and the analysis of Waarts (1992), fatalities in three zones are distinguished: in a zone with high flow velocities, a zone with rapidly rising waters, and a remaining zone (see also section 7.4.1). Table 5-5 shows the distribution of reported fatalities over the three categories.

Table 5-5: Categorised data regarding fatalities caused by the 1953 disaster in the Netherlands, based on (Waarts, 1992)

Zone	Fatalities	Fraction
Rapidly rising waters	1047	0,58
High flow velocities	260	0,15
Remaining zone	488	0,27
Total	1795	1

An official record, which lists all 1795 individual fatalities, is available at an internet website[16]. Based on these data a comparison between the age distribution of fatalities and the age distribution of the overall population in the Netherlands[17] is given in figure 5-7. This shows that during this event, especially the elderly over the age of 60 years were more vulnerable. A reason might be the decreased possibilities of self rescue of elderly. Further analysis showed that 49% of the fatalities were male and 46% were female. The gender of 5% of the victims was unknown. This does not necessarily indicate an increased vulnerability of one of the genders.

15 www.delta2003.nl, accessed January 2006.

16 http://www.zeeuwsarchief.nl/strijdtegenhetwater/ramp/slachtoffers-lijst.htm, accessed December 2004.

17 obtained from www.cbs.nl, accessed December 2004.

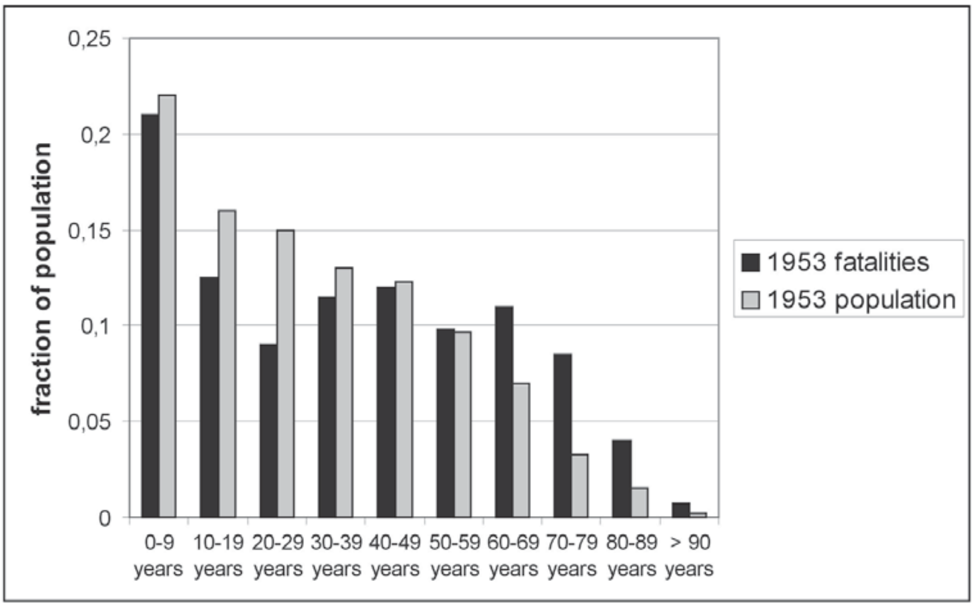


Figure 5-7: Comparison of distribution over the age categories for fatalities of the 1953 flood disaster and the 1953 population

Belgium

Also in Belgium the 1953 storm surge caused flooding. Of the 66 kilometres of coast line, 4,6 km were severely damaged. Martens (2003) mentions that in total 8 fatalities occurred in the coastal area: 7 in Oostende, and 1 at sea. Of the 7 fatalities in Oostende, 3 died in the city centre: 2 due to drowning and 1 due to a heart attack. The other 4 people drowned when a house in Sas Slijkens was flooded. Other sources report higher death tolls for Belgium: between 10 and 22, see (Gerritsen *et al.*, 2003) for an overview.

United Kingdom

The 1953 storm surge floods also caused large damage at the East coast of the United Kingdom. The following numbers give an idea of the extent of damage in the United Kingdom: 32.000 people were evacuated, 24.000 homes were damaged and 65.000 hectares of agricultural land were flooded. The economic damage is estimated at 50 million pounds. Figure 5-8 shows the flooded areas.

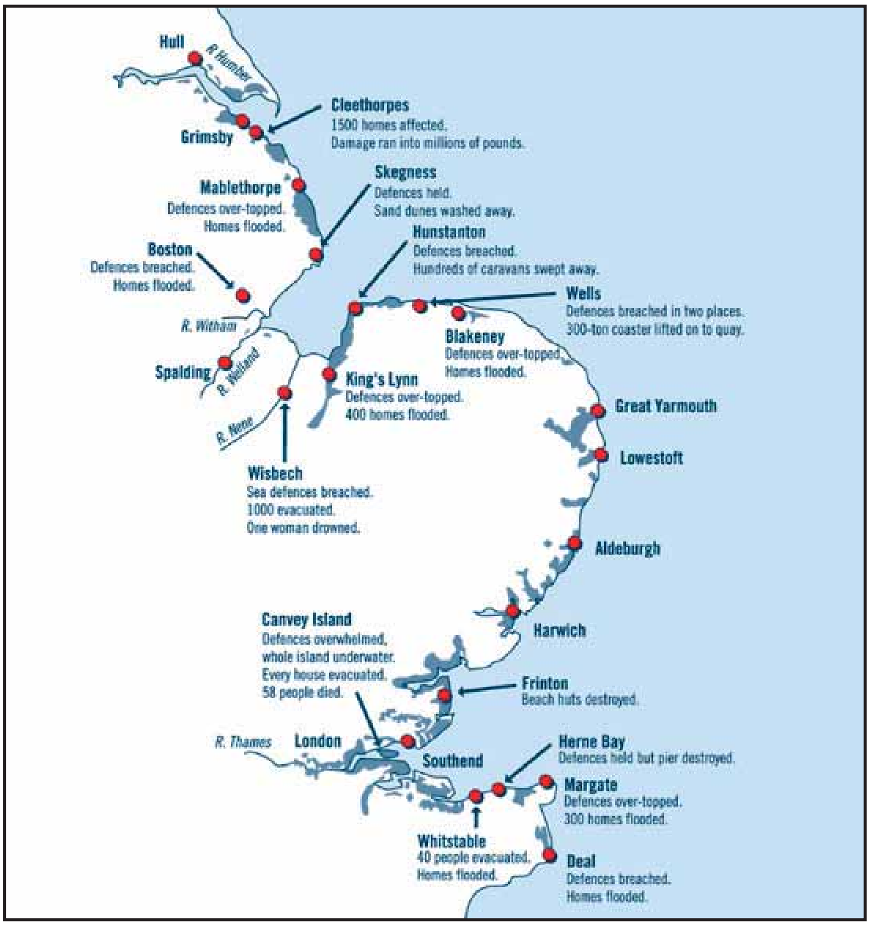


Figure 5-8: Flooded areas at the east coast of the United Kingdom during the 1953 floods (source: Environment Agency)

Kelman (2003b) gives a comprehensive overview of statistics on loss of life in the UK 1953 floods. The reported death toll ranges between 304 and 313. In addition 160 people deceased at sea, of which 130 when the ferry Princess Victoria sank. The high death toll is mainly due to the unexpected occurrence of the floods at night, without warning. Death tolls were highest at seaside towns with low quality buildings, often consisting of wooden prefabricated houses. The following quotation gives an indication of the importance of collapse of buildings: *"It is significant that the stretches along the stretches of coast where the casualties were heaviest – the Mablethorpe Sutton area of Lincolnshire, the Hunstanton to Lynn area, Jaywick, Canvey Island – were largely seaside shanty-towns consisting mainly of timber bungalows never intended for winter occupation."* (Pollard, 1978). Locations with the highest numbers of fatalities were Felixstowe (39 fatalities) and Canvey Island (58 fatalities, most of them in the Sunken Marsh area). At these locations people were surprised by the floods and he quality of buildings was poor.

In addition the elderly proved to be very vulnerable: *"And consistently, all round the east coast, the eventual death tolls showed that it was the elderly, who went to bed early and had meagre reserves of energy even if they had time to realise what was happening when the water hit them, who were most vulnerable…"* (Pollard, 1978). At Canvey Island, 42 out of 58 fatalities were aged over 60. At Jaywick, 28 of the reported 34 fatalities were over 60. In south Lynn, all 14 fatalities were over 60.

5.4.2 Japanese storm surges

Throughout history, Japan has been hit by several large storm surge floods caused by typhoons. Several authors have documented data regarding loss of life for specific events. The main findings are summarised below.

Ise Bay Typhoon 1959 (Tsuchiya and Yasuda, 1980; JWF, 2005)
On September 26 1959 the Isewan typhoon hit Central Japan. The most severely exposed area was the Ise Bay. The floods occurred in the late evening and at night due to overtopping and breaching of seawalls. At most locations no adequate warning could be given, as there was no electricity due to the storm. In total the floods left 5101 people dead, and about 430.000 people were exposed. Many fatalities occurred where the flood defences were breached, even if the length of the breached flood defence was relatively small. Most fatalities occurred at locations where the warnings were inadequate and where insufficient time was available for evacuation. In addition, large water depths were an important factor, "as the area of the inner part of the Ise Bay had been built by reclamation since the Edo area, and the land was lower than the sea level, there were no safe places for refuge." (Tsuchiya and Yasuda, 1980). Tsuchiya and Yasuda (1980) have documented statistics regarding loss of life and they provide information regarding the following factors: mortality, water depth, length of broken sea walls and level of warning.

Storm surges in Osaka Bay
Tsuchiya and Kawata (1981) have documented information regarding the loss of life for three historical storm surges in Osaka Bay. These were caused by the typhoons Muroto (Sept. 9 1934), Jane (Sept. 3, 1950) and Daini Muroto (Sept. 16 1961). Each of these storm surges flooded large areas of Osaka city (Muroto: 49 km^2, Jane: 39 km^2, Daini-Muroto: 31km^2). Based on a comparison of these historical typhoons the authors discuss some aspects that influence loss of life. The authors mention the relationship between the number of collapsed houses and the numbers of fatalities, as "the greatest loss of human life during storm surge disasters takes place when houses are ruined or swept away". The importance of warning is also investigated: "We concluded that adequate typhoon information and warnings to take refuge are exceedingly useful in reducing life risk". This is illustrated by the descriptions of the Daini Muroto typhoon in 1954. Despite large-scale floods no fatalities occurred. Due to timely warning more than 100.000 people evacuated or sheltered. The authors also state that the depth of flooding had a significant effect on mortality as it is related to possibilities for shelter. The statistics have been documented by administrative district and concern the submerged area, the average water depth, the numbers of inhabitants, numbers of fatalities and injured, and numbers of houses ruined.

Typhoon no. 18 in 1999: Flooding of Shiranui Town
Typhoon No. 18 hit the Kyushu and Chugoku regions in Japan on September 24 1999. Although the storm surge flooded several locations in Yatsushiro Bay no fatalities occurred in these locations due to adequate warning. Only in the Einu District in Shiranui Town no warning was given and 12 people were killed when the water overtopped the sea dike in the middle of the night. The fatalities were mainly children and elderly. Kato (2002) suspects that their death is related to their inability to evacuate. In addition, large numbers of buildings in this area were damaged and some were even destroyed. About 200 people

were living in the exposed area, and no warning was given. The floods rose up to a depth of about 2,6m above land level within 10 to 30 minutes (Kato, 2002; Takikawa, 2001).

5.4.3 Bangladesh cyclone in 1991

A relatively well-documented event is the 1991 Bangladesh cyclone. Two publications report epidemiological studies on flood mortality (Chowdhury *et al.*, 1993; Bern *et al.*, 1993). During this event large parts of coastal Bangladesh were flooded and the estimated death toll ranged between 67.000 and 139.000. The two available studies examined samples of the population in the most severely exposed areas[18]. For these areas mortality fractions of 0,1 or higher were reported. The available sources provide insight in the role of warning, shelters and collapse of buildings and individual vulnerability factors. However, no relationships between local mortality fractions and flood characteristics (e.g. depth) are reported[19].

Warning and evacuation: At most locations a warning was given 3 to 6 hours in advance. Due to the short warning time evacuation was not feasible. In the investigated communities warnings were mostly neglected. Many inhabitants did not believe the warnings or they did not expect the floods to be so severe. Most people had to flee to shelters in the last hour before the event or even during the impact phase. The sources do not provide information regarding the relationship between the level of warning and mortality.

Shelter and buildings: Both studies report that approximately one third of the population had taken refuge in shelters by the moment of impact of the storm surge. None of these people died. Chowdhury *et al.* (1993) report that 12 percent of the population used official / formal shelters. Others used other types of buildings as shelter, such as private houses and other public buildings. The death rate was two times higher in the population which did not take any shelter, compared with the total population. The authors estimate that 20 percent more deaths would have occurred without formal shelters. Death rates differed significantly between house types. Both studies found that death rates were highest in "kutcha" houses, which are made of straw and mud. Chowdhury *et al.* (1993) report that only 3% of the poor quality kutcha housings were strong enough to withstand the flood flow. The death rate was lower in brick ("pucca") houses and no deaths were reported amongst those living in two story buildings. The above findings indicate the importance of possibilities for shelter on higher floors of a building. Differences in mortality between housing types probably reflect the vulnerability of the poor quality buildings to collapse. Chowdhury *et al.* (1993) stress "the immense utility of trees as life savers". Bern *et al.* (1993) estimate that mortality was 0,11 for those who took refuge in trees, which is lower than the 0,22 mortality for those who sought refuge on high ground.

Individual vulnerability factors: Death rates were substantially higher for females than for males. Mortality was highest amongst children below the age of 10 years and amongst women older than 40 years. Higher vulnerabilities amongst these groups might be related to physical ability (size, strength, endurance, nutrition), style of clothing (women) and

18 Mortality was not investigated for areas with smaller mortalities, although these may have contributed to the total death toll significantly. The findings of the considered studies may thus not necessarily be representative for all areas.

19 Further assessment of the following reference is strongly recommended: Bangladesh Rural Advancement Committee (1991) Cyclone '91: a study of epidemiology. This source might provide more insights in the quantitative relationship between flood characteristics and mortality, but the report could not be obtained during the course of this study.

social role. This suggests that the ability of a person to take refuge during a flood is important for survival.

5.4.4 Other flood events

Laingsburg flood disaster, South Africa
In January 1981, floods occurred in large areas of the Karoo region. The town Laingsburg was most severely exposed. The village was flooded within several hours up to several metres until only the roofs were visible (estimated water depth is 4 metres). 104 People were killed and the number of exposed is estimated at 185 people (EMDAT, 2004).

River floods in the United Kingdom
Ramsbottom *et al.* (2003) report data regarding three river floods in the UK. The first event concerns the floods in town of Gowdall from the river Aire in autumn 2000. The flood depth reached about one meter, 250 people were affected, but no fatalities occurred as a warning was given in advance and many people were probably able to evacuate. Secondly, some facts on the river floods in Norwich in 1912 are reported. The speed of onset was gradual, but no flood warnings were given. Two thousand five hundred people were affected, and 4 people were killed in floodwaters that reached depths from 1 to 1,5 meters. Some people were warned in advance, but no full-scale evacuation was feasible. The third event is the flood that hit the town of Lynmouth in August 1952 due to flooding of the East and West Lynn rivers. There was no flood warning and the speed of onset was rapid. Four hundred people were exposed and the actual death toll was 34. Most fatalities occurred very near the river where water was estimated to rise to 3 meters. In addition about a quarter of the flooded houses were destroyed.

5.4.5 General findings with respect to factors that determine loss of life

Despite differences with respect to their temporal and geographical situation[20], the major factors that have determined the loss of life in these historical flood events seem to be very similar. Based on the available descriptive information and previous analyses (e.g. Tsuchiya and Yasuda, 1980; Bern *et al.*, 1993), the main factors that influence mortality are summarised below:

- The events with the largest loss of life occurred **unexpectedly** and without substantial **warning**. Many of the high-fatality events also occurred at night (Netherlands and UK 1953, Japan 1959), making notification and warning of the threatened population difficult.
- Timely **warning** and **evacuation** prove to be important factors in reducing the loss of life. Even if the time available is insufficient for evacuation, warnings can reduce the loss of life. Warned people may have time to find some form of shelter shortly before or during the flood.
- The possibilities for **shelter** are a very important determinant of mortality. Buildings can have an important function as a shelter, but possibilities to reach shelters will depend on the level of warning, water depth and rise rate of the water.
- **Collapse of buildings** in which people are sheltering is an important determinant of the number of fatalities. Findings from different events (Bangladesh 1991, Neth-

20 Further discussion of the transferability of data from case studies for quantitative analysis of loss of life of contemporary floods in the Netherlands is provided in section 7.1.2.

erlands 1953) show that most fatalities occurred in areas with vulnerable and low quality buildings.

- **Water depth** is an important parameter, as possibilities for shelter decrease with increasing water depth. Low-lying and densely populated areas, such as reclaimed areas or polders, will be most at risk (see also figure 5-5).
- The combination of larger **water depths** and **rapid rise of waters** is especially hazardous. In these cases people have little time to reach higher floors and shelters and they may be trapped inside buildings.
- High **flow velocities** can lead to the collapse of buildings and instability of people. In different cases (Netherlands and UK 1953, Japan 1959) many fatalities occurred behind **dike breaches** and **collapsed sea walls**, as flow velocities in these zones are high.
- Anecdotal evidence (e.g. Slager, 1992) shows that many lives were saved by individual bravery, whether or not they had any training or equipment. The literature does not provide evidence of substantial reduction of the loss of life due to **organised rescue actions** in the first hours of the flood. The actions of rescuers are important to remove people from the flooded area in the days after the event.
- When exposed to a severe and unexpected flood, **children** and **elderly** were more vulnerable. This suggests that chances for survival are related to an individual's stamina and his or her ability to find shelter. A further analysis of individual vulnerabilities is provided in the next section.

The above factors are important determinants of the loss of life. Local variations in the above factors may lead to differences between mortality fractions for different locations within one flood event. Especially unfavourable combinations of the above factors will contribute to high mortality. For example in the 1953 floods in the Netherlands, mortality was highest at locations where a) no flood warnings were given b) the waters rose rapidly to larger water depths and c) where the quality of buildings was poor. The event-based data (see appendices) show that for such locations mortality can range up to 0,1 to 0,4. For other locations more limited mortality fractions are reported, generally between 0 and 0,01.

5.5 Causes and circumstances of individual flood disaster deaths

Introduction and approach

In addition to the findings from global statistics and flood events, this section discusses the loss of life at the individual level. Past work analysed the causes and circumstances of flood fatalities for specific regions ((Coates, 1999) for Australia) and flood types ((French *et al.*, 1983; Mooney, 1983) for flash floods in the USA). A study (Jonkman and Kelman, 2005) has been carried out to improve the understanding of the causes and circumstances of flood disaster deaths at the individual level. This section is a summary of that study, further background and details are provided in the original publication. The study focussed on the causes and circumstances of flood fatalities and the effects of individual vulnerabilities (e.g. age, gender)

Following earlier recommendations for standardised data collection for floods (e.g. Hajat *et al.*, 2003; Legome *et al.*, 1995; WHO, 2002) a categorisation of causes and circumstances of death is proposed. It takes into account the medical causes of death, and also the relevant activity for some categories:

- Drowning: as a pedestrian, in a vehicle, from a boat, during a rescue attempt, in a building;
- Physical trauma: in water, as a pedestrian, in a vehicle, on a boat, during a rescue attempt, in a building;
- Other causes: heart attack, electrocution, carbon monoxide poisoning, fire, other.

Van Beeck *et al.* (2005) propose the following definition "drowning is the process of experiencing respiratory impairment from submersion / immersion in liquid". According to Bierens (1996), both hypothermia and asphyxiation can occur during the drowning process. In the available literature deaths are often indicated as drownings without any further description of the exact circumstances.

Analysis and results

Thirteen flood events from Europe and the United States were included, mainly considering inland (river) flood events. The events resulted in 247 reported flood fatalities. Each case study is relatively recent (within the past 20 years) and involved relatively few deaths (less than 50). Therefore the considered events are assumed representative for relatively well-predictable floods with moderate effects in western countries. The individual-by-individual data were aggregated for analysis. Results with respect to causes of death are presented in figure 5-9.

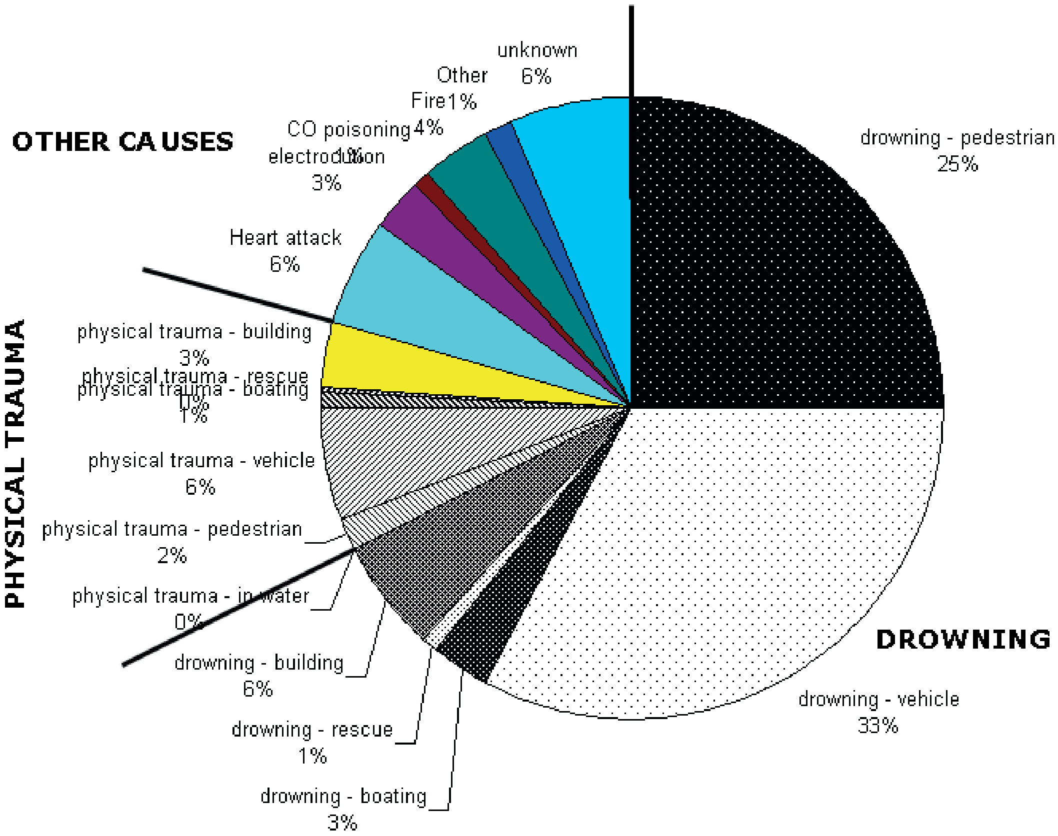


Figure 5-9: Distribution of the causes and circumstances of death for the 13 considered events, based on (Jonkman and Kelman, 2005)

Drowning accounts for the majority of the fatalities (67,6%), with the implication that approximately one third of flood disaster fatalities is not due to drowning. Vehicle-related drownings occur most frequently and result when people try to drive across flooded bridges, roads, or streams. Physical traumas account for 11,7% of the fatalities, most of them occurred in vehicles. Other relevant causes are heart attacks during evacuation and return (5,7%), electrocution deaths during clean up (2,8%), and deaths from fires following the floods (3,6%).

The influence of individual vulnerability factors has been investigated. Males have a high vulnerability to dying in floods, as approximately 70% of the reported fatalities are male. Likely causes are the high involvement of males in driving, the high proportion of males in the emergency and supporting services, and males' risk-taking behaviour. The way people respond to floods is an important factor in the associated morbidity and mortality (French and Holt, 1989). A substantial proportion of the flood-related deaths is believed to be attributable to unnecessary risk-taking behaviour. Descriptions of individual circumstances of fatalities reveal different forms of flood tourism, and recreational activities, as well as people entering the water unnecessarily. Similar observations with respect to the substantial influence of risk taking behaviour are given by Coates (1999), WHO (2002) and ICPR (2002). In contrast to previous studies (Coates, 1999; Mooney, 1983), this study did not show an overrepresentation of the young and elderly in flood death statistics. In the two cases where victims' alcohol blood levels were measured (Thorne *et al*, 2002; Staes *et al*, 1994), the majority of victims were impaired[21].

Discussion

From the above analysis recommendations can be abstracted to prevent loss of life. These concern a timely warning and raising public awareness to influence people's reaction and behaviour, as they are critical factors. People should be prevented from entering floodwaters, either by vehicle or foot, as much as possible. Mitigation strategies should also consider deaths from other causes than drowning. These include the prevention of heart attacks, due to preparation and planning of evacuations, and post impact deaths due to electrocution and carbon monoxide poisoning.

The conclusions of this study might apply only to the floods examined: that is, smaller-scale floods in Europe and the US. Higher-fatality events, such as coastal and flash floods, might exhibit different mortality patterns with respect to individual vulnerabilities compared to the smaller-scale events studied here. In the predictable floods analysed here, a substantial part of the fatalities might be due to risk taking behaviour. In more unexpected events (such as the events analysed in the previous section) other mechanisms and causes will be more important. For example, in contrast to the over-representation of male deaths found here, the 1953 floods in the Netherlands resulted in a nearly equal distribution of fatalities over the genders. Similarly, while only a few of the fatalities in this study occurred in buildings, a large proportion of the 1835 fatalities in the Netherlands during the 1953 storm surge occurred due to collapse of low-quality buildings (Slager, 1992). Also the transferability of the results of the work here to other regions should be considered. Unfortunately limited data are available for floods in developing regions, while most flood fatalities occur here. To provide a more solid basis for the formulation of prevention strategies, better systematic recording of flood fatalities is recommended, especially for covering different types of floods in all countries.

21 According to Hirschler *et al.*(1993) over 30% of fire fatalities had high alcohol blood levels. This suggests that impairment by alcohol could be an important factor for other event types as well.

5.6 Evaluation of the available information

Overview of available information regarding loss of life

In the preceding sections different aggregation levels of available information regarding loss of life caused by floods have been discussed. Table 5-6 summarises these different types of information.

Table 5-6: Summary of types of information regarding loss of life caused by floods

Scale	Type of information	Provides insight in	Strengths	Weaknesses
Macro (global)	Global statistics	Loss of life and average mortality by event type	Useful global indicators, insight in mortality by flood type	Large variations between events, no insight in underlying factors
Meso (event / location)	Flood events	Mortality by location and relationship with flood characteristics	Possibility to relate mortality to flood characteristics	Limited insight in root causes of individual flood deaths
Micro (individual)	Individual causes and circumstances of flood disaster deaths	Influence of individual vulnerability factors and causes of mortality	Insights for prevention and mitigation at the individual level	- No information regarding the relationship between hazard factors and event mortality. -Relevance of factors differs by event type

These types of information are related. Global statistics are aggregated from flood events, and mortality patterns for one flood event result from aggregation of individual fatalities. Given the limitations of the existing data, further collection of data at all three levels is recommended. This will provide a better basis for policy support and development of mitigation strategies. Eventually, also following previous recommendations (WHO, 2002; Hajat *et al.*, 2003), a general reporting system could be developed which also involves the non-lethal health effects and the longer-term mortality of flood disasters.

Applicability of different types of information for the development of a method for the estimation of loss of life

The paragraph below evaluates how the different types of information can be used to develop a method for the estimation of loss of life. Indicators derived from global statistics (sections 5.2 and 5.3) give a useful but rough estimate of the order of magnitude of event mortality. However, these statistics do not provide a sufficient basis for a case-specific estimation of loss of life, as the reported variations in these statistics are considerable.

At the other end of the spectrum, there is the analysis of individual causes of death and vulnerabilities (section 5.5). It is found that the occurrence of individual fatalities is mainly dependent on individual circumstances and behaviour. To model the individual probability of death a so-called mechanistic or process-oriented approach would have to be followed, that fully simulates the sequence of events and behaviour at the individual level. However, due to the number of factors involved a very large amount of data would be needed for calibration of all these factors in an empirical model. This approach is therefore not adopted in this study.

In order to give a reliable estimation event specific conditions have to be taken into account, such as flood characteristics, warning and evacuation. Given the above discussion and limitations of other types of information it is chosen to develop a method for the estimation of loss of life based on the information from historical flood events. By empirical analysis of case study data, dose-response functions can be derived to estimate mortality as a function of flood characteristics and other factors. Although the outcome for each exposed individual will be unknown, such functions allow estimation of expected mortality[22] in the exposed population. The benefit of this approach is that it is not more complex than needed[23] and that it is based on empirical data.

Factors to be included in the model for the estimation of loss of life
Based on the preceding analyses (section 5.4) and past work (Ramsbottom *et al.*, 2003; Aboelata *et al.*, 2003) table 5-7 provides an overview of potential factors of relevance for the estimation of loss of life. Following the systems categorisation proposed in section 1.3.2, factors are subdivided into elements related to physical effects and factors related to the physical and organisational system. For each factor it is indicated whether it influences the extent of the exposed population (by evacuation or shelter) or mortality amongst those exposed. A brief description is given for each factor. In the fifth column the availability of data in different types of sources is indicated. In the last column the relevance of these factors is ranked for the estimation of loss of life for floods of low-lying areas due to the failure of flood defences. A similar set of factors could be considered for other types of floods, such as dam breaks. However, for these cases the relevance of certain factors might be rated differently.

Especially unfavourable combinations of specific factors will be life threatening. For example, information from flood events showed that locations which had a combination of deep water, no warning and poor quality of buildings suffered highest mortality. Some of these factors may be interrelated. For example, water depth, rise rate and flow velocity have a physical relationship (see section 7.2). The above factors provide a basis for further development of a method for the estimation of loss of life for flood of low-lying areas due to breaching of flood defences in section 7.

22 With respect to this issue McClelland and Bowles (2002) argue that although one cannot know the outcome of any individual, it is possible to describe the probability distribution of outcomes over multiple individuals.

23 This is also an engineering principle: the model should be as detailed as is necessary for a sufficiently accurate estimation of outcomes. For example, in mechanics, fist a simple hand calculation is made and later a more detailed assessment with a finite element method is performed.

Table 5-7: Overview of relevant factors for the estimation of loss of life for floods.

Factor	Exposure	Mortality	Comments	Available data	Relevance
Physical event characteristics					
Water depth		X	Important as deeper water gives less possibilities for shelter. It will also influence collapse of buildings.	Case studies	High
Rise rate of the water		X	Determines the possibility for shelter and influences collapse of buildings.	Case studies	High
Flow velocity		X	High flow velocities can cause instability of people and lead to collapse of buildings		High
Arrival time of flood water at a location after breach	X		mainly determines the time available for evacuation	Dam breaks (Graham, 1999)	High
Moment of occurrence of breach (day / night)	X	X	It influences the predictability, preparedness and possibilities for warning and shelter		Medium
Time of day, week and year	X		It influences the presence of population in an area and the possibilities for warning		Medium
Debris		X	Floodwaters carrying debris present greater threat to people and buildings		Medium
Water temperature		X	determines the survival chances of people in water.		Medium / low
Waves		X	Can damage buildings (could be relevant for coastal floods)		Low / medium
Flood duration		X	Could influence mortality of people stuck in homes, less relevant for direct fatalities		Low
Water quality / Pollution		X	Can lead to injuries and illnesses but less relevant for direct mortality		Low
System characteristics					
System factors related to physical system configuration					
Infrastructure capacity	X		determines the time required for evacuation	-	High
Shelters	X	X	can prevent or reduce exposure to floodwater	-	High
Quality of buildings		X	Determines the possibility of collapse of buildings and consequent loss of shelter	Case studies	High
System factors related to organisation					
Prediction and warning	X	X	Essential for evacuation, also important for possibilities to find shelter.	Case studies (categorised)	High
Evacuation plans and organisation	X		These can fasten decision-making, warning and evacuation progress	-	High / medium
Population state and vulnerability (age, gender, health)		X	Important for individual survival, might be less relevant for larger 'average' populations	Individual (qualitatively)	Medium
Reaction and behaviour	X	X	Important for evacuation, and survival chances during the flood.	Individual (qualitatively)	Medium
Rescue actions	X		Remove people from dangerous locations (water, buildings, trees)	-	Medium
Hazardous installations		X	Can lead to secondary events (e.g. toxic release), but with small probability	-	Low

6 A review of models for the estimation of loss of human life caused by floods

Research question: Which models are available for the estimation of loss of life caused by floods? Are they applicable to estimate the loss of life caused by flooding of low-lying areas protected by flood defences?

Keywords: loss of life, floods, model, instability, flood hazards.

This section reviews the existing models for the estimation of loss of life developed in the Netherlands (6.1) and other countries (6.2)[1]. Specific attention is paid to the models for human instability in flowing water and their physical interpretation (6.3). All models are evaluated in section 6.4.

6.1 Models developed in the Netherlands

Throughout the last decades several models have been proposed in the Netherlands for the estimation of loss of life for sea and river floods. Most models are directly or indirectly based on data on the fatalities caused by the 1953 flood disaster in the Netherlands[2].

Duiser (1989) proposed a model that relates the local mortality fraction to inundation depth. More data on the 1953 floods have been added by Waarts (1992). He derived a general function for flood mortality[3] (F_D) as a function of water depth (h - [m]):

$$F_D(h) = 0{,}665 \cdot 10^{-3} e^{1{,}16h} \qquad F_D \le 1 \qquad \textbf{(Eq. 6-1)}$$

Waarts also proposed a more refined model that takes into account the effects of warning and evacuation, high flow velocities and collapse of buildings. However, not all factors in this refined model have been specified based on historical data.

Based on Waarts' general functions, an extended model has been proposed by Vrouwenvelder and Steenhuis (1997). Especially rapidly rising floods will cause hazardous situations for people, and therefore the rate of rise of the water (w – [m/hr]) is included in the mortality function[4] (see also figure 6-1):

$$F_D = 0 \qquad h < 3m \quad OR \quad w < 0{,}3m/hr$$

$$F_D(h,w) = \min(\max(8{,}5e^{0{,}6h-6} - 0{,}15;0) \cdot \min(\max(8{,}5e^{1{,}2w-4{,}3} - 0{,}15;0),1) \qquad \textbf{(Eq. 6-2)}$$

$$F_D = 1 \qquad h > 6{,}25m \quad AND \quad w > 2m/hr$$

It is noticeable that this function gives F_D=0 for h<3m. This is in contrast with the observations from the 1953 storm surge disasters, where about one third of the fatalities occurred at locations with water depths below 3 metres (see datasets in appendix 7.III).

1 Sections 6.1 and 6.2 are extended versions of Jonkman *et al.* (2002)

2 See section 5.4.1 for a description of this event.

3 If appropriate, the general symbols introduced in section 2 have been used in the (mathematical) description of the existing models.

4 In order to prevent discontinuities in the function, the constants in the exponential expression should be modified to 0,64 and 1,14 instead of 0,6 and 1,2.

For w>2m/hr and h>3m the function approximately corresponds to the above function of Waarts (1992), see equation 6-1.

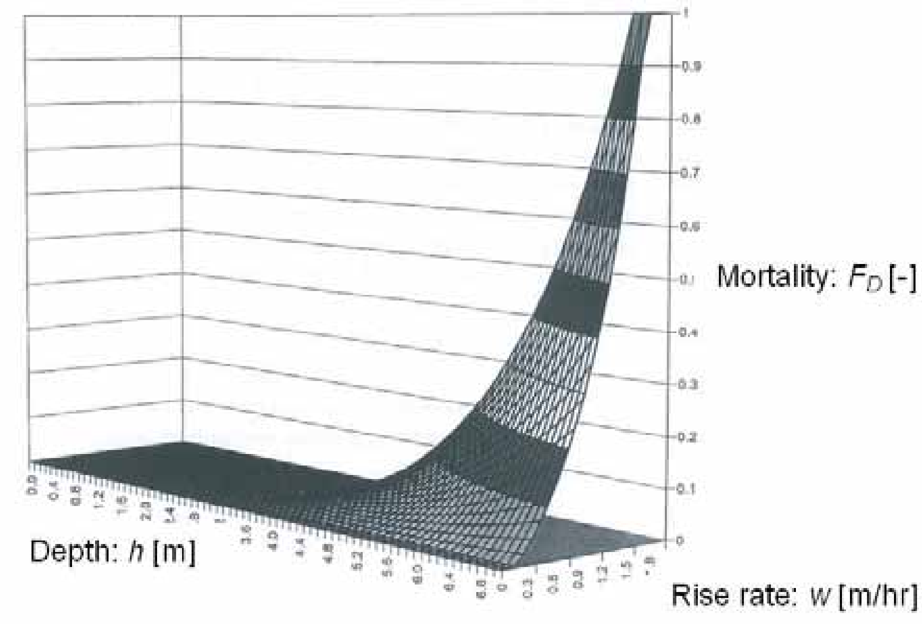


Figure 6-1: Mortality as a function of water depth and rate of rise (Kok *et al.*, 2002)

Vrouwenvelder and Steenhuis (1997) propose a model for sea and river floods. It takes into account the fraction of buildings collapsed (F_B), the fraction of fatalities near the breach (F_R), fatalities due to other factors (F_O) and the evacuated fraction of the affected population (F_E). Combination with the number of inhabitants (N_{PAR}) yields the total number of fatalities (N):

$$N = (F_O + P_B F_R + P_S F_B)(1 - F_E) N_{PAR} \quad \textbf{(Eq. 6-3)}$$

Where:
P_B probability of dike breach nearby a residential area [-]
P_s probability of storm (1 for a coastal flood, 0,05 for a river flood) [-]

Some of the factors in the above model, for example F_C and F_B, are not specified based on historical data, but derived from expert judgement. Nevertheless the approach includes several important factors that influence loss of life.

Jonkman (2001) proposes a model for the determination of loss of life for sea and river floods in the Netherlands. It accounts for the effects of water depth, flow velocity and the possibilities for evacuation. Based on the results from human stability tests in flood flows (Abt *et al.*, 1989; see section 6.3) a function to account for the effects of high flow velocities is given. Mortality becomes a function of flow velocity v [m/s][5], leading to $F_D(v)$. Mortality due to higher water depths is modelled with the general function of Waarts ($F_D(h)$, see above). It is also assumed that drowning due to water depth and flow velocity are disjunct events. The probability of a successful evacuation or escape is assumed to be a function of the time available for evacuation, leading to $F_E(T_A)$. Event mortality can now be expressed as:

5 In the report it is noted that actually the combination of velocity and depth is important, see also section 6.3.

$$F_D(h,v,T_A) = \left(F_D(h) + F_D(v)\right)\left(1 - F_E(T_A)\right) \qquad 0 \le F_D(h,v,T_A) \le 1$$

(Eq. 6-4)

All the above models are directly or indirectly based on findings from the 1953 storm surge. An evaluation of these models (Jonkman, 2004) showed the following. Comparison with the available observations regarding the loss of life caused by the 1953 storm surge showed that these models did not give a good prediction of the observed number of fatalities. In several of these models variables are included that are based on expert judgement and not on empirical data.

6.2 International models

In an international context, various models have been developed for the estimation of loss life for different types of floods. The considered applications include dam breaks floods, tsunamis, coastal storm surges and river floods.

6.2.1 Dam break floods

McClelland and Bowles (2002) give a comprehensive historical review of loss of life models for dam break floods and also discuss their merits and limitations. Here, some of the more recent models are summarized.

Brown and Graham (1988) developed a function to estimate the number of fatalities for dam breaks as a function of the time available[6] for evacuation (T_A) and the size of the population at risk (N_{PAR}):

$$\begin{aligned} N &= 0,5N_{PAR} && T_A < 0,25hr \\ N &= N_{PAR}{}^{0,6} && 0,25hr < T_A < 1,5hr \\ N &= 0,0002N_{PAR} && T_A > 1,5hr \end{aligned}$$

(Eq. 6-5)

The procedure is derived from the analysis of 24 major dam failures and flash floods. The formulas show large discontinuities. For example for N_{PAR} = 10000 the loss of life jumps from 5000 to 251 at T_A = 0,25 hr, and then jumps from 251 to 2 at T_A = 1,5 hr.

DeKay and McClelland (1993) make a distinction between “high lethality” and “low lethality” floods. They define high lethality floods as events with large hydraulic forces, for example in canyons, where 20% of the flooded residences are either destroyed or heavily damaged. Low lethality conditions occur when less than 20% of the houses are destroyed or damages and these usually occur on flood plains. The following relationships, again a function of population size and evacuation time, have been proposed:

$$N = N_{PAR}(1 + 5,207N_{PAR}{}^{0,513}e^{(3,838T_A - 4,012)})^{-1} \quad \text{for “high lethality” floods}$$

$$N = N_{PAR}(1 + 5,207N_{PAR}{}^{0,513}e^{0,822T_A})^{-1} \quad \text{for “low lethality” floods}$$

(Eq. 6-6)

6 Brown and Graham (1999) (and some other authors) originally use the concept of warning time and assume that this equal to the time available for evacuation. The available and warning time are not necessarily the same due to delays in warning in response (see section 2).

In both functions loss of life decreases very quickly when the time available increases. It is noted that re-ordering[7] of both the above models shows that mortality becomes dependent on the size of the population at risk. Application of this expression for short warning times gives mortality values in the order 10^{-2} to 10^{-4}. This is in the same order of magnitude as the reported mortalities for river and coastal floods in section 5.

Graham (1999) presents a framework for estimation of loss of life due to dam failures. Recommended fatality rates are provided based on the severity of the flood, the amount of warning and the understanding of the population of the flood severity. Quantitative criteria for flood severity are given in the form of water depth and the depth – velocity product. Three categories of warning time are distinguished: no / little warning (< 15 minutes), some warning (15 – 60 minutes) and adequate warning (> 60 minutes). The understanding of the flood severity depends on whether a warning is received and understood by the population at risk. The recommended fatality rates are based on the analysis of 40 historical dam breaks. In later work Reiter (2001) introduced factors in Graham's approach to account for the vulnerability of the population (number of children and elderly), and the influence of warning efficiency and possible rescue actions.

The models discussed above are based on statistical analyses of data from historical floods. Recent research has focused on more detailed simulation of flood conditions and individual behaviour of people after dam break floods. The 'Life Safety Model' developed by British Columbia Hydro (Watson *et al.*, 2001; Assaf and Hartford, 2002; Hartford and Baecher, 2004; Johnstone *et al.*, 2005) takes into account the hydraulic characteristics of the flood, the presence of people in the inundated area and the effectiveness of evacuation. An individual's fate is modelled mechanistically, i.e. individual behaviour and the causes of death are accounted for at an individual level. Drowning can occur in three different states: when the building in which a person stays is destroyed, when a walking person loses his stability, or when a person's vehicle is overwhelmed by the water. Calculations result in different values for loss of life for different times of the year, week and day due to differences in affected population and the effectiveness of warning. Johnstone *et al.* (2004, 2005) use the model for a reconstruction of the consequences of the Malpasset dam failure in France in 1959.

Utah State University (McClelland and Bowles, 1999, 2002; Aboelata, 2003) has developed a model ('Lifesim') loss of life estimation for dam break floods. It considers several categories of variables to describe the flood and area characteristics, warning and evacuation and the population at risk. A comprehensive analysis of historical dam break cases and the factors determining loss of life has been undertaken (McClelland and Bowles, 2002). However, due to the number of variables included and their interrelations it is difficult to abstract single variables as predictors of dam break flood mortality. Therefore, different flood zones are distinguished based on the characteristics of the flood (depth, velocity) and the availability of shelter. Mortalities observed in historical cases have differed distinctly between flood zones. In the most hazardous 'chance zones', historical mortalities range from F_D=0,5 to 1 with an average of 0,9. In 'compromised zones', where the available shelter has been severely damaged, the average death rate amounts to 0,1. The model has been

7 For example, the DekKay and McClelland expression for mortality in low lethality floods becomes:
$F_D = N / N_{PAR} = (1 + 5,207 N_{PAR}{}^{0,513} e^{0,822 T_A})^{-1}$

implemented in a GIS framework and can be used for both deterministic (scenario) and probabilistic (risk analysis) calculations.

6.2.2 Tsunamis

A model for the estimation of loss of life due to tsunamis is given in (CDMC, 2003). Based on historical statistics from Japanese tsunamis, mortality is estimated as a function of tsunami wave height (h_{ts} – [m]) when it reaches land:

$$F_D = 0,0282 e^{0,2328 h_{ts}} \qquad F_D \leq 1 \qquad \textbf{(Eq. 6-7)}$$

Correction factors are proposed which account for the tsunami arrival time and resident awareness, and thus for the effects of evacuation and warning. Furthermore the extent of dike and sea wall breaching is included in the mortality estimation.

Sugimoto *et al.* (2003) and Koshimura *et al.* (2006) propose models that combine a numerical simulation of the inundation flow due to tsunami and an analysis of the evacuation process. Both models use criteria for human instability in flowing water (see section 6.3) to estimate loss of life.

6.2.3 Coastal storm surges

Throughout history several large storm surges have struck Japan[8]. Based on such historical events Tsuchiya and Kawata (1981) derived a relationship between typhoon energy[9] and mortality. These authors have also investigated the relationship between mortality and factors such as the collapse of buildings, the time of warning and the volume[10] of flooding. However, no definitive model for the prediction of mortality is proposed.

Mizutani (1985; quoted in Tachi, personal communication) developed relationships for typhoons Jane and Isewan between average flood depth (h) and mortality[11]:

Isewan typhoon: $$F_D = 10^{(2/3 \cdot h - 11/3)} \qquad F_D \leq 1 \qquad \textbf{(Eq. 6-8)}$$

Typhoon Jane: $$F_D = 10^{(h - 5,5)} \qquad F_D \leq 1 \qquad \textbf{(Eq. 6-9)}$$

Due to the large differences in mortality between the events (e.g. a factor 30 for water depth of 1 metre) it is believed that other factors, such as warning and the available time have played an important role.

Boyd (2005) analysed the loss of life in the city of New Orleans (USA) due to flooding after hurricane Betsy (sept. 1965). Fifty-one fatalities were directly related to the flooding of parts of the city. Based on the limited amount of available data he proposed a linear relationship between mortality and storm surge height, F_D=0,304.10^{-5}h. In a later publication Boyd *et al.* (2005) derived a mortality function based on observations from seven flood events, including hurricanes Betsy (1965) and Camille (1969) in the United States. They proposed the following relationship between mortality and water depth:

8 See also section 6.5.2 for a discussion of some of these events.

9 Typhoon energy is determined by the pressure difference between central typhoon and outside pressure, and by the radius of the typhoon.

10 Volume of flooding = surface of flooded area multiplied by (average) water depth

11 Functions listed here have been derived based on the figures given in (Tachi, personal communication)

$$F_D = \frac{0,34}{(1+\exp(20,37-6,18h))}$$ **(Eq. 6-10)**

This functions is S-shaped and it has an asymptote for mortality F_D=0,34 for water depth values that are approximately above 4 meters. This implies that about two thirds of the population will always survive regardless of the water depth. With respect to this asymptote for mortality the authors state: "*One basic empirical fact of flood events is that there are always survivors. Rarely, if ever, has the entire population exposed to the flood perished. Instead, even if the water is extremely deep people tend to find debris, trees, attics, roofs, and other ways to stay alive. Only under the most extreme situations would one expect the fatality rate to reach one.*" (Boyd *et al.*, 2005). A further discussion regarding the shape of the mortality function and relationship with survival of people exposed is included in section 7.4.4.

6.2.4 Other models

Some authors developed more general models applicable to both river and coastal floods. Zhai *et al.* (2006) analysed data from floods in Japan. They derived a relationship between the number of inundated houses and the loss of life[12]. In these floods fatalities mainly occurred when more than 1000 buildings were inundated, and then increased as a function of the number of inundated buildings. The obtained statistical relations show considerable variation, which might be due to the influence of other factors such as warning, evacuation, flood characteristics, and the actual collapse of buildings.

Ramsbottom *et al.* (2003, 2004), see also (Penning-Rowsell *et al.*, 2005), developed an approach for assessing the flood risk to people, in a research project for the Environment Agency for England and Wales. The risk to people is determined by three factors: flood hazard, people vulnerability and area vulnerability. A flood hazard rating is indirectly based on the available tests for human instability and the effects of debris (see next section). The proposed values for the other factors are based on expert judgement. By combination of these three factors the numbers of fatalities and injuries are estimated. The model is applied to three case studies covering past river floods in the UK, and the obtained results agree well with the observed historical data.

Following the catastrophic flooding of New Orleans after hurricane Katrina in august 2005, a model for the estimation of loss of life for flooding of New Orleans has been developed in the context of the 'Interagency Performance Evaluation Taskforce' (IPET, 2006). This model is based on the principles of the Lifesim model that has been developed by Utah State University for dam breaks (see description above), but now it is applied to flooding associated with breaching of flood defences. In the model in the IPET study the exposed population is assigned to three different zones (walk away zone, safe zone, compromised zone). Each zone has a typical value[13] for the mortality rate. Local flood depths and building heights and the age of the population[14] determine the distribution over the

12 The number of inundated houses will be proportional to the number of affected persons. Thus, the derived ratios between fatalities and inundated buildings could be proportional to event mortalities (fatalities divided by exposed population), if the numbers of evacuated are similar for the events in the dataset.

13 To be more precise: each zone has a distribution of mortality. By means of Monte Carlo analysis, the mean number of fatalities is determined.

14 Because many of the fatalities due to the floods after hurricane Katrina were elderly, it is assumed in the IPET model that those over 65 years old are unable to evacuate vertically above the highest floor level.

three zones. The number of people exposed has been distributed over the three zones, so that the total number of observed fatalities[15] was approximated well. The model can be used to assess the loss of life for hurricane related flood events in the greater New Orleans area, e.g. in the context of a risk analysis that includes (future) flood scenarios for the area.

6.3 Human instability in flowing water[16]

Loss of human stability and consequent drowning in flood flows is an important contributor to loss of life (see also section 5.5). Therefore several authors have investigated the issue of human (in)stability in flowing water. This section provides an overview of past work in this field (6.3.1). Consequently a physical interpretation of instability is proposed (section 6.3.2) and this approach is used to interpret existing measurements on instability in section 6.3.3. Concluding remarks and recommendations are given in section 6.3.4.

6.3.1 Past work

Abt *et al.* (1989) probably did the first experimental study on this topic, as they state that "previous work of this nature was not located in literature". They conducted a series of tests in which human subjects were placed in a flume in order to determine the critical depth-velocity product (hv_c – [m^2/s]) at which a human subject becomes instable. Equation 6-11 was derived from the empirical data to estimate the value of the critical product as a function of the subject's height (L – [m]) and mass (m – [kg]):

$$hv_c = 0,0929\left(e^{0,001906Lm+1,09}\right)^2 \quad \textbf{(Eq. 6-11)}$$

Similar tests have been carried out in the Rescdam project (Karvonen *et al.*, 2000) to investigate the conditions of instability. Depending on the test person's height and mass, critical depth-velocity products were found between 0,64 m^2/s and 1,29 m^2/s. In Japan, experiments were conducted on the feasibility of walking through floodwaters (Suga *et al.*, 1994, 1995). Suetsugi (1998) and Tachi (personal communication) report these results in English indicating that people experienced difficulties in walking through water when the depth-velocity product exceeded 0,5 m^2/s.

Different authors have used the available test data to derive empirical functions for determining stability. Lind and Hartford (2000) derived theoretical relationships for the stability in water flows of three shapes representing the human body: a circular cylindrical body, a square parallelepiped body, and composite cylinders (two small ones for the legs, and one for the torso). Due to similarities in the stability functions for these shapes, they proposed a limit state function in the form of equation 6-12. The depth-velocity product forms the load and the resistance is determined by a person's mass and an empirical coefficient K_0, which is calibrated with the results of the tests by Abt *et al.* (1989):

$$Z(K_0, m, h, v) = K_0 m^{0,5} - hv \quad \textbf{(Eq. 6-12)}$$

Where:
$Z(K_0,m,h,v)$ reliability function for stability [-]

15 When the model was developed in February 2006, the number of observed fatalities due to the flooding of New Orleans was 887. A more extensive discussion of loss of life due to the flooding of New Orleans is presented in section 9.

16 A more extensive version of this section has been published as (Jonkman *et al.*, 2005).

K_0 Constant with an average value of 0,10 $kg^{-1/2} m^2 s^{-1}$ and a variation coefficient of 0,18. (for derivation see (Lind and Hartford, 2000)).

If Z<0, a person loses stability. As the distribution of constant K_0 is given, the probability of losing stability can be determined for a given depth-velocity product (*hv*).

Ramsbottom *et al.* (2004) derived a model for flood hazard estimation. It relates the stability of a person in floodwater to the depth and velocity of the water and to the amount of debris that is in the water. The effects of debris are represented by a factor DF [m^2/s]. The proposed flood hazard equation is:

$$Flood\ Hazard = h\ (v + 0{,}5) + DF \qquad \textbf{(Eq. 6-13)}$$

This formula ensures that flood hazard does not reduce to zero when velocity is zero. It is also a good fit to both the Abt *et al.* (1989) and the Karvonen *et al.* (2000) data sets. The relationship is extrapolated to find the flood hazard for children by using the height and weight figures of a 5 year old. The resulting graphs are then interpreted to provide danger thresholds to determine what flood conditions correspond to a low, moderate, significant or extreme hazard.

Green (2001) and USBR (1988) give semi-quantitative criteria that indicate certain hazard ranks (e.g. high and low danger zones) as a function of water depth and flow velocity.

Related work concerns instability of people due to sea wall overtopping of waves. Critical discharges for instability are in the following range: 1 – 10 l/s/m (see e.g. Bruce *et al.*, 2002). For tests in the Netherlands it is reported that somewhat higher discharges (20 to 30 l/s/m on average) lead to hazardous circumstances (Smith, 1999).

Table 6-1 summarises the available test data as a basis for further analysis. Figure 6-2 shows the cumulative probability distribution of the critical depth-velocity products for both datasets. The intersection with the horizontal axis indicates the measurement with the smallest hv_c, while the data point at the probability level of 1 indicates the measurement with the largest hv_c. Both sets of experiments can be approximated with normal distributions; average and standard deviation are indicated in the last column of table 6-1.

Table 6-1: Overview of available experimental data on human instability

Reference	Substrate / water conditions	Clothing and Safety equipment	Test conditions	Subjects	Nr. of measurements	Depth-velocity product statistics
Abt *et al.*, 1989	Grass, concrete, steel, gravel. Water 20-25°C	Jeans and shirt, harness, helmet	2-4 tests in 2 hrs., *v*: 0,36 – 3,05 m/s *h*: 0,42 – 1,2m	20 people, female and male, 19-54 years, good health, *m*: 41-91kg; *L*: 1,52-1,91m	Monolith: 6 People: 65	People: avg. hv_c=1,33m^2/s St. dev.: hv_c=0,28m^2/s
RESCDAM, (Karvonen *et al.*, 2000)	Steel grating-fairly slippery, Water 16°C	Goretex survival suits, helmet, safety ropes, handles	*v*: 0,6 – 2,75 m/s *h*: 0,3 – 1,1m	7 people, female and male. Some were professional rescuers. *m*: 48-100kg; *L*: 1,60-1,95m	People: 38	avg. hv_c=0,96m^2/s St. dev.: hv_c=0,16m^2/s

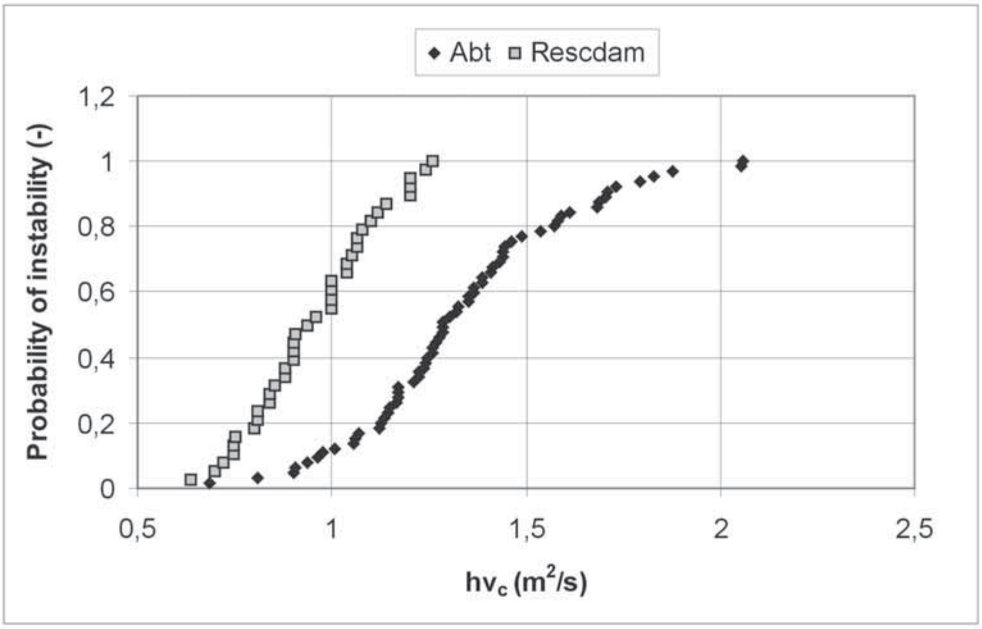


Figure 6-2: Distributions of critical depth-velocity products for the Abt and Rescdam datasets

Overall, the available studies show that people lose stability in flows with limited depth-velocity products. The obtained critical depth-velocity products range from 0,6 m^2/s to about 2 m^2/s. The differences in the reported test results can be related to test circumstances (bottom friction, test configuration) or personal characteristics (weight, length, clothing). Results from Abt *et al.* (1989) show that monoliths topple in much lower depth-velocity products (0,3 m^2/s) than human beings (0,6 m^2/s to 2 m^2/s). This leads to the assumption that human adaptation to flow conditions plays an important role in stability estimation. Examples are leaning into the flow and turning sideways into the flow, thus reducing the exposed body surface.

6.3.2 A physical interpretation of human instability

In literature the physical interpretation of human instability has received relatively limited attention. Therefore it has been attempted to improve the physical interpretation of the depth-velocity criterion and to relate the experimental data to the physical mechanisms for instability.

Two hydrodynamic mechanisms that can cause instability are distinguished: moment instability (toppling) and friction instability (sliding). **Toppling**, or **moment instability**, occurs when the force of the oncoming flow exceeds the moment due to the resultant weight of the body (Lind *et al.*, 2004). **Friction instability** or **sliding** occurs if the drag force is larger than the frictional resistance between the person's feet and the substrate surface (see also Keller and Mitsch, 1993). Both mechanisms are schematically shown in figure 6-3. Based on these schematisations general expressions for instability are derived from the equilibrium equations for moment and force.

For completeness, one other hydrostatic mechanism is mentioned: **floating**. As the density of the human body is similar to the density of water, floating will usually occur if water depth exceeds a person's height. Then, the person is no longer subject to the moment instability or friction instability calculations.

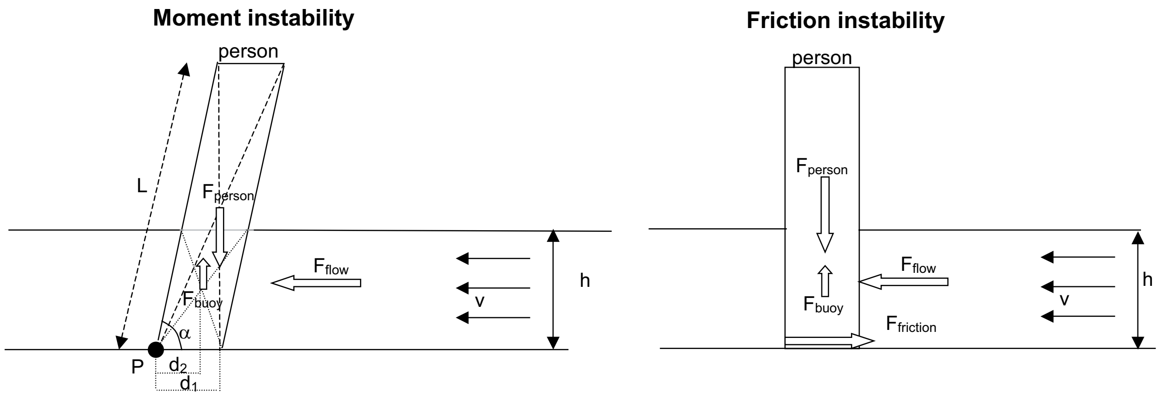


Figure 6-3: Models of human body for moment and for friction instability (symbols explained below)

Moment instability

To calculate moments, assume that the person is a block shape and leans forward. It is assumed here that the velocity distribution is uniform, and that person's characteristics can be represented as one surface (average width B in water depth h). In this simplified elaboration the upward buoyancy forces are neglected[17]. For people with average mass in average floods, buoyancy effect will be relatively small. For stability, $\Sigma M_P = 0$

$$\Rightarrow \quad F_{person}d_1 - 0.5hF_{flow} = 0$$

$$\Rightarrow \quad mgd_1 - 0.5h(0.5\rho v^2 C_D Bh) = 0$$

$$\Rightarrow \quad hv_c = (4mgd_1 / C_D B\rho)^{0.5} \qquad \text{(Eq. 6-14)}$$

$$\Rightarrow \quad hv_c = C_S m^{0.5} \quad with \quad C_S = (4gd_1 / C_D B\rho)^{0.5}$$

Where:

B	The average body width exposed normal to the flow [m]
C_D	Drag coefficient [-]
d_1	Distance from person's pivot point to their centre of mass [m]
d_2	Distance from person's pivot point to the mass centre of mass of the submerged part of the body [m]
F_{buoy}	Buoyancy force [N]
F_{flow}	The horizontal force of the flow on an object in the flow [N]
F_{person}	The person's weight [N]
ρ	Density of the flowing fluid [kg m^{-3}]

In the above equations, the value of C_D depends on the shape of the exposed object and Bh represents the wetted area's normal projection to the flow. Equation 6-14 implies that the critical hv_c value can be estimated as a function of a person's mass multiplied by constant C_S with unit [m^2/(s kg^{0,5})]. Further extensions of the above model are elaborated in (Jonkman *et al.*, 2005). For example, as the horizontal distance to the pivot point depends on a person's tilt and height, hv_c can be expressed as a function of person's mass and height.

17 A more complete elaboration that includes buoyancy is included in (Jonkman *et al.*, 2005), but in that case less simple expressions are obtained.

Friction instability

Friction instability occurs if $F_{friction} < F_{flow}$. The frictional force involves the coefficient of static friction μ [-], so that $F_{friction} = \mu mg$. The following critical product is obtained (again effects of buoyancy are neglected):

$$hv_c^2 = 2\mu mg / C_D B\rho = C_F m \qquad with \quad C_F = 2\mu g / C_D B\rho \qquad \text{(Eq. 6-15)}$$

To reach friction instability, the critical value of hv^2 has a linear relationship with mass. In this equation the constant C_F has unit [$m^3/(kg\ s^2)$]. The critical product hv^2 for instability changes for different surfaces and conditions, i.e. for varying μ. Endoh and Takahashi (1995) give measured values of μ for different surfaces and shoe types. Values can range between 0,38 for concrete covered with seaweed and 1,12 for rough concrete. They suggest μ=0,4 as a first conservative value.

6.3.3 Comparison of physical stability criteria with test results

The derived physical stability criteria have been compared with available experimental test data. In the first analysis **moment instability** for the Rescdam dataset is investigated. Figure 6-4 shows the measured depth-velocity products as a function of the person's mass and the derived best-fit trend line for the Rescdam dataset (Karvonen *et al.*, 2000). The trendline gives a good approximation of the observed depth-velocity products, as R^2=0,75.

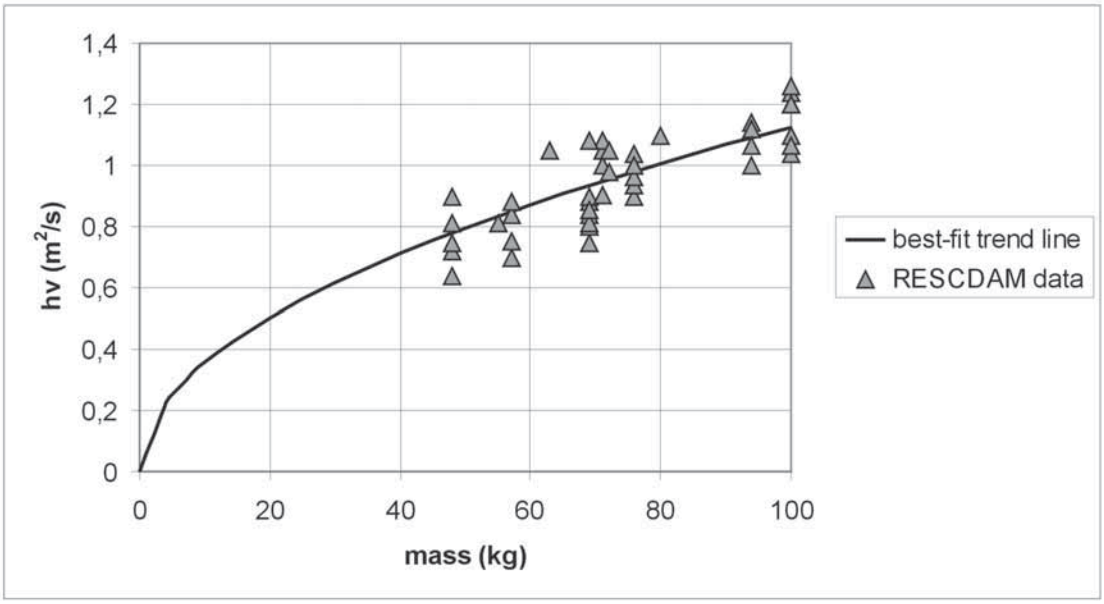


Figure 6-4: Depth-velocity product as a function of person's mass for the RESCDAM experimental data (Karvonen *et al.*, 2000) and best-fit trend line

For **friction instability**, especially the bottom material plays an important role. Two sub-datasets from Abt *et al.* are compared, namely the measurements on 1,5% slopes for concrete and steel. Concrete has a higher friction coefficient than steel, and instability occurs for higher hv^2 values than those for steel. In figure 6-4 the measurements on the critical hv^2 are plotted as a function of a person's mass. In addition, the two best-fit lines are shown.

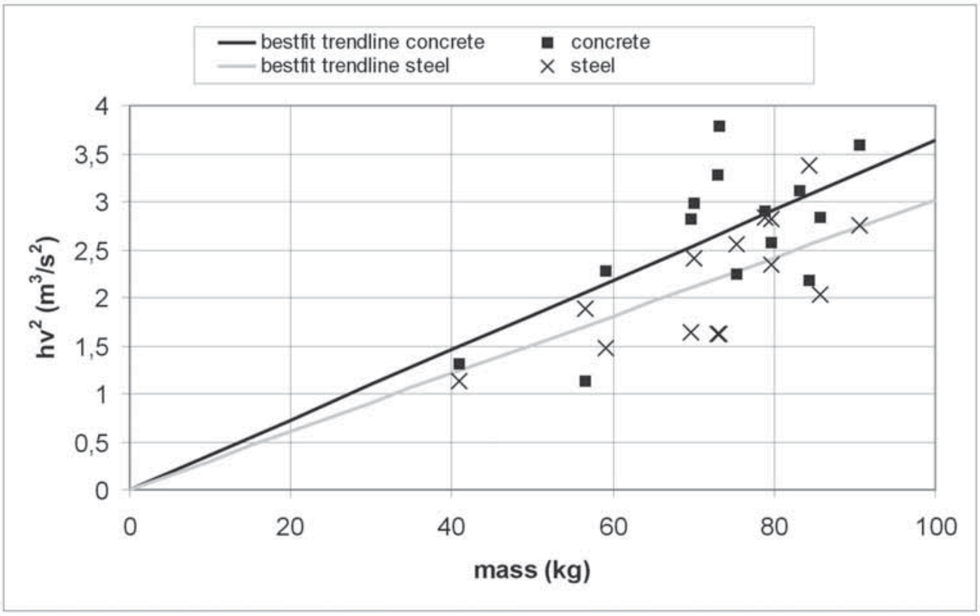


Figure 6-5: Friction instability: Comparison between experimental data from Abt *et al.* (1989) for concrete and steel bottom and derived relationship.

For both circumstances, 14 experiments were carried out. For 11, instability occurs at lower hv^2 values on steel than on concrete, due to the fact steel is more slippery (and has a lower friction coefficient). For different (sub)datasets table 6-2 presents the resulting values for C_F and correlation values. Using reasonable estimates for the drag coefficient and the width exposed to the flow (C_D=1,1; B=0,5m), also a corresponding value of friction coefficient μ is estimated.

Table 6-2: Friction instability: derivation of coefficient and corresponding value of the friction coefficient

Slope	Bottom	Measure-ments	C_F [m³/(kg s²)]	R^2	Value of friction coefficient μ
1.5%	Concrete	14	0,036	0,46	1,01
1.5%	Steel	14	0,030	0,54	0,83
All tests		65	0,031	0,36	0,87

6.3.4 Discussion

One question that emerges from these studies is whether the decisive criterion for human stability in water flows is moment or horizontal force. When a person loses stability in flowing water and is carried away by the stream, were they (a) overturned by being unable to balance the moments or (b) unable to counter the horizontal force and pushed downstream?

To identify the determining mechanism for human stability in flood flow, both moment and force equations are considered. Figure 6-6 shows the combinations of depth and velocity that are assumed to lead to friction and moment for a person with a mass of m=75kg. From the derived equilibrium equations for moment and friction instability the situation is determined where both criteria result in the same hv_c (see also figure 6-6):

$$h_c = C_F^2 / C_F = 2d / \mu$$
$$v_c = C_S / (C_F m^{0.5})$$ **(Eq. 6-16)**

Figure 6-6 shows that for smaller water depths and large flow velocities friction instability will be the dominating mechanism. The region where friction instability occurs depends on the value of the friction coefficient μ. For more slippery surfaces (a low μ) friction instability becomes more important. The moment criterion is the decisive mechanism for larger depths and limited velocities.

A further comparison between both mechanisms is given using the Abt *et al.* (1989) dataset. All experimental data have been plotted in figure 6-6 together with the theoretical relationships for moment and friction instability. Figure 6-6 and the analysis of correlations suggest that neither mechanism dominates. Instead, the combination of these two criteria could explain the data scatter and differences in the experimental results. For the range of physical hazard conditions tested (*h* between 0,4 and 1,1m and *v* between 0,6 and 3 m/s), the combination of moment and horizontal force likely plays an important role. Given the good agreement for the Rescdam tests to the moment equation (see above) and practical considerations (*hv* is a simpler product), it is recommended to use the moment instability criterion and the corresponding depth-velocity (hv_c) product for flood hazard analysis. Equation 6-14 could be used as a general formula. The value of constant C_S can be determined for specific cases, but is usually between 0,1 and 0,2.

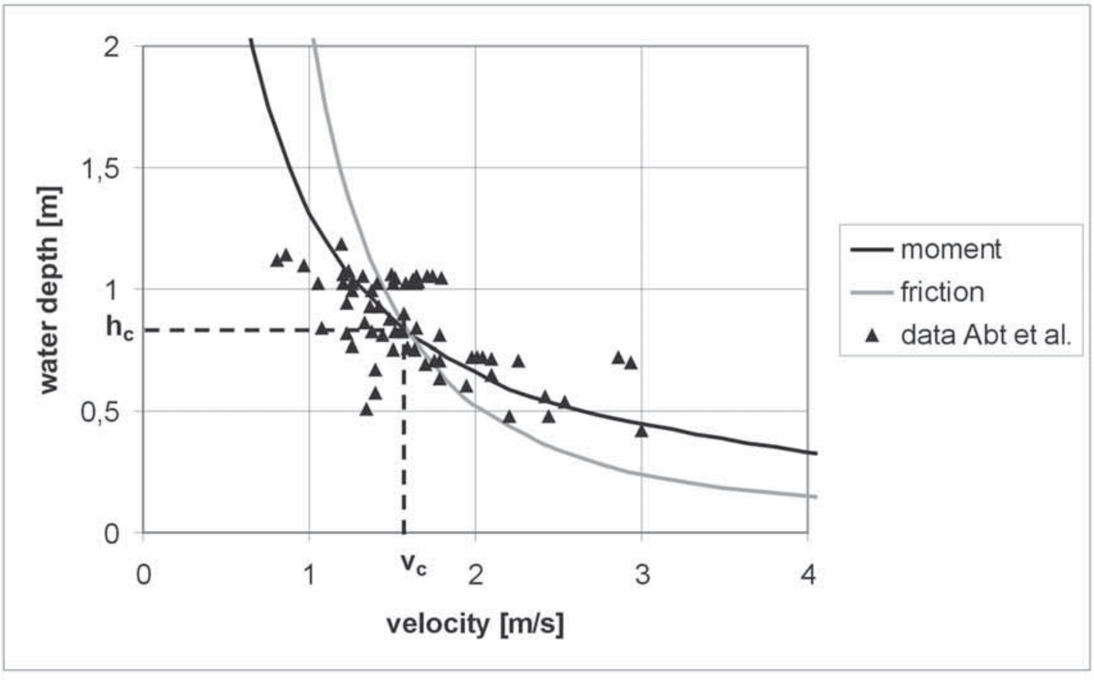


Figure 6-6: Comparison of moment and friction instability for the Abt *et al.* dataset

Discussion: application of instability criteria for loss of life estimation

Apart from the combination of depth and velocity, other phenomena could affect human stability in flows:

- Bottom characteristics: evenness and obstacles.
- More water characteristics: temperature along with ice, other debris or even animals (fish, snakes, alligators).
- Human vulnerability factors: additional loads such as clothing, disabilities, age and fatigue and hypothermia which would reduce muscle power and ability to tilt into the flow. In particular, the tests on people which have been completed so far used

healthy adults. Children and the elderly are likely to be particularly vulnerable to instability in flowing water.
- Lighting and visibility, wind and gusting, waves, and flow unevenness which suddenly changes water velocity and depth.

Another issue to consider is the correlation between instability and overall risk of being killed in a flood. Losing stability does not necessarily imply drowning. Bern *et al.* (1993) investigated risk factors for flood mortality during the 1991 Bangladesh cyclone by conducting a survey amongst people who were affected by the flood. Of the 285 people who were swept away during the storm surge, 112 (39%) died. Numerous first-hand accounts of survivors from the 26 December 2004 Indian Ocean tsunami also point out that many people survived, despite being picked up and battered by the tsunami and entrained debris. In many cases, the survivor became unconscious. Additionally, drowning, physical trauma, and hypothermia following instability are only one set of many flood death causes (Jonkman and Kelman, 2005). Thus, for a complete analysis of loss of life, other causes and circumstances should be considered additionally.

6.4 Evaluation of models for loss of life estimation

Despite the enormous impacts of floods on global scale a limited number of models is available for the estimation of loss of life caused by floods. This section has given a review of (known) available models and such a comprehensive overview was not available in literature so far. Below, the models are briefly evaluated with respect to their field of application, and background data and modelling approach. Table 6-3 summarizes the models, their field of application and shows which factors are taken into account in loss of life estimation. Especially for river and coastal floods this table gives an almost complete overview of the available literature.

Table 6-3: Overview of existing loss of life models, their field of application, and the factors included

Model	Field of application	Data basis	Factors taken into account in loss of life estimation: Water depth	Velocity	Rate of rising	Warning and evacuation	Collapse of buildings	Other
Duiser	River and coastal floods in low lying areas (esp. the Netherlands)	1953 storm surge disaster in the Netherlands	X					
Waarts			X					
Waarts detailled			X	X	X	X	X	
Vrouwenvelder and Steenhuis			X		X			
TNO			X	X		X	X	
Jonkman			X	X		X		
Brown and Graham	Dam break floods	Historical dam breaks				X		Affected Population
De Kay and McClelland		Historical dam breaks				X		Affected Population
Graham		Historical dam breaks	combined in severity classification			X		
BC Hydro Life Safety Model		Simulation	X	X		X	X	Individual behaviour
Utah State University		Historical dam breaks	Different hazard zones defined			X	X	
CDMC	Tsunami	Historical tsunamis				X	X	Tsunami wave height
Sugimoto *et al*.		Simulation	X	X		X		
Koshimura *et al*.		Simulation	X	X		X		
Tsuchiya and Kawata	Coastal floods (Japan)	Historical typhoons in Japan						Typhoon energy
Mizutani		2 typhoons	X					
Boyd *et al.*	Coastal floods (storm surge, hurricane)	Various storm surges	X					
Zhai *et al.*	river and coastal floods (Japan)	Historical floods Japan					X	
Ramsbottom *et al*.	river and coastal floods (UK)	Stability tests and expert judgement	X	X	X	X	X	Population vulnerability
IPET	Hurricane related flooding due to levee breaches (New Orleans)	Loss of life after hurricane Katrina	X			X		Shelter, age of people
Abt *et al**	Human instability in flowing water	Stability tests	X	X				People's mass and length
Rescdam*		Stability tests	X	X				

* only original stability tests are listed in the table, not the formulations derived from these test by other authors

The models have been developed for different types of floods in different regions. Applications that have received relatively much attention are dam breaks in the USA and Canada, coastal storm surges in Japan, floods in the Netherlands, and human instability in flood flows.

All of the reviewed models include some kind of dose response or mortality function which relates mortality to flood related characteristics. Depending on the flood type and type of area different variables will be most significant in predicting loss of life. For large-scale dam breaks warning time is very important, as people exposed to the effects of a large dam break wave have limited survival chances. For coastal and river floods, local water depth and rate of rising are important parameters for mortality. Despite the importance of collapse of buildings this factor is not included in most of the models. For all floods evacuation is a critical factor in loss of life estimation, as it reduces the number of people exposed to the flood. It is noted that this factor is not included in many of the approaches listed in table 6-3.

Figure 6-7 schematically compares some of the discussed models with respect to their level of detail[18] and modelling principles. Mechanistic models are those that model the individual behaviour and the causes of death. Empirical models relate mortality in the exposed population to event characteristics.

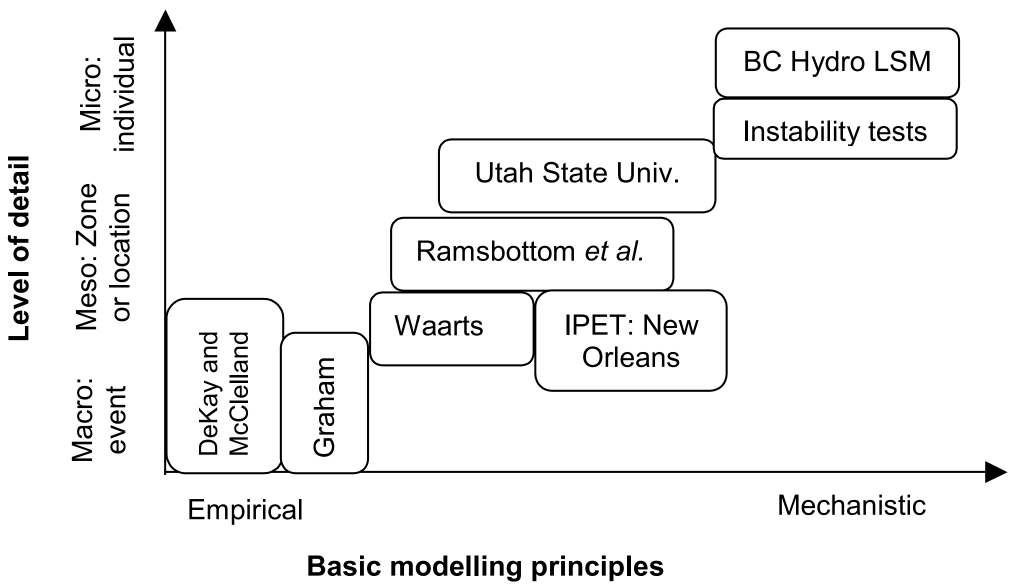


Figure 6-7: Comparison of the proposed model with other models for loss of life estimation (based on Johnstone *et al.*, 2005)

The models of Utah and BC Hydro use detailed local data and capture the mechanisms that lead to mortality. The model of BC Hydro is most detailed as it simulates an individual's fate during a flood event, while Utah State distinguishes groups of people, whose circumstances are comparable. The disadvantage of such an approach is that a large number of (behavioural) variables have to be assigned, for which very limited empirical information is available. Yet, detailed simulations can provide a) important information for the development of emergency evacuation strategies b) powerful visualisation tools for

18 These three levels of detail are discussed in section 2.1.2.

communication with the public and decision makers. More empirically based models have been proposed which take account of local circumstances (e.g. the models of Ramsbottom *et al* and Waarts), or give a purely empirical estimation of mortality for an event (e.g. the models of Graham and DeKay and McClelland). In general the single-parameter models (i.e. the models that include one factor such as water depth or warning time) are fully based on historical data. Probably due to the lack of historical data, not all the factors in multi-parameter models could be empirically derived.

Concluding remarks

The objective of this thesis is to investigate the possibilities for the improvement of methods loss of life estimation for floods of low-lying areas protected by flood defences, with specific emphasis on the situation in the Netherlands. Many of the available models have been specifically developed for other types of floods (e.g. dam breaks) and they are less suitable for the type of flood considered here. A group of models has been developed for the situation in the Netherlands (see section 6.1) and these are largely based on observations regarding loss of life caused by the 1953 storm surge in the Netherlands. An evaluation of these models (Jonkman, 2004) showed that these models did not give a good prediction of the observed number of fatalities in the 1953 flood. Overall, most of the existing models do not take into account the combined influence of different factors that are considered to be the most relevant determinants of loss of life, e.g. water depth, rise rate, evacuation, collapse of buildings, evacuation – see section 5.6. In addition, most of the existing models have a limited empirical basis and the influence of several variables is often estimated based on expert judgement. Given their different bases and natures, applying different loss of life models will give different results. Application of some of the discussed models to a region in the Netherlands with 360.000 inhabitants showed that the predicted loss of life varied between 72 and 88.000 (Jonkman *et al.*, 2002).

Given the above considerations it is expected that the available models are not able to provide an accurate[19] estimate of loss of life for large-scale floods of low-lying areas. Therefore a new method is proposed in the next section. It includes the most relevant determinants[20] of loss of life. The method is derived based on available empirical information regarding loss of life in historical flood events.

19 Accurate is interpreted as follows: the deviation between the mortality calculated with the loss of life model and the observed mortality that is used for validation of the model calculation should be no more than a factor 2 to 5 (see also section 7.4.2 for further details regarding this criterion).

20 These include water depth, rise rate, flow velocity, evacuation, shelter and building quality, see section 5.6 for an overview and discussion regarding the most relevant determinants of loss of life.

7 A method for the estimation of loss of life caused by floods

Research question: Is it, based on empirical data, possible to develop an improved method for the estimation of loss of life caused by floods?

Keywords: loss of life, floods, flood mortality, dose response function

7.1 Introduction and approach

7.1.1 Scope: large-scale floods in low-lying areas

This section contains a proposal for a method to estimate the loss of life caused by large-scale floods of low-lying areas due to failure of flood defences. These types of floods mostly occur in delta areas. These can be found in different parts of the world at the mouths of rivers, e.g. the Mississippi (USA), Rhine (Europe) and Yangtze (China). The Netherlands is situated in the deltas of the rivers Rhine, Meuse and Scheldt. Large parts of the country are below sea level or the high water levels at the rivers and lakes. Figure 7-1 shows the parts of the Netherlands that could be flooded without the protection of flood defences.

Figure 7-1: Parts of the Netherlands that could be flooded without flood defences (Source: Rijkswaterstaat)

In such Delta areas the land level is often below the (high) water levels at sea and the rivers. Protection of these areas is provided by flood defences such as dikes (synonyms: dyke, embankments, levee), sand dunes or hydraulic structures, such as storm surge barriers. In addition, drainage systems are needed to discharge rainwater from the so-called polders and to prevent rise of the groundwater table. As a consequence of the topographical situation, failure of the flood defence system in such Delta areas can lead to flooding of extensive areas up to large water depths with catastrophic consequences (see also figure 5-5).

The method developed in this section is generally applicable to flooding of low-lying areas in different countries. In the development of the method historical information from similar types of floods from different countries has been used. In the proposal of some elements in the method (e.g. evacuation and shelter) specific attention is given to the situation in the Netherlands. Flood types that exhibit distinctly different flood patterns, such as tsunamis, have not been explicitly considered. A brief discussion on the applicability of the proposed method to other regions and flood types is provided in section 7.5.3.

7.1.2 Approach for loss of life estimation

Following the general framework proposed in section 2, the following general steps need to be included in loss of life estimation for floods: 1) analysis of flood characteristics; 2) estimation of the number of people exposed (including the effects of warning, evacuation and shelter) and 3) assessment of the mortality amongst those exposed to the flood. In the previous section it has been concluded that the existing models do not take into account all these factors and that they often have a limited empirical basis. Therefore a new method is proposed in this section. The approach uses those factors as input that have been ranked as highly relevant[1] for loss of life estimation in section 5 (see table 5-7). The method is derived based on available empirical information regarding loss of life in historical flood events. The general framework for loss of life estimation is shown in figure 7-2. The output consists of an estimate of the loss of life caused by the flood at the event level, together with the number of evacuated, sheltered and rescued people.

1 Some factors that have been ranked as highly relevant for evacuation (infrastructure, evacuation plans, population behaviour and response) are taken account in the evacuation model and they are not separately shown in figure 7-3.

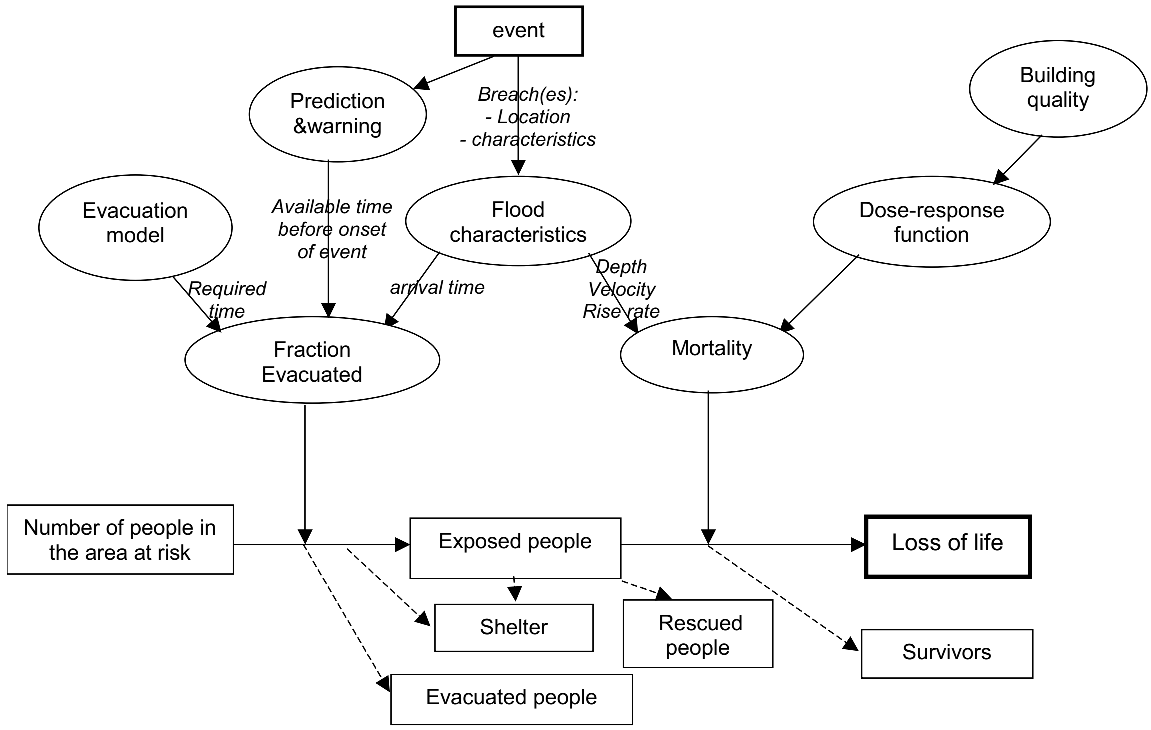


Figure 7-2: General approach for loss of life estimation for floods, The variables used as input are shown in italics.

The following sections deal with the general steps in the above approach. Section 7.2 considers the simulation of flood characteristics. Section 7.3 describes the modelling of evacuation, shelter and rescue and the assessment of the number of people exposed. As previous work has already focussed on the analysis of these two steps they are treated relatively briefly. Most emphasis is given to the development of dose response functions (indicated here as mortality functions) for floods in section 7.4. In the final section (7.5), the validation of the model, uncertainties and sensitivities and other issues are discussed.

7.2 Simulation of flood characteristics

A large-scale flood in a Delta area, such as the Netherlands, is most likely to occur due to failure of flood defences along the coast, lakes and rivers. The first question is where the breach will occur and how many breaches there will be[2]. In the context of flood risk analysis the probability of breaching has to be estimated, by taking into account the different potential locations of breaching and the failure mechanisms that can lead to a breach (Vrijling, 2001; Lassing *et al.*, 2003). The development of the breach in the flood defence determines the extent of the inflow and thus the flood characteristics and eventual damage. Visser (1998) and Zhu (2006) investigated breach growth in dikes. The development of the breach depends mainly on a) the difference between the water levels outside and inside the flooded area; b) geotechnical properties of the embankment c) hydraulic roughness of the area behind the breach.

The most relevant flood characteristics for loss of life estimation include: water depth, rise rate, flow velocity and arrival time of the water (see also table 5-7). Information regarding these variables can be obtained from flood simulations. Other potentially relevant characteristics that are more difficult to analyse are the effects of debris and water temperature.

2 See also section 9.3.1 for a discussion regarding the possibility of multiple breaches.

The term flood scenario is often used to refer to one breach or a set of multiple breaches in the dike ring and the resulting pattern of flooding, including the flood characteristics.

Simulation of flood characteristics
Several approaches are available for the simulation of flood characteristics. In the one dimensional (1D) basin storage approach the development of water depth over time in a confined area is determined as a function of inflow discharge and surface of the flooded area.

$$\frac{dh}{dt} = \frac{Q(t)}{A(h)} \qquad \textbf{(Eq. 7-1)}$$

Where : t – time [s]; $Q(t)$ – discharge entering the area as function of time [m^3/s]; $A(h)$ – surface of the flooded area as function of water depth [m^2]

From this equation the water depth and rate of rising can be directly estimated as a function of the breach discharge. The simple formula above conceptually shows how different flood characteristics are interrelated. Examples are the relationships between water depth (h) and rise rate (dh/dt) and the relationship between surface area (A) and rise rate (dh/dt). Rise rates will be especially large for polders / compartments with small surfaces. There is also a relationship between the flow velocities and rise rate via the breach discharge[3].

The **rise rate** of the water is expected to be an important determinant of loss of life as it influences the possibilities to find shelter on higher grounds or floors of buildings. The rise rate can be derived from the development of water depth over time. In the context of loss of life estimation it is proposed to estimate the average rise rate at a location from initiation of flooding up to a depth of 1,5 metres. Then it approximates the human head level and becomes hazardous for people (see figure 7-3). This approach prevents finding very high rise rates over small incremental changes of water depth, for example over the first decimetres of water in figure 7-3. As rise rate is averaged it is indicated with symbol w [m/hr].

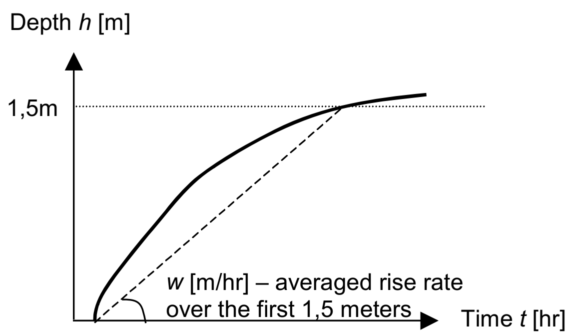


Figure 7-3: Estimation of (averaged) rise rate over the first 1,5m of water depth.

3 Flow velocity and rise rate will both be dependent on breach discharge $Q(t)$. Average flow velocity in the breach at time t can be approximated with $v_{avg,breach}(t)=Q(t)/A_{breach}$. Where A_{breach} is the surface of the breach. Flow velocities will generally reduce with distance to the breach.

The simplified one-dimensional method does not account for important factors such as the arrival time of the water[4] and local variations in flow velocity and rate of rising. Therefore it would be needed to estimate the progress of a flood flow through a certain area. For dam break flows an analytical solution for the one-dimensional movement of flood flow can be obtained from the Saint-Venant equations. This solution is mainly applicable to narrow canyons, but less suitable for the two-dimensional flood pattern in a polder. Several authors (Mai and von Lieberman, 2001; Sarma and Das, 2001; Paquier *et al.*, 2005) proposed simplified analytical approximations of 2-dimensional flood flows for breaches, but no standardized analytical approach for this problem has been developed yet.

More detailed simulations of overland flood flow can be obtained using numerical methods. An example is the Sobek 1D2D model (Asselman and Heynert, 2003). In the simulation of flood flows it is important to account for the roughness and geometry of the flooded area. Certain line elements, such as local dikes, roads, railways and natural heights, might create barriers that can significantly influence the flood flow and the area, thereby dividing the area in smaller compartments.

Analysis of flood characteristics
Empirical analysis of loss of life in historical floods requires information regarding flood characteristics during the event. These can be derived by measurement from watermarks or qualitatively from eyewitness reports. Also, satellite imagery in combination with elevation data can be used to assess flood depths (Cunnigham *et al.*, 2006). It is often difficult to find information regarding velocity and rise rate after a flood in the field. Flood simulation in hindsight can be used to estimate flood characteristics.

In the context of consequence and risk studies, hypothetical flood scenarios are analysed and estimates of flood characteristics are used as input for loss of life estimations. For a first order simulation of flood characteristics a simplified 1-dimensional approximation might be used. In general, the application of the output of 2-dimensional simulations is preferable, as the most relevant variables are obtained directly. Locally occurred maximum values for depth and velocity are generally used as input for calculations, possibly leading to somewhat conservative damage estimates[5].

7.3 Analysis of evacuation and the number of people exposed

This section describes an approach for the estimation of the number of people exposed for large-scale floods. It is based on the approach for analysis of evacuation proposed in section. First, the elements that determine the time available (7.3.1) and the time required (7.3.2) are discussed. Consequently, the reduction of the number of people exposed due to shelter (7.3.3) and rescue (7.3.4.) are described.

4 The 1-dimensional basin storage approach assumes that the arrival time of the water equals the moment of occurrence of the breach.

5 An overestimation of consequences might be obtained in particular when the depth velocity product is used as input for the damage model. Maximum values of depth and velocity need not have occurred simultaneously, i.e. $h_{max} v_{max} \neq (hv)_{max}$

7.3.1 Evacuation: Time available before flooding

The time available is determined by two elements[6]: 1) The time available between the first signs and the initiation of the flood, i.e. the breach; 2) The time available between the breach initiation and the arrival of the floodwaters at a certain location (the so-called arrival time).

Time available before the initiation of the flood

The time lag between the first signs and the occurrence of a flood depends on the type of flood. For example heavy rainfall can cause flash floods within several hours, but high river discharges might be predicted days in advance. The time available also depends on the predictability of the occurrence of the mechanism that leads to failure of the flood defence. The occurrence of some failure mechanisms of can be predicted well in advance. For example, the mechanism of overtopping is directly related to the water levels and its occurrence can be predicted in advance. Other failure mechanisms, such as piping and instability, occur more unexpectedly. It is noted that, although the occurrence of critical situations might be predicted in advance, the exact location and timing of the breach (and whether it occurs or not) are difficult to predict. Probabilistic methods can be used to predict the possible occurrence of breaches at different locations (ter Horst, 2005).

Barendregt *et al.* (2004, 2005) proposed representative values for time available for different combinations of the above factors. Values were collected in an expert judgement study, and some results are shown in table 7-1. Next to a central estimate, the experts also provided estimates of the 5% and 95% confidence intervals[7].

Table 7-1: Estimates of the time available for evacuation for different types of floods and failure mechanisms in the Netherlands. 5%, 50% and 95% estimations are shown based on expert judgements. These estimates do not cover all parts of flood defence system and not all failure mechanisms. A more complete overview is given in (Barendregt *et al.*, 2004).

System	Failure mechanism	Time available estimations (hrs)		
		5%	50%	95%
Coastal (North Sea)	Overtopping	4	12	51
River: Rhine	Overtopping	24	60	120
	Piping	24	54	120
	Failure of hydr.structure	24	58	120
River: Meuse	Stability	16	28	41
River: Meuse Rotterdam	Stability	4	11	21

Arrival time of floodwaters after breach initiation

The arrival time of the water at a certain location can be obtained by means of flood simulation. By combining it with the estimated time until dike breach, the total time available at a certain location is obtained. As the velocity of the flood front is in the same order of magnitude as the evacuation speed, forced evacuation after the breach might still be possible (see also section 2.3.6). In a conservative approximation it seems reasonable to assume instantaneous arrival of floodwaters after breaching. In this case the additional time needed for propagation of the flood wave is neglected, because evacuation will be difficult after breaching of the dike because of traffic jams, organisational problems etc..

6 These two elements are discussed in more general terms in section 2.2.

7 These values can be used to derive continuous distributions used for sensitivity analysis and probabilistic evaluation of the evacuation process (see also figure 2-8).

7.3.2 Evacuation: Time required for evacuation

As a first step in the evacuation analysis, the exposed area and the magnitude of the population at risk (N_{PAR}) need to be identified. For large-scale areas it seems reasonable that N_{PAR} equals the population in the area, implying that population dynamics are neglected[8].

In the Netherlands there is limited practical experience with the evacuation of large populations. During high river discharges in 1995 about 250.000 people were evacuated preventively and this process took about 1,5 day. Given the shortage of historical evacuation data, a survey of international literature[9] has been conducted to derive representative values for modelling of the first three phases of evacuation (namely prediction & decision-making, warning, response) for the situation in the Netherlands. Results are summarized in table 7-2, but more extensive backgrounds are provided in appendix 7.I and (Frieser, 2004). A distinction is made between preventive evacuation (flood foreseen and evacuation occurs before the flood) and the case of an unexpected flood and thus forced evacuation (evacuation after initiation the event). The development of the phases of evacuation is expected to differ between these two types of floods.

Table 7-2: Overview of phases that determine time required for evacuation

	Foreseen flood - Preventive evacuation	**Unexpected flood - Forced evacuation**
Decision time	4 hours	2 hours
Warning time	2 to 3 hours	2 to 3 hours
Fraction of population warned	0,95 to 1	Depends on situational factors (first suggestions: Official warning: 0,8 to 1 No official warning: 0,3 to 0,5
Response time	Mean: 2,5 hours Whole population after 6 hours	Mean: 1 hour Whole population after 2 hours
Fraction of population that complies to warning	0,95	No indications from literature

Simplified approximations can be used to obtain a first order estimate of the time required for the actual evacuation. For example, Edelman (1955) assumes evacuation on foot and estimates time required for evacuation by dividing the distance to the exit by the walking speed. Actual evacuation development can also be modelled with simulation models that include traffic flows and population behaviour, see e.g. (Simonovic and Ahmad, 2005). For analysis of flood evacuation in the Netherlands, a macro-scale traffic model has been developed (Barendregt *et al.*, 2002; van Zuilekom *et al.*, 2005). The model accounts for:

- The number of inhabitants in the area
- Departure time distribution of evacuees
- Road capacities and network
- Exit capacity
- Effects of traffic management

This model provides the time required to evacuate a certain fraction of the population as output. Also the delays for decision-making, warning and response need to be accounted

8 For consideration of floods in smaller areas, population dynamics might be more significant. For example, for dam break floods N_{PAR} is estimated for different times of the day, weekdays and seasons e.g. (Johnstone *et al.*, 2005).

9 More experience based information is available in other countries, e.g. in the USA for hurricane evacuation.

for. By combination with estimates for the time available (table 7-1) the evacuated fraction of the population is obtained.

An example of an evacuation analysis for an area in the Netherlands is given in figure 7-4. The area concerns the dikering 'Land van Heusden / de Maaskant'. It has 360,000 inhabitants and it is threatened by flooding of the river Meuse. For this area a conservative estimate of the time available is 16 hours. By combination with the results evacuation model, the evacuated fraction is estimated at F_E=0,5. F_E reduces to 0,4 if no traffic management is used, e.g. in the case of an unorganised evacuation.

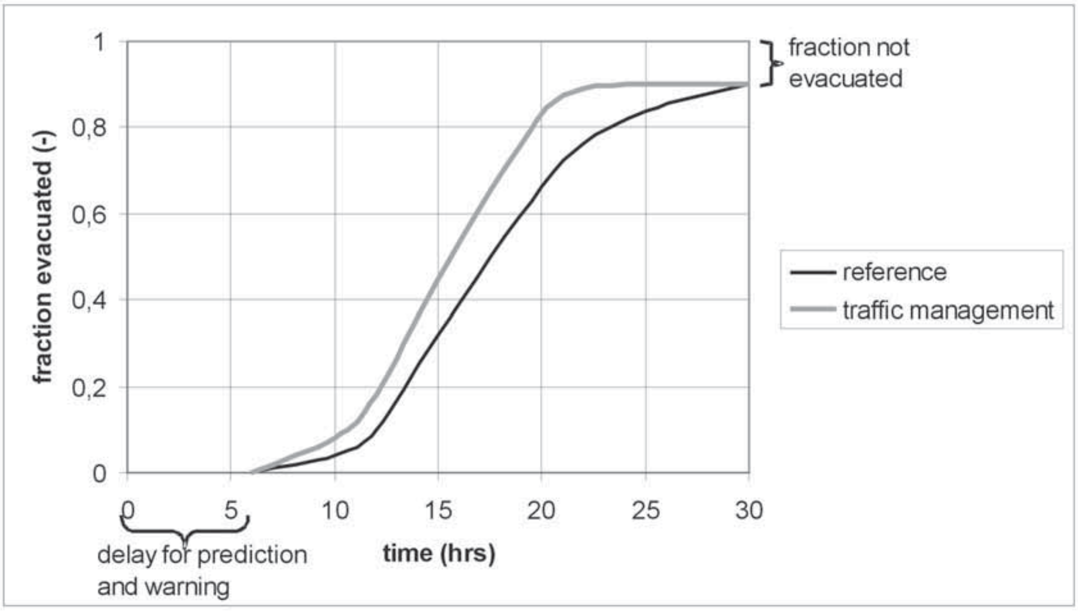


Figure 7-4: Estimation of the fraction evacuated, based on estimates of the different phases that determine the time required and the point estimate of the time available.

In this analysis the evacuation fraction is assumed constant for the whole exposed area. In a more detailed assessment the spatial variation in evacuation fraction can be accounted for by including the arrival time of the floodwater at a certain location, see (Asselman and Jonkman, 2003) and appendix 7.II.

Here it is also assumed that no movement out of the area is possible if people are exposed to the floodwaters (i.e. escape is not accounted for). This is assumed as literature on human instability indicates that people lose their stability already at low depth-velocity combinations (see section 6.3), and that vehicles are very limited in their movement through floodwaters. Some other approaches (Edelman, 1954; Suetsugi, 1998; Koshimura *et al.*, 2006) take into account the possibility of escape through floodwaters with limited depths.

7.3.3 Shelter

In addition to the number of people that evacuate the area, it is necessary to take into account those that seek shelter. In the analysis of data from historical floods (see section 7.4) the effects of local sheltering in buildings, trees and objects is implicitly accounted for. The influence of large-scale sheltering needs to be accounted for separately. Evidence from literature (Bern *et al.*, 1993; Mushtaque *et al.*, 1993; McClelland and Bowles, 2002) suggests that fatalities in intended shelters have been extremely rare. As a first order approximation of the effects of sheltering it is proposed to assume that all people present in buildings with more than three stories are safe. Calculations by Roos (2003) indicate that most high-rise concrete buildings are likely to withstand flood flows. In the Netherlands the fraction of people living in higher buildings could range between 0% (rural areas) to 20% (urban areas). For specific cases the presence of formal shelters and / or high grounds can be discounted additionally. The possibilities to reach shelter depend on the level of warning, and also on the rise rate and depth of the water. Further investigation of (the modelling of) movement of people to shelters is recommended.

7.3.4 Rescue

The actions of emergency and rescue services during floods can attempt to prevent flooding (by strengthening weak sections in the dike, e.g. with sand bags), reduce the number of people exposed (due to rescue of people from the exposed area) or mortality (due to treatment of injured people). Given the scope of this study, the reduction of the number of exposed and mortality due to rescue actions are discussed.

Overall, due to their unexpected occurrence, the floods with greatest loss of life have generally claimed the lives before professional rescuers were able to arrive. Rescue actions are expected to have a limited effect on fatalities in the direct impact phase, i.e. the first hours of the event.

After the direct impact phase rescue actions could help to remove people who are exposed to the flood conditions and thereby limit the number of fatalities. Large-scale coordinated rescue actions will be most effective for people who are present at hazardous locations, such as roofs, treetops and damaged buildings. The survival of people in the floodwaters mainly depends on the water temperature, see figure 7-5. People in (cold) water lose body heat, which can lead to consequent mortality due to hypothermia. For example, storm surge floods in the Netherlands will mainly occur in wintertime with a water temperature around 5°C. Expected survival time for people in the water is between 1 and 3 hours and rescue will be a matter of small chance.

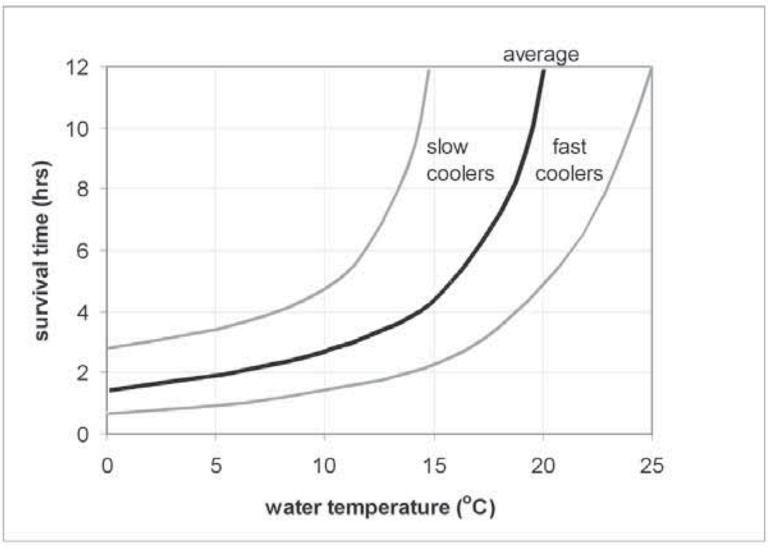


Figure 7-5: Representation of Hayward's curve (Hayward, 1986) that indicates survival time in water as a function of temperature. Grey lines indicate the band of uncertainty.

Rescue actions in the water pose additional hazards to the rescuers themselves, especially in swift-water. Analyses of past floods (Coates, 1999; Duclos, *et al.*, 1991, Jonkman and Kelman, 2005) show that a substantial part of the fatalities are associated with rescue operations.

A simplified approach is proposed to correct the number of people exposed for the effects of rescue. Based on expert judgements (Röpke, personal communication) the capacities of rescue services have been estimated for the situation in the Netherlands. Using the available boats and helicopters a maximum capacity of 500 rescued people per hour is estimated[10]. Most fatalities will occur in the first 48 hours of the flood (based on descriptions Slager, 1992) and thus the number of people exposed can be corrected for the number of people rescued (N_{RES}) within that period. It is also necessary to account for the time needed for initiation of rescue actions and the limited rescue capacity during this first phase, see figure 7-6. During the 1953 storm surge in the Netherlands the initiation of rescue took more than 24 hours and at some locations more than 48 hours. Due to the improvement of communication technologies a shorter initiation time can be assumed, somewhere between 12 and 24 hours. However, it is noted that after the flooding of New Orleans due to hurricane Katrina in the year 2005 there was also a substantial delay before rescue actions started (see also section 8).

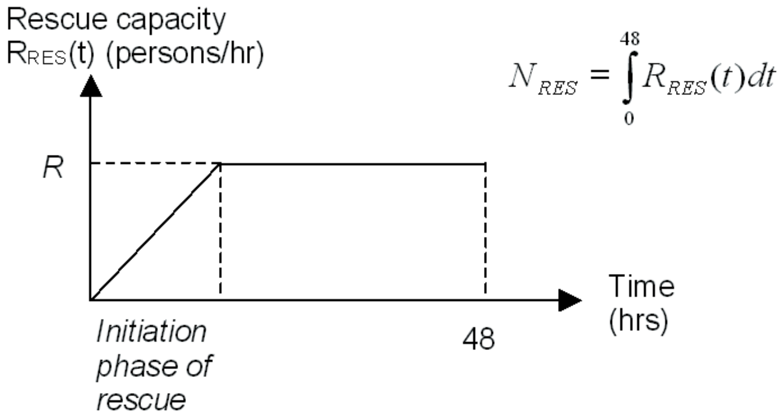


Figure 7-6: Proposed relationship between rescue capacity and time

Using the estimated values, the total rescue capacity is estimated at approximately 16.000 people within the first 48 hours. Thus, for large-scale floods, which can affect more than 100.000 people, the rescue capacities will be insufficient to rescue substantial parts of the population. Given the rough estimates, more thorough investigations of rescue capabilities and operational preparation for large-scale floods in the Netherlands are recommended.

7.3.5 Summary of the method for the estimation of the number of people exposed

The proposed general steps for estimation of the number of people exposed (N_{EXP}) are summarized below[11]:

10 Röpke (personal communication) estimates that the rescue capacity of helicopters in the Netherlands will be approximately 250 people per hour. A similar rescue capacity is assumed for boats (e.g. 100 boats, rescuing 5 people, mission duration 2 hours).

11 The general symbols introduced in section 2 have been used.

- The number of people at risk in the flooded area: N_{PAR}
- The evacuated fraction of the population: $F_E(T_A)$. It is determined based on the estimate of time available (T_A) and the distribution curve for time required (F_E).
- The fraction of the (remaining) population that has the possibility to find shelter. In this first approximation it is assumed to equate the fraction of inhabitants living in high rise buildings: F_S
- The number of rescued people: N_{RES}

The number of people exposed equals:

$$N_{EXP} = \left(1 - F_E(T_A)\right)\left(1 - F_S\right)N_{PAR} - N_{RES} \qquad \text{(Eq. 7-2)}$$

In a first order and general analysis the evacuation and shelter fractions can be assumed constant for the whole exposed area. In a more detailed assessment the spatial distributions of evacuation and shelter fractions can be accounted for, by including local road and shelter capacities. By combining an evacuation model with a flood simulation the availability of safe evacuation routes could be assessed, thereby providing important information for emergency management.

7.4 Estimation of the mortality amongst the exposed population

In this section a method is proposed for the estimation of mortality amongst the exposed population for the flooding of low-lying areas due to failure of flood defences. First, the general approach is introduced (7.4.1). Based on data from historical flood events (discussed in section 7.4.2) mortality functions are empirically derived for different hazard zones in the flooded area (7.4.3 to 7.4.5). Consequently, the influence of warning and shelter (7.4.6) and the collapse of buildings (7.4.7) are discussed. The method for the estimation of mortality is summarized in section 7.4.8.

7.4.1 General approach

After analysis of flood characteristics and evacuation, the next step is the determination of mortality amongst those exposed to the flood. An approach is proposed in which hazard zones are distinguished. For locations in every hazard zone mortality is estimated by means of a dose response function, indicated here as a **mortality function.** Hazard zones are areas that differ with respect to the dominating flood characteristics and the resulting mortality patterns[12]. Based on the findings from historical events (section 5) and past work (Waarts, 1992) it was found that many fatalities occur behind breaches and in areas with rapidly rising waters. Three typical hazard zones are distinguished for a breach of a flood defence protecting a low lying area (see figure 7-7).

- **Breach zone:** Due to the inflow through the breach in a flood defence high **flow velocities** generally occur behind the breach. This leads to the collapse of buildings and instability of people standing in the flow.

12 The concept of hazard zones is also used in other loss of life models for both coastal and river floods (Ramsbottom *et al*, 2003) and dam break floods (McClelland and Bowles, 2002).

- **Zones with rapidly rising waters:** Due to the rapid rising of the water people are not able to reach shelter on higher grounds or higher floors of buildings. This is particularly hazardous in combination with larger water depths.
- **Remaining zone**: In this zone the flood conditions are more slow-onset, offering better possibilities to find shelter. Fatalities may occur amongst those that did not find shelter, or due to adverse health conditions associated with extended exposure of those in shelters.

For other types of floods, the situation and proportional area of the hazard zones might be different. For example for dam breaks in narrow canyons, the hazard zone associated with high flow velocities will be much larger.

The boundaries of the rapidly rising waters can be formed by line elements that create barriers, such as building rows, lowered streets, dikes, or steep contours. Also, depending on topography of the area and flow patterns, rapid rise of the water or high flow velocities are possible in local compartments or contractions, for example due to breaching of local dikes.

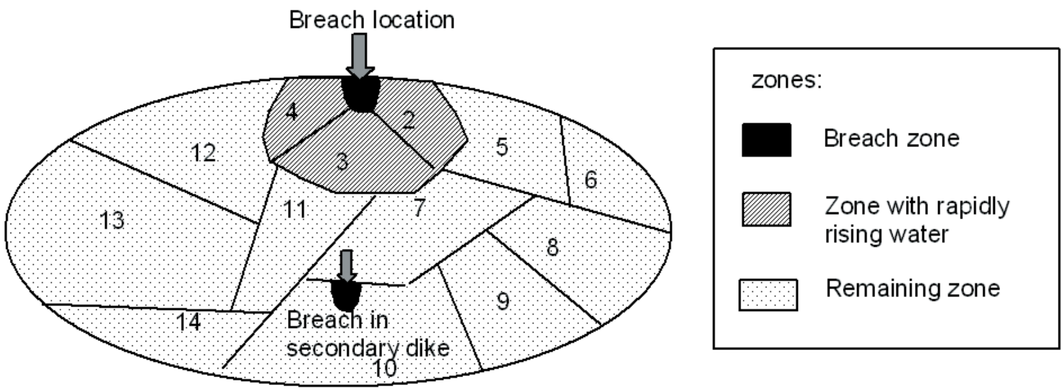


Figure 7-7: Proposed hazard zones for loss of life estimation. Numbers indicate locations.

Depending on the variability of flood characteristics it might be necessary to distinguish different locations in the exposed area to give a realistic estimate of loss of life. Each hazard zone can thereby be subdivided into **locations**. A location is defined in this context as an area for which flood characteristics (water depth, rate of rising, flow velocities) and area characteristics (e.g. shelter possibilities) can be assumed relatively homogeneous. For (relatively) flat areas, locations could include whole polders or villages. If there are large local variations within one village, e.g. in land level, it could be divided into multiple locations. If the output of detailed flood simulations is available, GIS[13] methods can be used to assess the values of hydraulic characteristics for a certain spatial unit, e.g. per hectare.

7.4.2 Derivation of mortality functions based on historical flood events

In this section it is described how mortality functions for different hazard zones are derived by means of empirical analysis of historical flood events. The collected historical data are described and issues in the analysis of the data are outlined.

13 Geographical Information System

Derivation of mortality functions

For the three hazard zones **mortality functions** are derived to relate mortality fraction to flood characteristics. Empirical data from historical flood events are used to analyse whether a statistical relationship exists between the mortality fraction and certain flood characteristics. Not absolute fatality numbers, but **mortality fractions** are analysed, as it is expected that for a given set of flood conditions the mortality (fraction) is independent of the magnitude of the exposed population[14]. Mortality functions are derived by means of a **least square fit**. In order to achieve a robust statistical analysis only factors for which sufficient data are available are taken into account, such as water depth and the collapse of buildings (see discussion below). The correlation[15] between observed and calculated mortality fractions are reported. The available dataset is split into data used for **calibration** (i.e. derivation) of the mortality functions and data used for **validation** (i.e. verification) of the proposed functions. In the validation phase it is checked whether the proposed method results in an accurate prediction of the number of fatalities for some historical events. **Accurate** is interpreted as follows: the deviation between the mortality calculated with the model and the observation should be no more than a factor 2 to 5 ([16]), to be verified based on case studies. Finally, **model uncertainties** in the mortality functions are presented by means of the 95% confidence interval around the bestfit trendlines. The confidence interval is determined by means of a numerical bootstrap analysis of available data, see (van den Hengel, 2006) for details.

The occurrence of flood fatalities is determined by a large number of interacting factors such as individual vulnerabilities, human behaviour and local flood conditions. Mechanistic modelling of all these processes is not attempted here because there is not enough data to determine the influence of all these factors in an empirical way (see also section 5.6). Instead, the mortality fraction is related to the factors that are expected to have the largest influence on the extent of loss of life, e.g. the water depth. In this context it is also noted that the proposed empirical mortality functions do not directly account for the causes of death in a hazard zone. Still, it would be expected that certain causes of death dominate mortality in a specific hazard zone. For example, the causes of death associated with high velocities, such as human instability and collapse of buildings, will occur often in the breach zone. Nonetheless, multiple causes of death usually occur within one flood zone, due to local variations in behaviour, flood and area characteristics.

Compilation of a database with information regarding historical flood events

In order to derive empirical mortality functions a database with information regarding flood fatalities in historical flood events has been compiled. The database enables uniform storage of data and might provide a source for future research. Similar datasets exist for the Netherlands 1953 flood (Waarts, 1992; Jonkman, 2004) dam break floods (McClelland and Bowles, 2002) and for global disasters (EMDAT, 2004).

14 This implies the following: for example assume two locations A and B. A has ten times as many inhabitants as B. If A and B are exposed to identical flood characteristics, A will suffer ten times more fatalities than B.

15 Correlation gives a measure for linear dependence between two variables, in this case the calculated and the observed mortality.

16 This order of magnitude is chosen as deviations in existing methods for risk quantification in the chemical sector give a variation of a factor of around 10, as has been shown in benchmark studies by Ale *et al.* (2001).

In the flood fatalities database information has been included on a large number of factors that are relevant for the investigation of loss of life. The data categories that have been reported for each record include event characteristics (name, location, date), flood characteristics (depth, velocity, rise rate), information regarding warning, evacuation, shelter and collapse of buildings, and more descriptive information regarding circumstances and vulnerabilities of flood fatalities. Individual records have been created for locations for which conditions could be assumed relatively homogeneous, so one event can involve multiple locations. Information regarding the above-mentioned fields has been obtained from literature. To allow empirical analysis, mainly information from references that provide quantitative data is included. Table 7-3 summarizes the available information per event[17]. The flood fatalities database is included and described in more detail in appendix 7.III.

Table 7-3: Overview of events with data on loss of life reported in the flood fatalities database. Columns indicate the fields that have been reported quantitatively in the underlying sources. Abbreviations used: *h*-water depth; *w* – rise rate; F_B – collapse of buildings

Date	Event / cause	Country and area	Fatalities*	Exposed*	Nr. of locations	Reported factors	Reference
Events used for **calibration**, i.e. derivation of mortality functions							
9-9-1934	Typhoon Muroto	Japan, Osaka Bay	843	Unknown# (1,7million inhabitants)	10	h, F_B	Tsuchiya and Kawata, 1981
3-9-1950	Typhoon Jane	Japan, Osaka Bay	204	Unknown# (850.000 inhabitants)	10	h, F_B	Tsuchiya and Kawata, 1981
30-1-1953	Storm surge, North Sea	UK, East Coast	197	26.900	13	h, warning	Grieve 1959, Summers 1978
1-2-1953	Storm surge, North Sea	NL, Southwest	1795	206.400	91	h, w, F_B, duration, warning	Waarts, 1992; Duiser, 1982, Van den Hengel, 2006
26-9-1959	Ise Bay typhoon	Japan, Ise Bay	4152	432.465	30	h, F_B, warning, sea wall breakdown ratio	Tsuchiya and Yasuda, 1980
8-9-1965	Hurricane Betsy	USA, SE Louisiana	51	Unknown# (200.000 inhabitants)	4	F_E, h	Boyd, 2005
Cased used for **validation**							
1912	River floods	UK, Norwich	4	2500	1	h	Ramsbottom *et al.*, 2003
August 1952	River floods	UK, Lynmouth	34	400	3	h	Ramsbottom *et al.*, 2003
25-1-1981	Flash floods	South Africa, Laingsburg	104	185	1	h	EMDAT, 2004
24-9-1999	Typhoon No. 18	Japan, Shiranui town	13	200	1	h	Takikawa, 2001 Kato, 2002
Autumn 2002	River floods	UK, Gowdall	0	250	1	h	Ramsbottom *et al.*, 2003

*: Included in the table are total numbers of fatalities and exposed as reported in the flood fatalities database in this study. These total numbers can thus be smaller than the overall event totals, because not all locations might have been included in the database. # - for these events the numbers of inhabitants are known, but the number of exposed cannot be estimated adequately due to the effects of evacuation.

17 Some of the events have in the database have been described in more detail in section 5.4 of this thesis.

In total the database covers over 165 locations, which have been abstracted from 11 events. The locations included could be considered as separate observations each representing different exposure conditions. The first five events in table 7-3 have been used for calibration (derivation of mortality functions), as these included large numbers of records. The other events, which included single locations, would add limited weight in the statistical analysis and have been used for validation of the model.

Only for a limited number of factors sufficient data are available to allow statistical analysis of their influence on loss of life. Predominantly for water depth a substantial number of records is available. Mortality functions will thereby primarily be derived based on water depth, which was also found to be an important determinant of mortality in historical flood events (see section 5.4). The influence of other factors of which data are available, e.g. rise rate, collapse of buildings and warning level, will be investigated. Due to lack of data, other potentially relevant factors, such as debris, flood duration or temperature, could not be included in the empirical analysis. The influence of these factors can be reflected in the (observed) mortality fractions, but is not included in the proposed mortality functions. The influence of these missing factors could thus (partly) explain differences between model predictions and observations, which is the model uncertainty associated with the mortality function.

Flow velocities are often not reported[18]. Especially near breaches, the velocities can be high and important for loss of life. Therefore the effects of flow velocity are included in the mortality function for the breach zone (see next section).

Issues in the collection and analysis of information from historical events
Issues in the collection of historical data and compilation of the database included:

- Uncertainties in the reported numbers: Apart from the data for the North Sea storm surge of 1953 it was difficult to check the accuracy of the reported numbers.
- Determination of representative values for flood characteristics, such as a representative water depth, for a location. Values have been mainly abstracted from underlying sources, but due to local variations[19] it could be difficult to determine a representative value. Several assumptions that were used in the analysis of these factors are described in appendix 7.III.

Despite these issues the compiled flood fatalities database is believed to be a valuable source for research on flood fatalities. In the future, further completion of the database with information for other events is encouraged.

The database includes events covering different conditions, periods and regions. The data have been joined in one dataset for the derivation of mortality functions. Below, it is discussed how temporal and regional differences between events and inclusion of evacuation could affect the outcomes.

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18 Flow velocities will exhibit large local variations depending on topography and local orientation of objects, such as buildings. Therefore it is difficult to determine a representative value of flow velocity for a larger area.

19 Within one location circumstances may vary significantly, for example due to variation in land levels within one village. If large variation exists within an area, than it has been divided into multiple locations.

Firstly, it can be questioned to what extent **regional differences** in area characteristics have affected mortality for the events included. Important factors include the number of higher buildings and their quality, the availability of higher grounds and other objects (e.g. trees). For the selected events in Netherlands, UK and Japan, larger low-lying areas have been flooded (polders) with all limited possibilities for shelter on higher grounds. Also the quality of buildings and the availability of higher buildings (as shelters) is believed to be comparable for the events. Thus, the events used for quantitative analysis (i.e. the flood events for Japan, Netherlands and UK) are believed to be relatively homogeneous in this respect.

Secondly, **temporal differences** between events could affect the outcomes. Many of the events occurred in the 1950's (or even earlier). Developments since then may have reduced the validity of these datasets for loss of life estimation for contemporary floods. Firstly, main changes concern the possibilities of evacuation, as prediction, warning, communication and transportation systems have improved. Also, the quality of buildings has been improved and nowadays a larger number of higher buildings is available for shelter. McClelland and Bowles (2002) conclude that, if these two factors (1) warning, evacuation and 2) building quality) are taken into account, life loss patterns appear consistent and similar across time. The influence of these factors is analysed separately in sections 7.4.6 (warning) and 7.4.7 (collapse of buildings).

Thirdly, during the considered historical events **evacuation** might have reduced the number of people exposed, while information regarding evacuation was not reported and included in the dataset. The events that have been used for calibration occurred unexpectedly (often at night) and no organised evacuation could take place[20]. In these cases it is reasonable to assume that the whole population in the flooded area has been exposed.

7.4.3 Mortality in the breach zone

Introduction and past work

Reports from historical floods show that, if breaching occurs in populated areas, mortality can be high in the area behind the breach. Especially due to the high flow velocities[21] and forces associated with breach inflow, buildings can collapse and people can lose their stability.

Some authors have investigated loss of life near breaches. Waarts (1992) assumes that all people present within a circular area with a radius of twice the breach width do not survive. Ramsbottom *et al.* (2005) simulated breaching of water defences in the context of a study on flood risks to people. For different breach discharges (and associated water heads) they plot a semi-quantitative hazard rating as a function of the distance to the breach. Together with information regarding the area vulnerability, the hazard rating could be converted into an expected mortality. Their results show that the risks to people rapidly decrease with distance from the breach. For the Ise Bay floods in Japan in 1959, Tsuchiya and Yasuda (1980) report mortalities and sea wall breakdown ratio. The sea wall breakdown ratios is the fraction of total sea wall or flood defence length that has been destroyed or breached. These data are shown for different locations in figure 7-8.

20 For example for the 1953 floods in the Netherlands it is mentioned in (Rijkswaterstaat, 1961) that most of the people stayed in their homes and that only locally refuge action was taken.

21 Just behind the breach flow velocities have been reported from 3 to 8 m/s (Waarts, 1992).

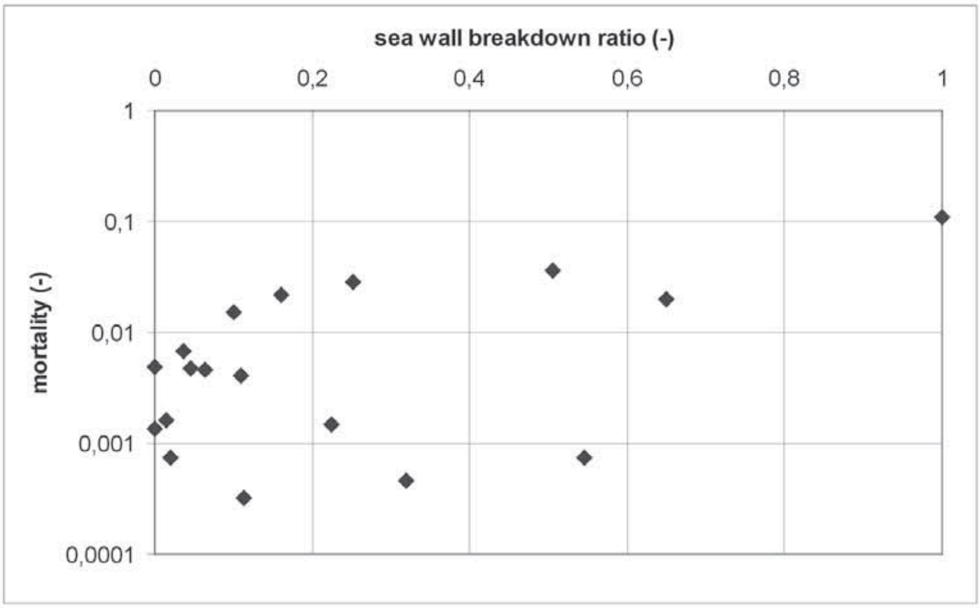


Figure 7-8: Relationship between sea wall breakdown ratio and mortality for the Ise Bay typhoon in 1959 in Japan (data: (Tsuchiya and Yasuda, 1980))

Although these results indicate some relationship between sea wall breakdown ratio and mortality, the variations are large. This could relate to differences between locations in the presence of population near breaches. If breaching occurs near a densely populated area sea wall breakdown ratio could be low, while mortality is high. Therefore it is necessary to take into account the location of the breach, the characteristics of flood flow and the actual presence of people in the area behind the breach.

Proposed mortality function for the breach zone

None of the available sources relates mortality in the breach zone to the relevant flood characteristics (depth and velocity). Thus the available case study data do not provide enough evidence for empirical derivation of mortality functions for the breach zone. Therefore, an approach is proposed based on information from literature. People's instability and damages to buildings are both generally estimated as a function of the depth-velocity product. Clausen (1989) proposes a criterion for the damage to buildings in flow conditions. The RESCDAM study (Karvonen *et al.*, 2000) supports these findings and recommends them for use in assessing potential structural damages of Finnish houses. Total destruction of masonry, concrete and brick houses occurs if the product of water depth and flow velocity[22] exceeds the following criteria simultaneously:

$$hv \geq 7m^2/s \qquad and \quad v \geq 2m/s \qquad \textbf{(Eq. 7-3)}$$

It is proposed to use this function to define the boundaries of the breach zone. For the characteristic flood pattern following a breach in a flood defence (see figure 7-7) velocities are high mainly near the breach and more moderate in other parts of the polder. It is noted that the above criterion can also be used for other areas where the depth velocity product exceeds the above threshold. It is assumed that most people remain indoors during the flood and that people do not survive when the building collapses. Then, it can be assumed that mortality in the breach zone equals F_D=1. This assumption may be conservative as

22 The *hv* product is related to moment. In addition, horizontal force could be important for collapse of buildings, resulting in a critical hv^2 product (see also discussion in section 6.3)

those who will be picked up by the flood may still have survival chances (see also the discussion in section 6.3.4)

Simple approach for the estimation of the size of the breach zone
The size of the breach zone can be estimated with a simplified analytical approach. Firstly, we assume a constant breach discharge Q_{breach} [m^3/s] and a radial development of the flood front behind the breach. Now the discharge at radius (*Q(R)*)can be expressed as a function of water depth and flow velocity at radius *R* [m] (see figure 7-9).

$$Q(R) = \pi R h(R) v(R) \qquad \textbf{(Eq. 7-4)}$$

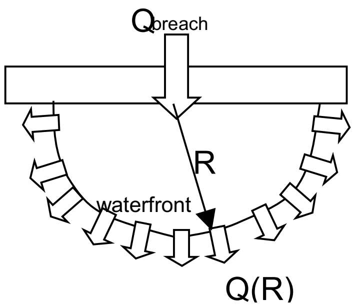


Figure 7-9: Schematic view of the breach zone.

A volume equilibrium is used, while assuming a constant breach discharge and neglecting storage of water in the flooded area behind the breach. Then, the radius of the area where the critical depth velocity product (hv_c=7m^2/s) is exceeded (R_C – [m])can be approximated as follows[23]:

$$Q_{breach} = Q(R) \quad \Rightarrow \quad R_C = Q_{breach} / (\pi h v_C) = C_c Q_{breach} \qquad \textbf{(Eq. 7-5)}$$

Where C_c - constant which equals: $1/(\pi h v_c)$=0,045 s/m^2

The proposed relationship can be compared with more detailed hydraulic simulations[24] of flood flow behind the breach. Flood characteristics have been calculated for different configurations of:

- The difference between outside water level and land level in the flooded area;
- The soil material of the dike (clay, sand);
- The hydraulic roughness of the area behind the breach.

In that analysis the size and shape of the area in which the critical depth velocity product is exceeded has been examined. The results show that the breach zone for a flat polder approximately has a circular shape. For both approaches the radius of the breach zone with 100% mortality is plotted as a function of breach discharge in figure 7-10. The analytical and simulation results show relatively good agreement; differences might be related to neglecting the volume storage and the effects of breach growth in the analytical approach.

23 Note that in addition it should be checked whether the additional condition (v>2m/s) is fulfilled.
24 Source of the model calculations: Appendix 7 of (Jonkman, 2004).

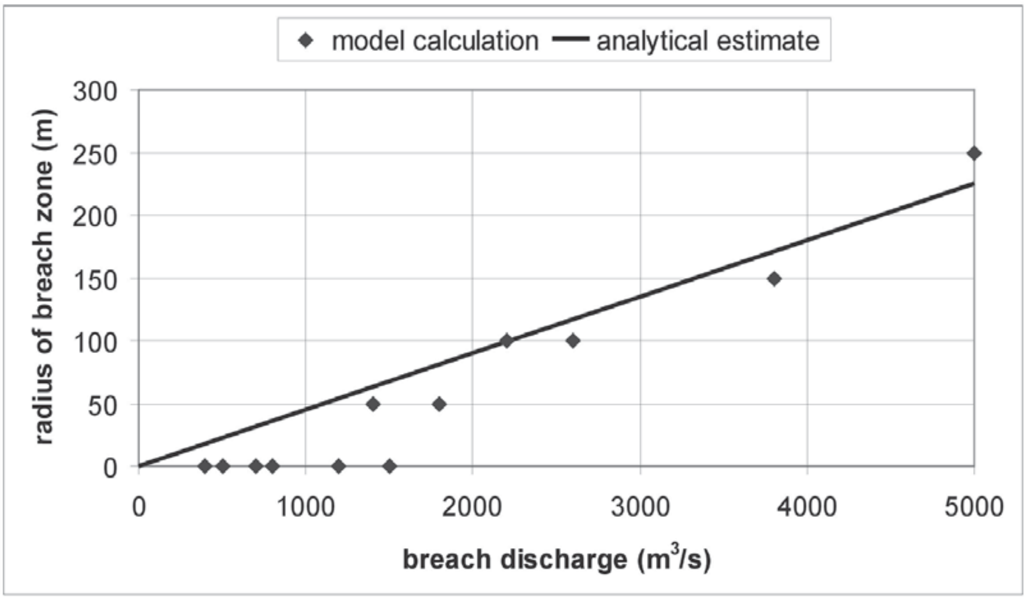


Figure 7-10: Radius of the breach zone as a function of breach discharge[23].

In combination with a breach growth and flood simulation model, the proposed approach can be used to estimate the size of breach zone and consequently the number of fatalities, see for example Kawaguchi *et al.* (2005). For the further development of an empirical function for mortality in the breach zone it is recommended to collect data on historical death rates near breaches and to relate these to breach size, and local flood characteristics.

7.4.4 Mortality in the zone with rapidly rising water

Rapidly rising water is hazardous as people may be surprised and trapped at lower floors of buildings and have little time to reach higher floors or shelters. The combination of rapid rise of waters with larger water depths is particularly hazardous, as people on higher floors or buildings will also be endangered. Observations from historical events also show that this zone is often characterised by a large number of collapsed buildings (see section 7.4.7).

Data on fatalities caused by rapidly rising waters are available for the floods in the Netherlands in 1953 (12 locations), UK 1953 (1 location) and Japan 1959 (2 locations). Based on available (descriptive) information the flood flows at these locations have been categorised as being rapidly rising.

Relationship between rise rate and mortality
Firstly, the relationship between mortality and rise rate has been examined. For 8 locations in the 1953 disaster in the Netherlands, Waarts (1992) derived quantitative estimates of the rise rate from eyewitness accounts. Figure 7-11 shows observed mortality fractions as a function of rise rate for these 8 locations, indicating no direct relationship between these variables. All the points categorised as being in the rapidly rising zone, had rise rates of 0,5 m/hr. This value is proposed as a first conservative threshold for the distinction between the rapidly rising and remaining zone. However, figure 7-11 indicates that given the lack of data the threshold value could be chosen anywhere between 0,5 and 4 m/hr. Further collection of data from historical floods is recommended to improve the foundation of the threshold value.

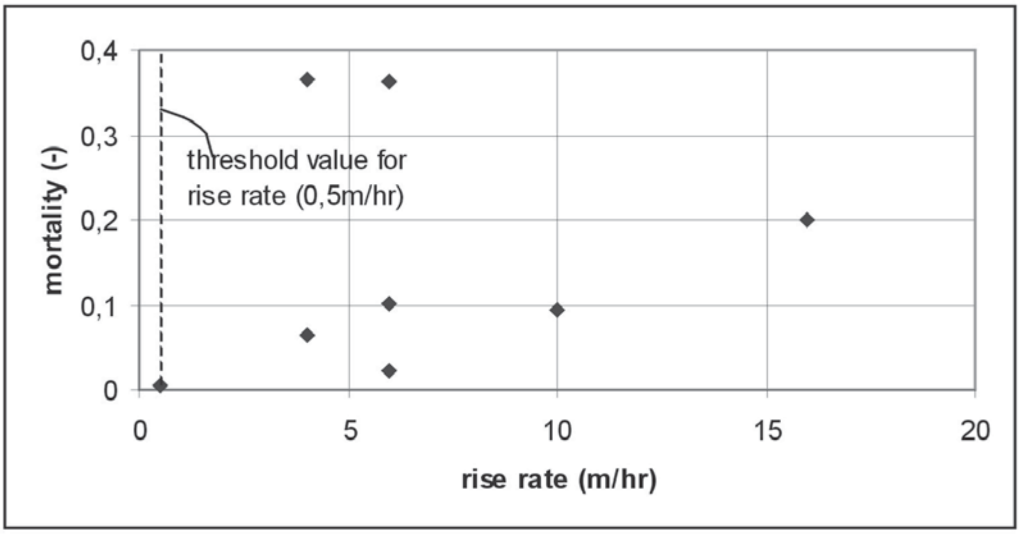


Figure 7-11: Mortality and rate of rising for eight locations from the 1953 storm surge floods in the Netherlands.

Relationship between water depth and mortality

Figure 7-12 shows the relationship between the water depth and mortality, indicating a relationship between these variables. This implies that the combination of water depth and rise rate is important. A bestfit trendline is found for the lognormal distribution[25]:

$$F_D(h) = \Phi_N\left(\frac{\ln(h) - \mu_N}{\sigma_N}\right) \qquad \textbf{(Eq. 7-6)}$$

$$\mu_N = 1,46 \qquad \sigma_N = 0,28$$

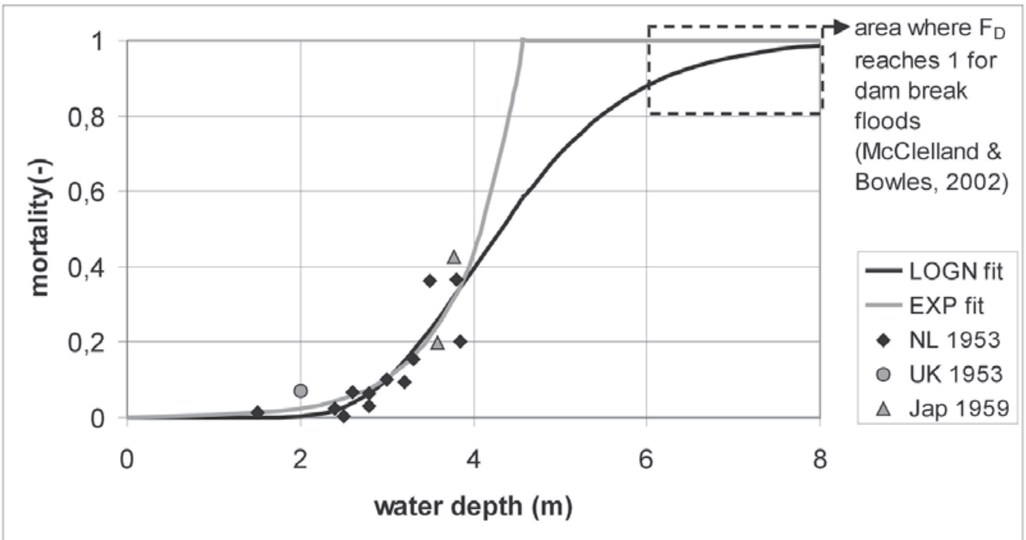


Figure 7-12: Relationship between mortality and water depth for locations with rapidly rising water. Right hand figure shows mortality calculated with the model as a function of the observed mortality.

25 As has been shown in section 2 the lognormal distribution can also be expressed as a probit function, with: constants a=-0,21; b=3,57 n=1 and $Pr=a+b*\ln(h)$.

For the whole dataset[26] this relationship gives a good correlation between observations and results of the model (R^2=0,76). Additionally, another good fit (R^2=0,74) is obtained with an exponential distribution (*A*=4,57; *B*=0,69 in equation 2-6), which is shown with a dashed line in the graph. The exponential function has the disadvantages that a) F_D>0 if *h*=0 and b) it approximates F_D=1 very rapidly for higher water depths. The benefit of the lognormal function is that it is also used to model human response of exposure to other substances and that it asymptotically approaches F_D=1 for higher water depths (see also the interpretation below). The 50% mortality value is reached for a water depth of 4,3m (corresponding to a value of exp(μ_N)).

For the lognormal dose response function model uncertainties are indicated in figure 7-13 by means of the 2,5% and 97,5% confidence intervals. As a result, a conditional distribution of mortality can be given for every water depth. Uncertainties are larger for higher water depths as no data are available for these conditions. For depths between 2 and 5 meters the uncertainty bounds are approximately a factor ½ above and below the average mortality function.

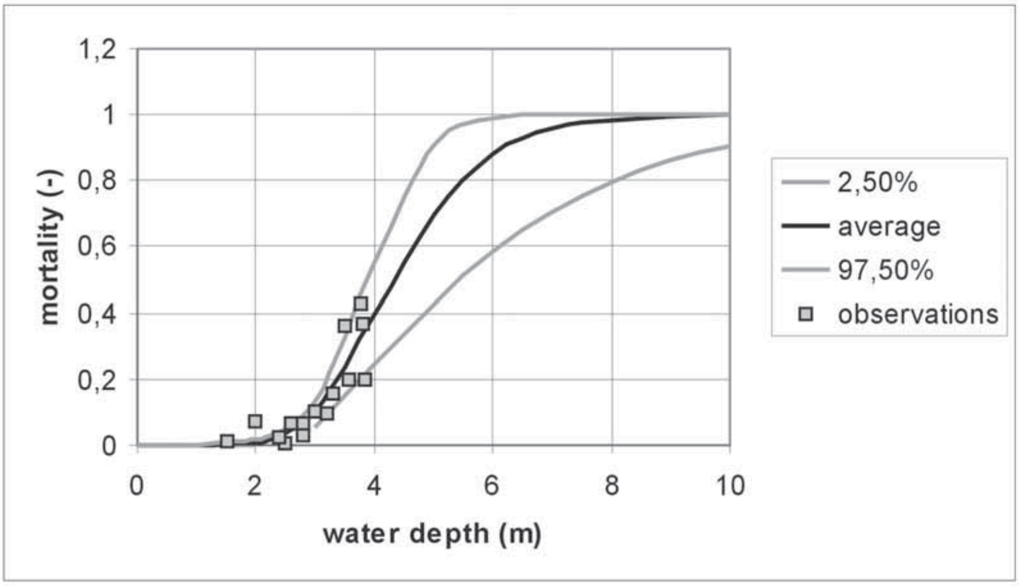


Figure 7-13: 2,5% and 97,5% confidence intervals representing model uncertainty for the mortality function for the zone with rapidly rising water.

Interpretation of the course of the mortality function[27]

The course of the lognormal mortality function can be interpreted as having different stages. The stages are related to the water level relative to the typical building height[28], see figure 7-14 and Boyd *et al.* (2005) for further discussion. Initially, as the water rises to about head or first floor level, the probability of death will increase as people outside buildings are overwhelmed by the water (0 to 2 metres). In the second stage (2 -5 metres) mortality rises quicker, as people who sought refuge on the higher floors and roofs of houses may also be exposed to floodwaters. Finally, for higher water depths (> 5 metres) the function

26 A first analysis of data for the Netherlands 1953 flood results in a correlation of R^2=0,75. It is found that the correlation slightly improves when data from the other events (UK 1953 and Japan 1959) is added.

27 The ideas in this paragraph are based on personal communication with Ezra Boyd, LSU Hurricane Center.

28 IPET The influence on mortality of the water depth relative to building height is also included in the loss of life model for the flooding of New Orleans by IPET (2006), see also section 6.

is expected to approach 100% mortality[29] asymptotically when the water depth exceeds the roof level of houses, which is generally 5 to 7 metres. Additional support for the course of the function for higher water depths is provided by an analysis of loss of life in historical dam break floods (McClelland and Bowles, 2002), see also figure 7-12. They found that when the water depth reaches about 6,5 metres (20 feet) mortality becomes 100%. This corresponds to the upper right part of the lognormal distribution deduced here. By combining the above stages an S-shaped lognormal curve is found. To strengthen the empirical basis of this curve further collection of data is recommended, especially for larger water depths.

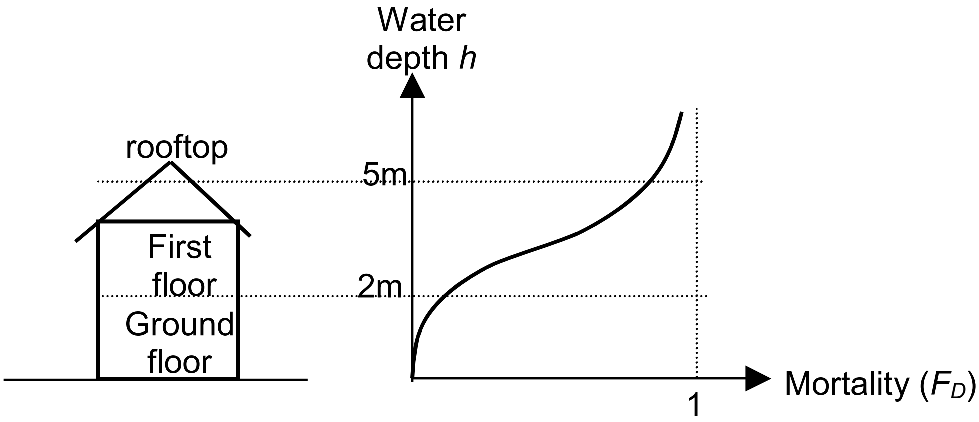


Figure 7-14: Mortality function for zone with rapidly rising water, relative to water depth and building height (Boyd *et al.*, 2005)

7.4.5 Mortality in the remaining zone

A remaining zone is distinguished to account for fatalities outside the breach and rapidly rising zone. In this zone the flood conditions are more slow-onset (w<0,5 m/hr), offering better possibilities to find shelter. Fatalities may occur amongst those that did not find shelter, or due to adverse health conditions associated with extended exposure of those in shelters.

The first five case histories in table 7-3 (Japan 1934, 1950, 1959, Netherlands and United Kingdom 1953, US 1965) provide data on mortality in the remaining zone for 93 locations. Mortality fractions are plotted as a function of water depth in figure 7-15.

29 The expectation of 100% mortality for larger water depths is in contradiction with the assumption of Boyd *et al.* (2005). They assume that mortality will reach some asymptote (F_D=0,34) as "there are always survivors".

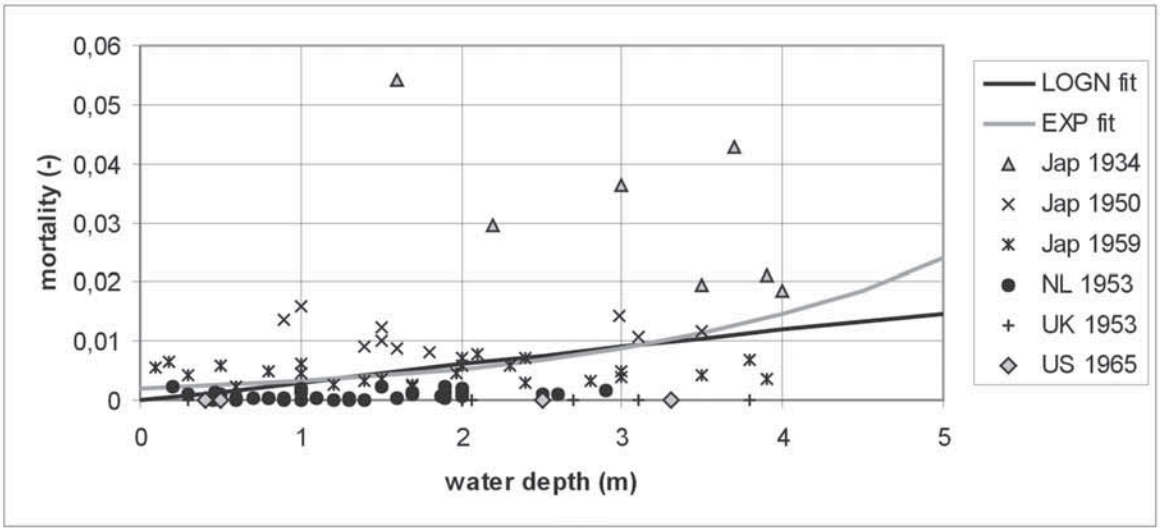


Figure 7-15: Mortality as function of water depth for the remaining zone. Data from different flood events have been included.

The following mortality function is found for the lognormal distribution[30]:

$$F_D(h) = \Phi_N\left(\frac{\ln(h) - \mu_N}{\sigma_N}\right) \quad \textbf{(Eq. 7-7)}$$

$$\mu_N = 7,60 \qquad \sigma_N = 2,75$$

A very weak correlation between observations and model calculation of R^2=0,09 is obtained. Confidence intervals for model uncertainty are indicated in figure 7-16.

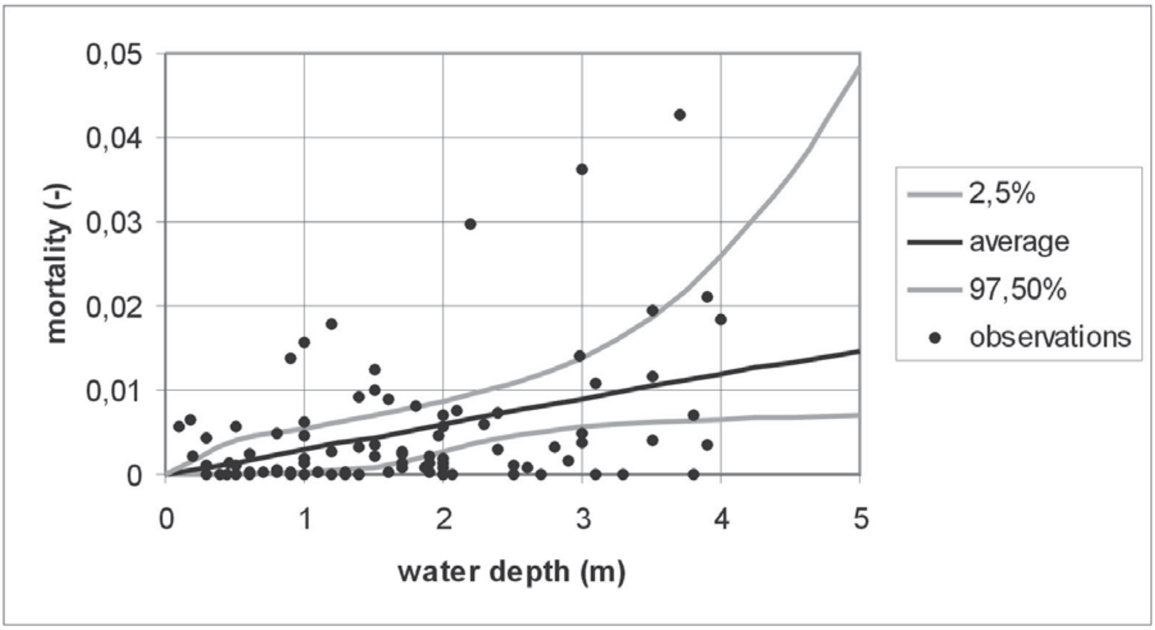


Figure 7-16: 2,5% and 97,5% confidence intervals representing model uncertainty for the mortality function for the remaining zone with rapidly rising water

30 A slightly higher correlation of R2=0,10 is found for the exponential distribution, with A=12,4 and B=1,99. Given consistency with the format of the function for the zone with rapidly rising waters and similarity to other applications of the dose response function (see section 2) the use of lognormal function is preferred.

Discussion
The correlation for the mortality function for the remaining zone is very poor, as there is a large variation in observed mortalities. The derived mortality function gives a poor fit for absolute mortality, but it provides insight in the order of magnitude of mortality, which is generally between 0 and 0,02.

The poor correlation is influenced by some outliers with high mortality. For example during the floods at the east coast of the UK in 1953, 2 of the 37 inhabitants of Wallasea Island did not survive resulting in a 0,054 mortality. Descriptions of the 1953 floods in the Netherlands (Slager, 1992) show that locations that received no warning had high mortalities. The level of warning is expected to influence the possibilities to find local shelter and thus influences loss of life[31]. This issue is investigated further in the next section.

7.4.6 Influence of warning and shelter on mortality

When people cannot evacuate from the exposed area, timely warning may still play a key role in preventing loss of life. It will allow people some time to find shelter on higher grounds or in buildings. The relationship between the level of warning and mortality is investigated below.

Classification method and available data
Information regarding warning levels is available for two of the historical events. Firstly, Tsuchiya and Yasuda (1980) investigated the relationship between risk to life and warning for the Ise Bay typhoon in 1959 in Japan for 27 locations. The authors categorised the local level of warning for 27 locations and used the ranking system indicated in table 7-4. They found that mortality was high at locations with insufficient warning, but they did not consider the combined influence of warning and flood depth.

Table 7-4: Classification of flood warning levels according to Tsuchiya and Yasuda (1980)

Warning Rank	Description
A	Evacuation order was proclaimed beforehand and people could take refuge before flood
B	Warning was given several hours before flood, but preparation actions could not be completely finished
C	Warning was given shortly before or just after the flood and some people managed to take action
D	No warning given, warning perceived by hardly anyone

The second case concerns the 1953 floods in the Netherlands. A large-scale and organised evacuation was not possible, but this disaster did not occur completely unexpected at all locations. In many of the flooded locations some sort of warning (e.g. by church bells) was given and people had the possibility to move to higher grounds or buildings. Based on qualitative descriptions by (SNSD, 1956; WGGO, 1954; Slager, 1992) the warning levels for 39 locations have been rated with the classification system proposed in table 8-4. All observations in the zone with rapidly rising waters had a poor level of warning (C) or no warning at all (D). No further analysis is carried out for this zone.

31 Another cause of the outliers in the remaining zone could be the classification procedure used to identify whether a location was in the remaining zone or rapidly rising zone. A location was categorised as being in the remaining zone when no information was available on circumstances. This could imply that, due to lack of information, locations were assigned to the remaining zone while actually rapidly rising waters occurred.

Effects of warning on flood mortality for the remaining zone
Figure 7-17 shows the relationship between water depth, flood mortality and level of warning for locations from the two case studies (Netherlands 1953 and Japan 1959).

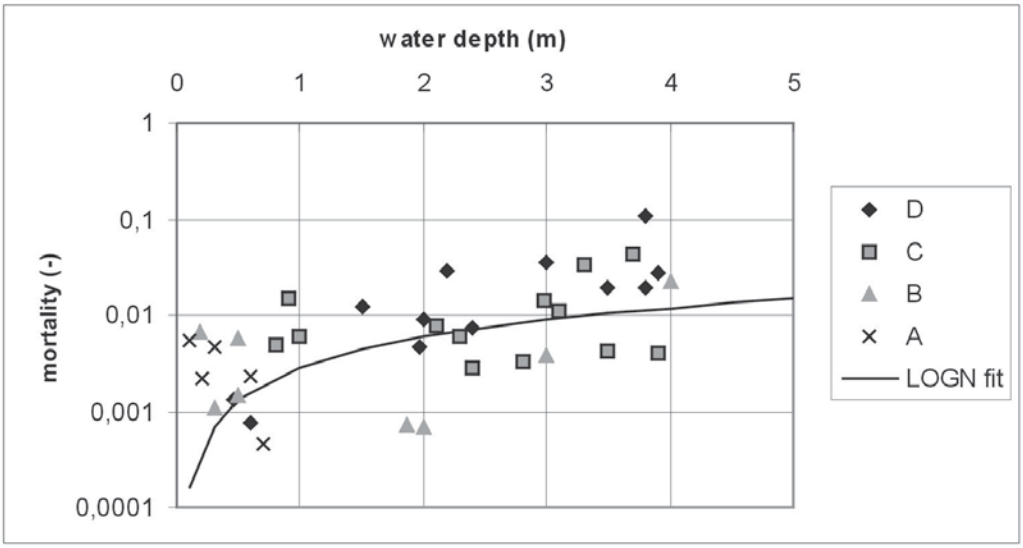


Figure 7-17: Relationship between mortality (logarithmic scale) and water depth for different levels of warning. The line shows the mortality function for the remaining zone derived in section 7.4.5.

It shows that observed mortalities in the remaining zone were highest where a) little (C) or no warning (D) was given and b) where water depths were high. Further analysis shows that many outliers in figure 7-15 had a poor level of warning or no warning at all. For other outliers (e.g. Wallasea Island) no information is available on the level of warning. The above results suggest that the level warning has an influencing on mortality in the remaining zone. However, differentiation of mortality functions by the level of warning does not lead to an improvement of correlation between observations and prediction. Further research in this direction is recommended.

7.4.7 Influence of the collapse of buildings on mortality

Introduction and past work
Historical flood events show that death rates are high where buildings collapse and fail to provide a safe shelter (see section 5.5). Especially wooden buildings, mobile homes, informal, temporary and fragile structures (including campsites and other tented dwellings) may give rise to significant loss of life (Ramsbottom *et al.*, 2003). Particularly during more severe and unexpected coastal floods, such as those in the UK and Netherlands in 1953, building vulnerability has been an important factor influencing the large numbers of deaths. It is noted that the collapse of buildings is also a significant factor in the number of deaths resulting from other events, such as earthquakes[32] and windstorms.

32 Loss of life caused by earthquakes is strongly related to collapse of buildings. Extensive literature is available for collapse of buildings under earthquake loads, see for example the HAZUS Technical manual (FEMA, 1999). This model assumes that 5-10% of the people in the collapsed buildings are immediately killed, and large percentages (60 – 70%) are injured. Kanda and Shah (1997) show that the ratio between fatalities and collapsed houses equals 0,1. However, for floods mortality ratios for people in collapsed buildings are believed to be higher. Many people will drown after collapse, and those trapped in the debris will have minimal chances of surviving without immediate rescue.

Several authors have investigated the collapse of buildings in floods. Black (1975) calculated the maximal bending moments due to hydrostatic and dynamic pressure for timber frame houses. Clausen (1989) derived damage criteria for brick and masonry buildings, in the format of a critical depth velocity product leading to wall collapse. Kelman (2002) and Kelman and Spence (2004) investigated physical vulnerability of residential properties in coastal areas and added the influence of rise rate. Roos (2003) developed a comprehensive probabilistic model for collapse of buildings, which takes into account two failure modes that can lead to partial or full collapse of a building. These are 1) the scour of foundations 2) the failure of walls. The model of Roos considers hydrostatic and hydrodynamic loads, as well as the impacts of waves and pounding debris. Also the strength (resistance) of the building type is considered. A general weakness of these buildings vulnerability models concerns their limited practical validation. Most of the presented relationships are based on theory or scale model tests.

Some work has considered the relationship between the collapse of buildings and loss of life in floods, e.g. in the field of dam breaks (Johnstone *et al.*, 2005; McClelland and Bowles, 2002). Graham (1999) shows that for dam breaks the highest fatality rates occurred in the zones where residences were destroyed. Zhai (2003) proposed a relationship between the number of flooded buildings and the loss of life for historical floods in Japan, but does not consider the actual collapse of buildings. Bern *et al.* (1993) and Mushtaque *et al*. (1993) show for the 1991 Bangladesh cyclone that death rates vary strongly between house types (see also section 5.4.3). Some overall ratios between the loss of life (N) and the number of collapsed buildings (N_B) for some historical floods are given in table 7-5.

Table 7-5: Relationship between loss of life and total number of buildings collapsed for some historical floods

Flood	Fatalities (N)	Nr. of collapsed buildings (N_B)	Ratio: N/N_B	Reference
Netherlands 1953	1835	3300	0,55	Slager, 1992
Muroto typhoon, Japan 1934	843	1785	0,47	Tsuchiya and Kawata, 1981
Malpasset dam failure	423	150	2,82	Johnstone *et al.*, 2003
Typhoon Jane, 1950, Japan	204	4807	0,04	Tsuchiya and Kawata, 1981

Table 7-5 shows that the ratio (fatalities / buildings collapsed) differs between events. As a single factor the collapse of buildings cannot be used as a predictive variable for loss of life. Additional conditions have to be considered, such as the actual presence of people and the level of warning. The number of fatalities per collapsed building will be high if an unexpected flood occurs, as possibilities to escape out of the area will be limited. For example the Malpasset dam failure occurred unexpectedly and there was very little possibility for refuge actions in the narrow valley. This resulted in a relatively high number of deaths per collapsed building.

Relationship between the collapse of buildings and loss of life for the Netherlands 1953 floods

This relationship has been investigated further, using available data on the collapse of buildings from different sources (SNSD, 1956; WGGO, 1954; Duiser, 1988). Figure 7-18 plots the relationship between the fraction of the total number of buildings that collapsed

(F_B) and mortality (F_D), for locations in the zone with rapidly rising water and the remaining zones.

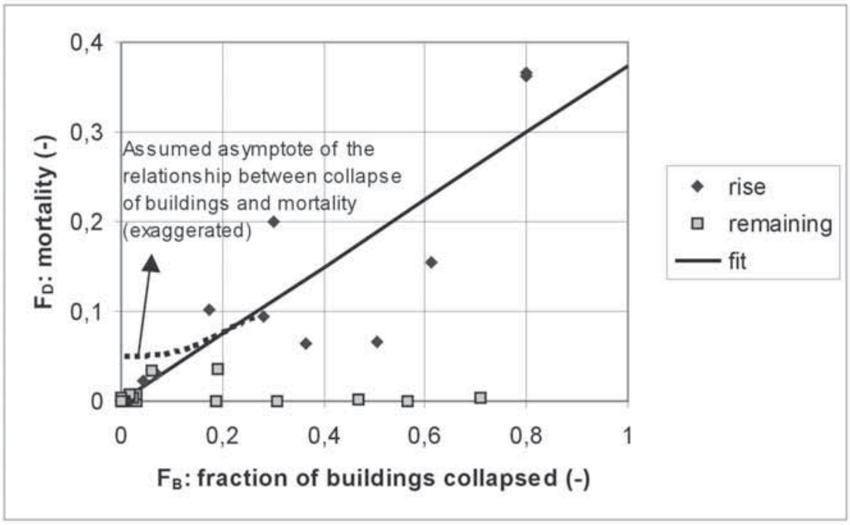


Figure 7-18: Relationship between the fraction of buildings collapsed and mortality by location for the 1953 floods in the Netherlands.

For the zone with rapidly rising water a rather strong correlation (R^2=0,73) exists between collapse of buildings and mortality. The function can be approximated with F_D=0,37F_B. A rapid rise of the water leads to pressure differentials between water levels inside and outside the building (Kelman, 2002). This effect, in combination with the effects of water depth and flow velocity, could contribute to the collapse of buildings. In the above linear function mortality becomes 0 if collapse of buildings reduces to F_B=0. However, it is still likely that fatalities will occur due to other causes. Therefore an asymptotic relationship is assumed and schematically shown in figure 7-18.

As a first order validation, the obtained relationship is compared with observations from the flooding of Lynmouth in the UK in 1952 as reported in (Ramsbottom *et al.*, 2003). The number of houses destroyed amounts 38 of an estimated total of 165 houses, leading to a collapsed building ratio of F_B=0,23. With the relationship derived above, mortality is estimated at F_D=0,37*0,23=0,085, which is equal to the actually reported mortality of F_D=0,085.

Figure 7-18 shows that for the remaining zone a less strong relationship exists between collapse of buildings and mortality. In this zone the flood are more slow-onset, and people have more time to find shelter at safer locations. Based on these findings it is assumed that the collapse of buildings is only a significant factor in the zone with rapidly rising waters.

Modification of the mortality function for the factor collapse of buildings
During the 1953 floods many of the collapsed buildings were working class houses of poor quality. Current building quality is better, and it is investigated below how this can be accounted for in the mortality function. Based on (Asselman, 2005) it is estimated that improvement of building quality to today's standards would lead to a reduction in the

collapse of buildings of approximately 57%[33]. The above analysis indicated a linear relationship between collapse ratio and mortality for the zone with rapidly rising water. Then, observed mortality fractions for the 1953 storm surge in the Netherlands can be scaled with the same factor. With these transformed observations a new mortality function can be derived, which gives an estimate for the situation with current building quality, see figure 7-19.A lognormal function is obtained with parameters μ_N=1,68, σ_N=0,37. It is noted that this (corrected) function is mainly based on the situation in the Netherlands. For other regions, where other building types are used, different relationships could be developed.

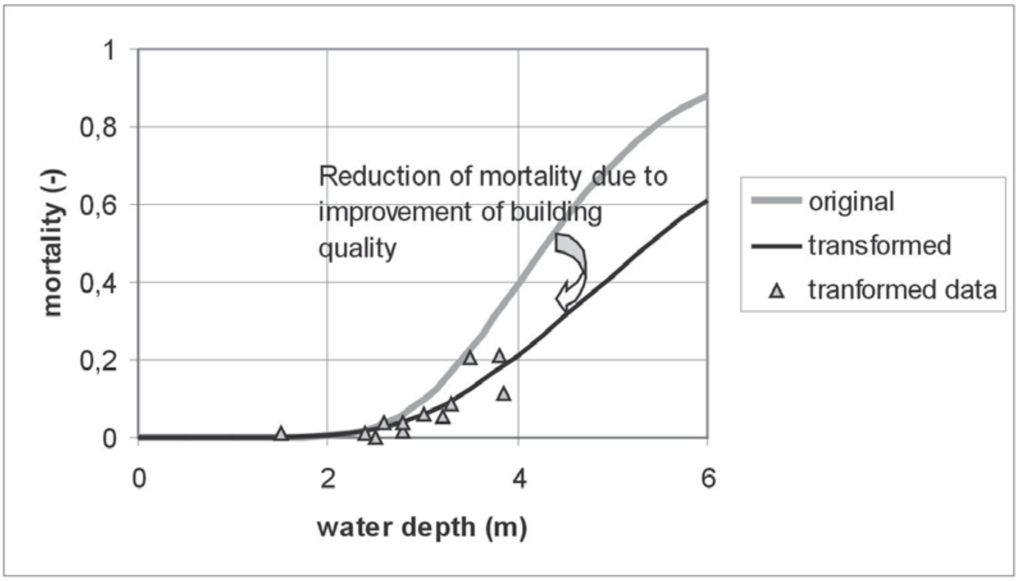


Figure 7-19: Mortality function that takes into account reduction of mortality due to improvement of building quality to current standards, for the zone with rapidly rising water. Figure also shows the original mortality function derived in section 7.4.4.

7.4.8 Summary of the proposed method for mortality estimation

This section briefly summarizes the application of the derived mortality functions. After analysis of the flood characteristics (section 7.2) and the number of people exposed (section 7.3), mortality for the different hazard zones can be estimated as follows:

Mortality in the breach zone:

$$F_D = 1 \qquad if \quad hv \geq 7m^2/s \qquad and \quad v \geq 2m/s$$

Mortality in the zone with rapidly rising water:

$$F_D(h) = \Phi_N\left(\frac{\ln(h) - \mu_N}{\sigma_N}\right)$$

$$\mu_N = 1,46 \qquad \sigma_N = 0,28$$

$$if \quad (h \geq 2,1m \quad and \quad w \geq 0,5m/hr) \quad and \quad (hv < 7m^2/s \quad or \quad v < 2m/s)$$

33 Asselman (2005) shows that if all housed had consisted of brick cavity walls, collapse ratio would have been about 20% lower. If all houses had made of concrete the reduction would have been 93%. For a first order analysis of the current situation we assume a 50-50 distribution of buildings over both building types, More detailed assessment of distributions of building types and their collapse ratio will be needed to obtain a better estimate.

The function for the zone with rapidly rising water is only used when it gives higher mortality fractions than the function for the remaining zone, so for water depths larger than 2,1m. The mortality function for the zone with rapidly rising water can be corrected for improved building quality to current standards. For a first order estimate of this effect the following constants can be assumed in the lognormal mortality function: μ_N=1,68, σ_N=0,37

<u>Mortality in the remaining zone:</u>
For remaining areas, mortality can be estimated as follows:

$$F_D(h) = \Phi_N\left(\frac{\ln(h) - \mu_N}{\sigma_N}\right)$$

$$\mu_N = 7,60 \qquad \sigma_N = 2,75$$

$$if\ \left(w < 0,5m/hr \quad or \quad (w \geq 0,5m/hr \ \ and \ \ h < 2,1m)\right) \quad and \quad \left(hv < 7m^2/s \quad or \quad v < 2m/s\right)$$

The range of flood conditions for which the above mortality functions can be applied are indicated in figure 7-20. In addition, uncertainty bounds for these mortality functions have been proposed to account for model uncertainties.

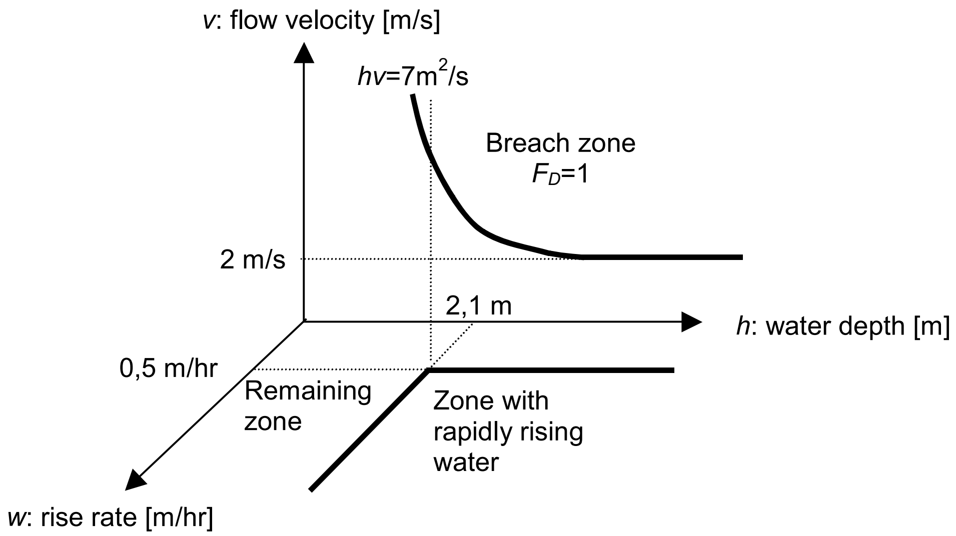
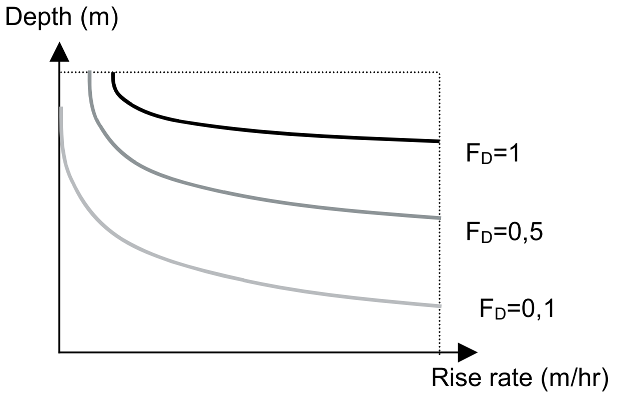


Figure 7-20: Area of application of mortality functions, as a function water depth, rise rate and flow velocity.

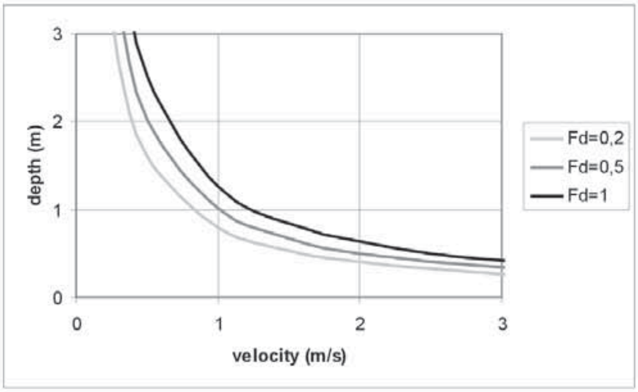
The proposed mortality functions can be easily implemented into computer code, for example the standardised damage model used in the Netherlands (Kok *et al.*, 2005). The developed mortality functions, which mainly use water depth as an input parameter, are conceptually similar to the depth-dependent damage functions that are used in many damage models to estimate the extent of economic damage.

Discussion
The outcomes of this method are sensitive to the value of the rise rate of the water. The proposed approach leads to an increase of mortality if the rise if the rise rate exceeds 0,5 m/hr. The value of this threshold has been chosen based on a limited amount of data (see figure 7-11). Further data collection and investigation of the influence of the rise rate are recommended. When more data becomes available, for example synthetic data from simu-

lations of historical floods, mortality can be statistically related to the combination of water depth and rise rate[34]. In this case it is no longer needed to separate the zone with rapidly rising water and the remaining zones, but one continuous mortality function can be derived for the whole range of rise rates and water depths. An example of such a function is given in figure 7-21a. The proposed method also distinguishes a discrete breach zone (i.e. the boundaries of the breach zone are defined by deterministic value of the depth-velocity product). When more data become available a more continuous mortality function could be derived which relates probability of death to the combination of depth and velocity. An example of such a relationship is derived based on the test data for human instability from Abt *et al.* (1989), see figure 7-21b.



a) Possible format mortality function as a function of depth and rise rate



b) Possible format of mortality function for breach zone as a function of depth and velocity

Figure 7-21: Possible formats of future mortality functions

In the proposed approach three hazard zones are distinguished based on the influence of flow velocity and rise rate. Depth dependent mortality functions have been proposed for these zones. One alternative application would be the derivation of one depth dependent mortality function based on all available data, see appendix 7.IV. However, it is found that the proposed approach (based on the three zones) gives the best fit with available data.

34 Some authors (van Gelder and Kraak, 1994; Vrouwenvelder and Steenhuis, 1997; Kok *et al.*, 2002) have proposed functions, which contained the combined influence of water depth and rise rate. However, the influence of rise rate was mainly quantified using assumptions and expert judgement and it did not rely on historical data.

7.5 Discussion of the proposed method for loss of life estimation

Firstly, a first order validation of the method is presented (7.5.1). Consequently, the main uncertainties and sensitivities (7.5.2) and the accuracy of the method (7.5.3) are discussed. A comparison with other models (7.5.4) and a discussion regarding applications (7.5.5) are also included.

7.5.1 Validation of the method

As a first order validation, the outcomes of the proposed method for loss of life estimation are compared with observations from some historical flood events. Five flood events included in the flood fatalities database are investigated. The selected events concern a flash flood (Laingsburg, South Africa, 1984), a coastal flood (Shiranui Town, Japan, 1999) and three river floods in the UK. Table 7-6 compares the results following from the proposed model with observed mortality and fatality numbers. Appendix 7.V gives the input information used for calculations of the number of fatalities.

Table 7-6: Comparison between reported mortality figures for some historical flood events and the results calculated with the model.

Flood	Flood type	Observations			Method	
		Exposed	Fatalities	Mortality	Fatalities	Mortality
Norwich river floods, 1912	River	1250*	4	$1{,}6.10^{-3}$	5	$3{,}6.10^{-3}$
Lynmouth floods, 1952	River / flash	400	34	0,085	11	0,028
Laingsburg, South Africa, 1981	Flash	185	104	0,56	73	0,39
Shiranui Town, Japan, 1999	Coastal	200	13	0,065	7	0,035
Gowdall river floods, 2002	River	25*	0	0	0,07	$2{,}8.10^{-3}$

*: Based on descriptions by (Ramsbottom *et al.*, 2003) evacuation has been assumed for the Norwich and Gowdall events.

Overall, the results show good agreement between observations and model results. For all events mortality (and the number of fatalities) are estimated within a bandwidth of a factor 2, except for the Lynmouth case[35].

Van den Hengel (2006) applied the proposed mortality functions[36] to give a hindcast of the consequences of the 1953 storm surge flood in the Netherlands. As input for flood characteristics he used available flood simulations of the disaster. The exposed population was estimated based on historical maps and population data. He found that it was possible to give a reasonable approximation of the total number of fatalities for the whole disaster (1298 observed fatalities in the considered areas vs. 1705 predicted). However, locally (e.g. per village) large deviations existed between the observed and the predicted number of fatalities. These deviations are due to various factors including: deviations between the observed and the simulated water depth and the sensitivity of outcomes for the rise rate.

35 This is believed due to the fact that many fatalities occurred near breaches. Ramsbottom *et al.* (2003) mention that 38 houses were destroyed. However, due to lack of data on flood conditions the breach zone is not accounted for in the calculations with the model, leading to an expected underestimation of loss of life with the model.

36 Actually van den Hengel (2006) used the mortality functions from Jonkman (2004). These are similar to the mortality functions proposed in this thesis.

7.5.2 Uncertainties and sensitivities

The proposed method combines the assessment of flood effects, analysis of evacuation and estimation of mortality amongst those exposed. Thus, the eventual loss of life estimate results from a chain of calculation steps and uncertainties in individual steps can propagate through this chain. Some main uncertainties and sensitivities that are associated with limited knowledge are outlined below.

Firstly, several uncertainties are associated with the location and timing of breach. Although flood simulation models predict the flood development reasonably well, **the location of the breach(es)** and the number of breaches[37] concern important uncertainties. To gain insight in the effects of different breaches multiple flood scenarios can be elaborated in the risk analysis. Also the timing of the flood initiation and the resulting available time are very important for estimating the possibilities for evacuation and the number of people exposed. Due to uncertainty in the breach initiation, estimates of the time available are uncertain (see also table 7-1).

Secondly, loss of life estimates are sensitive to **the rise rate** of rising, as the mortality function becomes steep when w>0,5m/hr. As the choice of this threshold value is based on limited data (see figure 7-8), further data collection and consequent investigation of the influence of the rise rate are recommended. For the zone with rapidly rising waters the collapse of buildings is an important determinant of loss of life. Further investigations on the combined influence of the collapse of buildings and the influence of the rise rate are recommended.

Uncertainty bounds have been derived for the mortality functions. These reflect model uncertainties, e.g. due to the fact that several relevant factors are not included in the model. Examples of such potentially relevant factors are waves and water temperature. Further data collection and analysis of other factors could reduce this model uncertainty. The mortality function for the remaining zone gives a poor correlation with observations. Preliminary analysis suggests that the level of warning has an influence on mortality in the remaining zone.

Further research on the factors mentioned above could improve the estimates of loss of life to some extent. A practical issue is that a lot of empirical information will be needed to evaluate the influence of various factors. The availability of such data is limited and moreover the data are the byproduct of the enormous human suffering due to events that we strive to avoid. In addition, it is expected that, even when the influence of several factors can be predicted more adequately, the mortality at a location under a given set of flood conditions remains inherently uncertain to some extent. This is due to the fact that human behaviour, which has a large influence on loss of life, will differ per event. Experiences with circumstances and behaviour during a past flood disaster are not necessarily representative for a future flood event. Finally, in defining the need for further research it has to be considered how much the inclusion of additional factors in the model improves the accuracy of the eventual estimate of loss of life, as will be discussed further in the next section.

37 A more extensive discussion of the possibility of multiple (simultaneous) breaches is included in section 9.3.1.

7.5.3 Discussion regarding the accuracy of the proposed method

In this section issues related to the accuracy of the proposed method are discussed.

The above validation shows that, with the proposed method, it is possible to predict the observed loss of life during historical events within a bandwidth of a factor 2. The method thereby gives an accurate[38], but indicative estimate of the overall loss of life caused by a flood event.

The derived mortality functions and the outcomes of the method show similarity with the indicators for average event mortality that have been derived from global event data (see section 5.2 and 5.3). Average event mortality for river floods equals $F_D \approx 0{,}005$ and for coastal floods $F_D \approx 0{,}01$. This corresponds to the order of magnitude of mortality that follows from the function for the remaining zone, where mortality is generally between $F_D=0$ and 0,01 for smaller water depths. Global statistics show that mortality becomes larger if the water becomes deep and rises rapidly, e.g. for flash floods. This is also reflected in the steeper mortality function for the zone with rapidly rising waters.

An added value of the proposed method is that it gives insight in the factors that influence the mortality at a more local level inside an area affected by a flood event. For example, local mortality is higher than the average event mortality near breaches and in areas with large water depths. Thereby the method enables the analysis of the contribution of a location to the overall consequences. It also allows the analysis of the effects of measures that have a local influence on consequence and risk levels. Examples are measures in the field of spatial planning and the use of compartment dikes.

Several uncertainties are associated with the quantitative influence of factors that determine mortality at a local level, such as the rise rate. It is expected that further investigations could improve the prediction of mortality for single locations within one event, but it is not expected to have a substantial influence on the mortality and loss of life estimates for the whole event. Experiences with the proposed model show that under- and overestimates of mortality for different locations within one event generally compensate each other, so that the event mortality is approximated well (see e.g. (van den Hengel, 2006)). In defining the need for further research it is thus important to consider how much the inclusion of additional factors in the model improves the accuracy of the eventual estimate of loss of life. An important related issue is the role of loss of life estimates in the decision-making regarding flood defence strategies and protection levels. This is further discussed in section 9.5.5.

7.5.4 Comparison with other loss of life models

It is interesting to compare the proposed loss of life model with some other methods that have been recently developed. Figure 7-22 schematically indicates some models with respect to their level of detail and modelling principles (see section 6 for a review of other models and an explanation of terms).

38 Accurate is interpreted here as follows: the deviation between the mortality calculated with the model and the observation should be no more than a factor 2 to 5, see also section 7.4.2.

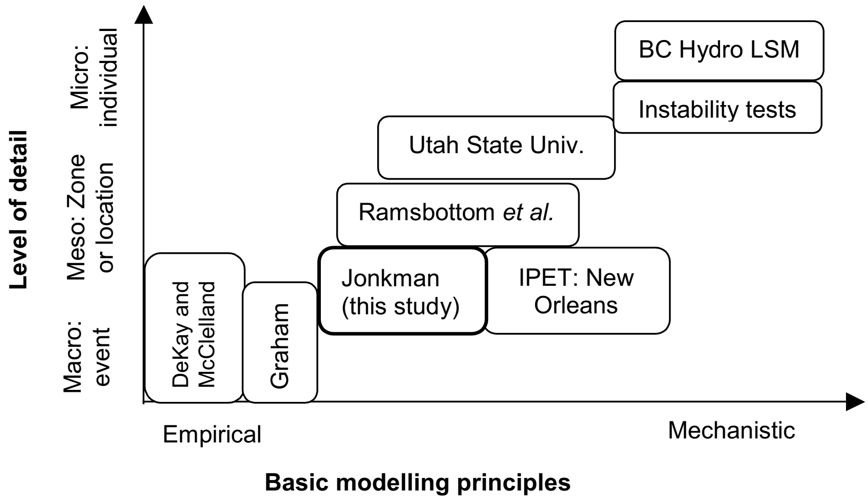


Figure 7-22: Comparison of the proposed method with other models for loss of life estimation (based on Johnstone *et al.*, 2005).

The models of Utah and BC Hydro use detailed local data and capture the mechanisms that lead to mortality. The model developed by Ramsbotom *et al.* (2005) uses a similar level of detail as the model proposed in this study, but mortality functions are not based on empirical analyses of historical data. In contrast to the purely empirical models of DeKay and McClelland (1993) and Graham (1999) the proposed model in this study also contains some more mechanistic elements, such as collapse of buildings, shelter and evacuation. The modelling approach used in the IPET study for New Orleans (IPET, 2006) is relatively similar[39] to the approach proposed in this study.

The benefit of the approach proposed in this study is that it is relatively simple. It is not more complex than needed to obtain an overall estimate of loss of life, because the influence of most relevant factors is quantified based on empirical data. In addition, the proposed mortality functions have some physical basis, i.e. they are related to the processes and mechanisms that are associated with loss of life. The dependency of mortality on flood depth shows that the probability of shelter decreases and drowning becomes more likely with increasing water depth. The depth-velocity criterion that has been proposed for the breach zone that is related to the physical mechanisms that lead to collapse of buildings and human instability in flood flows.

Possibilities for a more simulation-based approach for loss of life estimation

The proposed approach in this study does not capture individual behaviour and the individual causes of loss of life. Possibilities for a more mechanistic approach of loss of life estimation following up on the proposed approach are briefly discussed below, as impetus for further work in that direction.

The currently proposed model is static, i.e. it assumes that people are either evacuated from the area or they are present at their original location. Interacting dynamic processes, especially between escape and flood development, can be important for the number of fatalities. Numerous descriptions of circumstances during the 1953 floods in the Netherlands

39 In the IPET model the mortality fraction is kept constant for a certain zone, while the vertical distribution of the population relative to the water level is varied depending on local water depth (see IPET, 2006 and section 6 for description). In this study, the mortality fraction is modeled dependent on water depth.

(Slager, 1992) show that people perished when they were overwhelmed by floodwaters during their escape. Nowadays, it is expected that this hazard will be even larger. When large numbers of people are attempting to evacuate by car, traffic jams are likely to occur in the deepest parts of the polder that will flood first. To capture these interacting processes, more detailed simulations of escape behaviour of individuals or groups of people will be necessary. By combining the modelling of individual (escape) behaviour with detailed mortality functions (e.g. for instability, collapse of buildings) a dynamic and more mechanistic loss of life model is obtained. Such simulations can provide a) important information for the development of emergency evacuation strategies b) powerful visualisation tools for communication to the public and decision makers. The disadvantage of such an approach is that a large number of (behavioural) variables have to be assigned, for which very limited empirical information is available. It is suggested to investigate the application of such a dynamic approach for a pilot area in the Netherlands. Findings can be compared with historical observations (e.g. storm surge 1953) and the results obtained with the static and empirical model presented in this study.

7.5.5 Applications of the method for loss of life estimation

Applications to flood risk analysis

The proposed model can be applied to provide quantitative estimates of loss of life caused by floods in the context of safety evaluation, either in deterministic (scenario) or probabilistic (risk) calculations. Below it is described how the proposed approach can be applied to risk analysis. The current practice of flood risk analysis is limited to the elaboration of a number of deterministic flood scenarios, see e.g. (van Manen and Brinkhuis, 2005). The simulation of flood characteristics for a flood scenario provides input for loss of life estimation.

In addition, the occurrence of an evacuation is an important determinant of loss of life, as this influences the number of people exposed. Related factors, such as the possibility of warning, the time available before flooding and the response of the population, are generally uncertain variables and thus they can be described in stochastic terms (see also figure 2-7). This implies that for a given breach location and a corresponding (deterministic) flood pattern, different situations with respect to warning and evacuation can be distinguished. For example, an official warning can be given or not, or the population can fail to perceive the warning. To account for the above phenomena, the use of an event tree is proposed to distinguish different possible states for warning and evacuation[40], see figure 7-23 for an example. For each combination of prediction, warning and response, the magnitude of the evacuated and exposed population can be estimated. Consequently, the number of fatalities can be estimated for each branch of the event tree. In order to include these results in risk analysis, probabilities can be assigned to the occurrence of a successful prediction, warning and response. As these factors are case-specific and little historical data are available (e.g. on warning success rates), such probability estimates are often based on expert judgements[41].

40 For loss of life estimation for dam break floods, a similar approach is used to account for the magnitude of the exposed population behind the dam depending on time of the day, and day of the week, see e.g. Johnstone et al., 2005.

41 Such estimates comply with the Bayesian interpretation of probability. Then a probability is a numerical measure of a state of knowledge or a degree of belief (see also section 1.2.1). Event trees can also be used for other fields of application to assess the probabilities of having different sizes of the exposed population for one initial event. (Brussaard *et al.*, 2004) give an example for tunnel fires, which can occur with (large N_{EXP}) or without (small N_{EXP}) traffic jam.

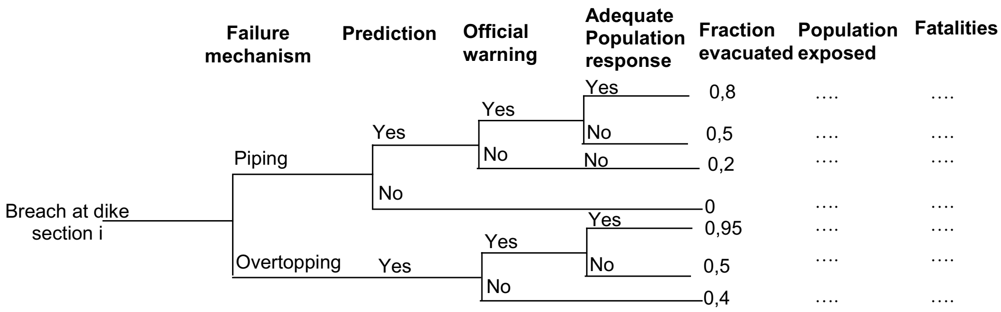


Figure 7-23: Event tree for estimating the evacuated fraction of the population for a given dike breach

Other applications of the proposed method

The developed model allows broader applications. As the model includes the most relevant factors that determine loss of life, it also offers the possibility to take into account measures that reduce consequence and risk levels. Different measures (e.g. land use planning, improving warning, evacuation possibilities, shelter or building quality) can be assessed. One particular application of the proposed model concerns the assessment of the effects of future land use developments on the consequences and risks of flooding. The mortality functions indicate that especially the spatial development of densely populated areas in deep polders can lead to a substantial increase of the number of fatalities.

The findings from the evacuation model and flood simulations are useful for the development of evacuation and emergency management strategies. In addition models for loss of life estimation could provide important information regarding the extent of loss of life and the exposed population to emergency responders and decision makers in the first phases after a disaster, see also (Boyd, 2006). The use of such models in these circumstances could improve the reliability of the overall consequence estimate. In addition, vulnerable locations, e.g. near breaches and in deep parts of the exposed area, could be identified in order to prioritise emergency operations. Further development and utilisation of the proposed method for disaster management is recommended.

Application to other types of floods

A method has been proposed to estimate the loss of life caused by large-scale floods of low-lying areas due to failure of flood defences. For this type of flood, three typical hazard zones have been distinguished and the most relevant flood characteristics are included in the model. The method is not directly applicable to floods that show distinctly different flood patterns. For example, for dam break floods and tsunamis, the effects of flow velocities will be more important throughout the whole exposed area. However, the principles proposed above can be applicable to other types of floods, such as dam break floods, tsunamis and drainage floods. For these types of floods the decisive variables that determine the loss of life and the typical hazard zones will have to be analysed, preferably based on historical data. Part of the findings from this study might be more broadly applicable to other types of floods. For example flash floods may show some similarities in flood pattern and resulting mortality with the zone with rapidly rising waters. Some other findings may be transferable between flood events, e.g. information regarding the vulnerability of buildings to certain flood conditions. Based on the available empirical data for different flood types (tsunamis, storm surges) it might be possible to develop a generic model for building vulnerability that can be used for different flood types.

8 Case study: Preliminary analysis of loss of life caused by the flooding of New Orleans after hurricane Katrina

The first parts of this section were written in cooperation with Ezra Boyd (LSU Hurricane Center). Bob Maaskant (TU Delft) contributed to the analysis of the data.

Research questions: Which factors determined the loss of life caused by the flooding of New Orleans after hurricane Katrina? What was the relationship between flood characteristics and mortality?

Keywords: Loss of life, flooding, New Orleans, hurricane Katrina, mortality

8.1 Introduction

In late August 2005, the New Orleans metropolitan area suffered the destructive power of hurricane Katrina. Large parts of the city flooded. This section aims at the presentation and first interpretation of the available data regarding Katrina related fatalities for Louisiana, with specific emphasis on the fatalities associated with the flooding of New Orleans. The information and analyses in this section are intended to:

- Indicate the impact of hurricane Katrina in Louisiana in terms of loss of life;
- Provide a presentation of causes and circumstances of Katrina related fatalities in Louisiana;
- Provide a preliminary analysis of the relationship between mortality[1] and flood characteristics for the flooded parts of New Orleans.

Data regarding loss of life for other states affected by Katrina is not discussed in detail here. MMWR (2006a; pp.239-242) provides a review of mortality for the states Florida (14 fatalities) and Alabama (15 fatalities). Currently, it is estimated in press reports that more than 230 fatalities occurred in Mississippi, but no official list of victims is available.

This study focuses on loss of life. Several sources provide comprehensive discussions of other types of consequences, such as economic losses (RMS, 2005; Brinkmann and Ragas, 2006; DHS, 2006; IPET, 2006; Kok *et al.*, 2006; LACPR, 2006a), physical and mental health impacts (Bourque *et al.*, 2006; MMWR, 2006a; MMWR, 2006b; Sullivent *et al.*, 2006) and pollution from industrial and household chemicals that mixed with floodwaters (Pardue *et al.*, 2005; Presley *et al.*, 2006; Reible *et al.*, 2006). A general analysis of different types of consequences is given in the report of the Interagency Performance Evaluation Taskforce (IPET, 2006).

The outline of this section is as follows. Section 8.2 presents general information regarding hurricane Katrina and related processes, such as the floods, the evacuation and the search and rescue operations, that are important to understand the context of the fatalities. Section 8.3 reports the results of flood simulations that give insight in the flood characteristics. The following section (8.4) provides an overview of the available information regard-

1 Mortality is defined as the number of fatalities divided by the number of people exposed, see section 2.

ing Katrina related fatalities. Characteristics and circumstances of fatalities are evaluated in section 8.5. Section 8.6 describes predictions of the number of fatalities after Katrina and the hindcast of the death toll with the method that has been proposed in section 7 of this thesis. The relationship between flood characteristics and mortality is analysed in section 8.7. Concluding remarks are discussed in section 8.8.

8.2 General information regarding hurricane Katrina

This section gives a general description of hurricane Katrina, mainly focusing on the New Orleans area and issues most relevant for the analysis of loss of life. Several other studies give a more comprehensive description of the characteristics of hurricane Katrina, e.g. (Knabb *et al.* 2006), and the performance of the flood protection system (IPET, 2006; Seed *et al.*, 2005, 2006; van Heerden *et al.*, 2006).

8.2.1 General situation and past studies

New Orleans is situated in the delta of the Mississippi river. The city and its surrounding suburbs make up a metropolitan area that is largely below sea level and entirely surrounded by levees (synonyms: flood defences or dikes). Therefore the area has a so-called 'polder'[2], 'bowl' or 'bathtub' character. As a consequence of its geographical situation, the area is vulnerable to flooding from hurricanes, high discharges of the Mississippi river and heavy rains.

Figure 8-1: Location of the city of New Orleans

2 Polder: relatively low-lying area protected from flooding by flood defences such as dikes. Drainage systems are needed to discharge rainwater from the polder and to prevent rise of the groundwater table

The possibility of a major storm surge flood disaster in New Orleans was already known long before hurricane Katrina formed. In the 20th century the city experienced floods after hurricanes in 1915, 1947 and 1965 (hurricane Betsy).

Numerous publications have reported the threats associated with hurricanes. In June 2002, the *Times-Picayune* newspaper published a five part series entitled "Washing Away." This series of articles claims that as many as 200.000 residents of the area would not be able to evacuate and that "between 25.000 and 100.000 people would die" (Schleifstein, 2002). One year before Hurricane Katrina, a joint federal, state, and local planning exercise looked at fictitious Hurricane Pam scenario: A slow moving category 3 hurricane passes just West of New Orleans with a 20 ft (~6,5m) storm surge that overtops levees and inundates the entire city. In this scenario, search and rescue crews would have to conduct over 22.000 boat and helicopter missions, 1,1 million people would experience long-term displacement, nearly 400.000 suffer injury or illness and over 60.000 people perish (IEM, 2004).

8.2.2 General characteristics of hurricane Katrina.

Hurricane Katrina formed as a tropical storm in the Atlantic Ocean South East of Florida. On August 25 2005 Katrina made landfall near Miami, Florida, as a Category 1 hurricane on the Saffir-Simpson scale. In Florida it resulted in 14 fatalities (MMWR, 2006a). The storm weakened slightly as it crossed Florida and entered the Gulf of Mexico on August 26 as a tropical storm. Katrina quickly regained hurricane status and it began to take aim for Southeast Louisiana, see figure 8-2. Between 26 and 28 August the storm initially strengthened to a category 5 storm. Before making its second landfall near Buras, Louisiana, it weakened to a category 3 status with sustained winds of 125 mph (205 km/h).

Figure 8-2: Track of hurricane Katrina (source: Wikipedia; map from NASA; hurricane track from the U.S. National Hurricane Centre)

8.2.3 Preparation: evacuation, shelter in place

In the days before landfall, computer models predicted possible flooding of New Orleans. The first evacuation orders came early on Saturday (August 27) morning from the outlying coastal areas, such as Plaquemines and St. Bernard. Utilizing lessons learned one year earlier from Hurricane Ivan, state and local officials initiated the staged hurricane evacuation plan officially on Saturday. The next morning, shortly after Katrina was upgraded to Category 5 strength, Mayor Nagin issued a mandatory evacuation order for New Orleans. By the time storm conditions reached New Orleans, 430.000 vehicles had fled the metropolitan region using primary roads (Wolshon, 2006a; Wolshon *et al.,* 2006) with an estimated additional 10.000-30.000 using secondary roads. Based on these traffic counts, Wolshon (2006a, 2006b) estimates that 1,1 million people, or 80 to 90 percent of the population at risk in Southeast Louisiana, evacuated the area before the storm.

In addition to the evacuation of the general population, hurricane Katrina forced the nursing homes and hospitals in the region to quickly make hard decisions about who to evacuate and how. These challenges presented no easy solutions, as both evacuation and sheltering-in-place presented risks to nursing home and hospital patients. Among the area's nursing homes, 21 evacuated before the storm and 36 did not evacuate before the storm (Donchess, 2006). Local authorities set up various shelters in the city. In St. Bernard parish[3], two schools were offered as shelters. In Orleans parish, the Superdome and Convention Center were set up as shelters. Boyd (2006a) estimates that of the 72.000 people who remained the city after the evacuation an estimated 26.000 individuals sheltered in the Superdome, see also (Anon, 2005a), but in later estimates a number of 10.000 to 15.000 is used. Initially, the Superdome served it purpose as a shelter-of-late resort well. The problems that developed later mainly resulted from delays in the post-storm evacuation.

8.2.4 Impacts: levee breaches and flooding

During its final landfall on August 29, Katrina's storm surge caused massive flooding and devastation along a 170 mile (~ 270 km) stretch of the United States Gulf Coast. The entire coastline of the state Mississippi suffered massive destruction. The storm surge also caused massive overtopping and breaching of levees around New Orleans. The flooded area of the city basically consists of **three bowls**: the central part of the city (Orleans), New Orleans East and St. Bernard[4], see also figure 8-3. The first flooding of residential areas in greater New Orleans occurred almost two hours before the storm's landfall. Between 4:30am and 5:00am water was already rising in the Industrial Canal[5]. The waters flowed into the Orleans bowl to the west, and into the Orleans East bowl on the other side of the Industrial Canal. Later that morning more catastrophic breaching occurred along the southern arm of the Industrial Canal. Two major breaches in the floodwalls resulted in a rapidly rising and fast moving flood of the St. Bernard bowl with catastrophic consequences. Especially the neighbourhood the Lower 9th Ward, which was closest to the breach, was most severely affected. In the Orleans bowl the levees in the 17th street and London Avenue drainage canals failed, leading to flooding of a large part of the central area. The Orleans

3 Parish: administrative subdivision that is used in Louisiana. Note that the parish name does not always correspond to the name of the flooded 'bowl'. For example, Orleans parish covers the Orleans bowl, Orleans East bowl and a small part of the St. Bernard bowl.

4 It is noted that parts of the St. Bernard bowl are actually in Orleans parish. In the remainder of this section the concept of the bowl is used.

5 The official name of the Industrial Canal is the Inner Harbour Navigation Channel (IHNC).

East bowl flooded more gradually due to a number of smaller breaches and overtopping cases. An area of approximately 260km^2 of the city flooded, more than 4 metres deep at some locations. Figure 8-3 gives an overview of the flooded area and the locations of the levee breaches. It took over 40 days to dewater the city.

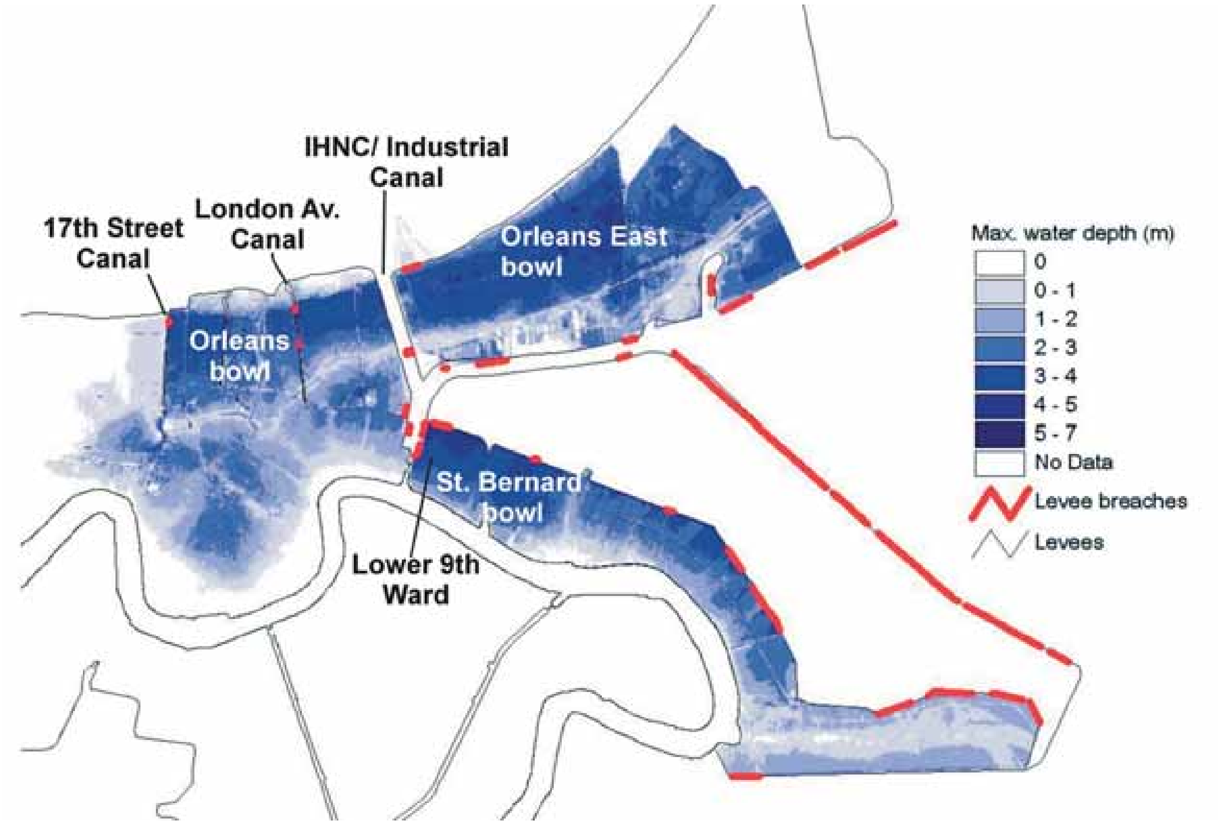


Figure 8-3: Overview of flooded area, levee breach locations and maximum water depths. Data are based on field observations and are provided by the LSU Hurricane Center (Ezra Boyd, Hampton Peele, Rob Cunningham, DeWitt Braud, G. Paul Kemp).

8.2.5 Aftermath: search and rescue operations

The flooding of large part of metropolitan New Orleans necessitated a massive urban search and rescue effort that involved numerous local, state, federal and private organizations. Individuals in peril had to be rescued from roofs and attics. Patients, staff, and family members had to be evacuated as hospitals and nursing homes flooded. In the five days that followed Hurricane Katrina, rescue workers completed an estimated 62.000 water, roof, and attic rescues by either boat or helicopter. Over 100 helicopters and 600 boats were utilized (LaOHSEP, 2006).

Reflecting their first priority to protect the lives of those trapped by the flood, search and rescue (S&R) teams initially transported people from attics and floodwaters to higher grounds, such as elevated highways and bridges. Following this immediate rescue, available ground transportation was used to bring people to the Superdome, the Convention Center, and the I- 10 Cloverleaf (LaCaze, 2006). The sheltering population at these locations continued to grow in the days that followed the hurricane. As the days passed before relief arrived, hunger, thirst, and desperation took hold. Finally, on Thursday, September 1, three days after Hurricane Katrina made landfall, buses began evacuating people from the Superdome. The evacuation of Convention Center began the next day. When the post-storm evacuation of New Orleans finished on September 4, an estimated 78.000 displaced persons had been relocated to shelters set-up across the nation (Select Bipartisan Committee, 2006). In the first phase that covered approximately 10 days, search and rescue operations focused on saving the living. After that the sad task of the recovery of the deceased began.

8.3 Simulation of flood characteristics

8.3.1 Introduction

Several organisations, including the Federal Emergency Management Agency (FEMA) and the Louisiana State University (LSU) Hurricane Center, have made floodmaps that provide insight in the water depths in the flooded parts of New Orleans, see for example figure 8-3. These maps have been made by combining terrain elevation data and information regarding the extent of the flooded area and water levels (Cunningham *et al.*, 2006). The size of the flooded area can be derived from aerial photography or satellite imagery. Water levels in the flooded area can also be identified based on watermarks on buildings, see figure 8-4 for an example. However, due to effects of the tide and pumping, multiple watermarks are visible and a uniform interpretation is often difficult.

Figure 8-4: Water marks on a building near the breach in the 17th Street Canal.

However, for an analysis of flood fatalities, other flood characteristics than water depth could be relevant as well. These include flow velocity, rise rate and arrival time of water (see section 5). These characteristics have not been observed in the field during the flood event. However, there might be some indirect and mostly qualitative evidence, such as eyewitness accounts that describe flood conditions and damage patterns that indicate the severity of local flow conditions (e.g. damage to buildings due to flow velocity). To gain more insight in these flood characteristics flood simulations have been made for the Orleans and St. Bernard bowls (De Bruijn, 2006; Maaskant, 2007). The results of these simulations have been used to analyse the relationship between the flood characteristics and mortality in section 8.7. In addition, the simulations could be useful for visualisation and communication of the course of flooding. They can provide valuable insights in the contribution of different sources (breaches) to the flood pattern.

8.3.2 Approach for the flood simulations

The following points summarise the approach used for flood simulations. De Bruijn (2006) and Maaskant (2007) give further background information:

- Flood simulations of overland flow have been made by means of a two dimensional hydraulic model, SOBEK-1D2D developed by WL| Delft Hydraulics.
- For terrain height a digital elevation model has made using data from USGS[6].
- Levee heights and breach locations are based on information provided by the LSU Hurricane Center. This information is based on observations in the field.
- In the flood simulation a terrain model has been used with a rectangular raster with grid cells of 28m x 28m.
- A uniform terrain roughness has been assumed in the simulation with a Manning value of 0,3m. This value is representative for rural terrain. The effects of single objects such as buildings on the roughness are not directly assessed, but it is assumed to be included in the average roughness.
- Only inflow through the main breaches has been considered. Overtopping of levees, the effects of rainfall, drainage canals and pumping have not been considered.
- Breach widths are based on descriptions by Seed *et al.* (2005, 2006) and (IPET, 2006). Based on these reports the growth rate of the breach has been estimated. Inflow discharges through breaches are determined based on the outside water levels reported in (IPET, 2006) and estimates of the development of the breach profile over time.
- Simulations have been made for the Orleans (De Bruijn, 2006) and St. Bernard (Maaskant, 2007) bowls. No simulations are available for Orleans East.

Given the above assumptions and limitations regarding the input data it is important to realize the limitations of these simulations. They give a first order insight in flood conditions in the affected area, but are not detailed or exact approximations of the flood flow conditions.

8.3.3 Results

Information on the water depth, flow velocity, rise rate and arrival time is obtained as output from the simulations. Figures 8-5 to 8-9 show the simulated water depth, velocity, depth-velocity product[7], rise rate[8] and arrival time of the water for the Orleans and St. Bernard bowls.

6 USGS: United States Geological Survey.

7 The depth velocity product is important for the analysis of the collapse of buildings and human instability in flood flow. It is related to the moment associated with the flow (see section 6.3 for further details).

8 According to the approach proposed in section 7.2 rise rate has been determined over the first 1,5m of water depth.

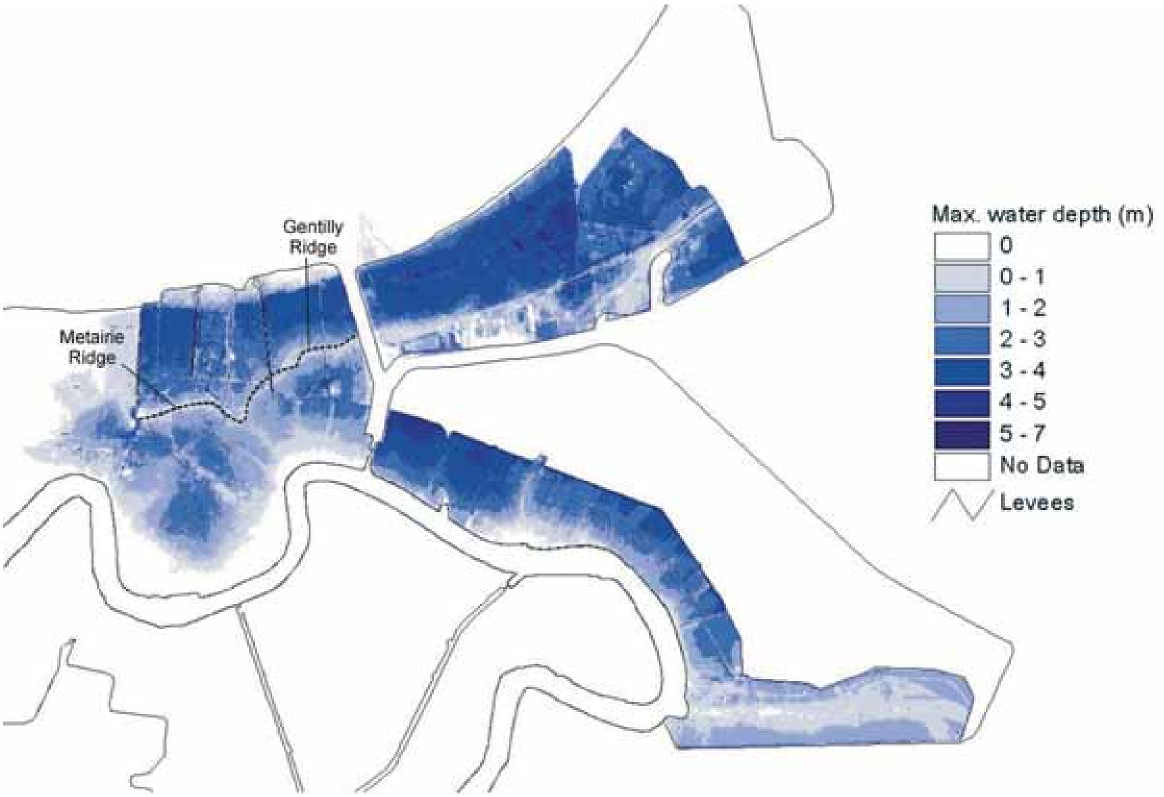


Figure 8-5: Maximum water depth. (For the Orleans and St. Bernard bowls it is obtained from simulations. Water depth for the Orleans East bowl is based on the flood depth map provided by the LSU Hurricane Center.)

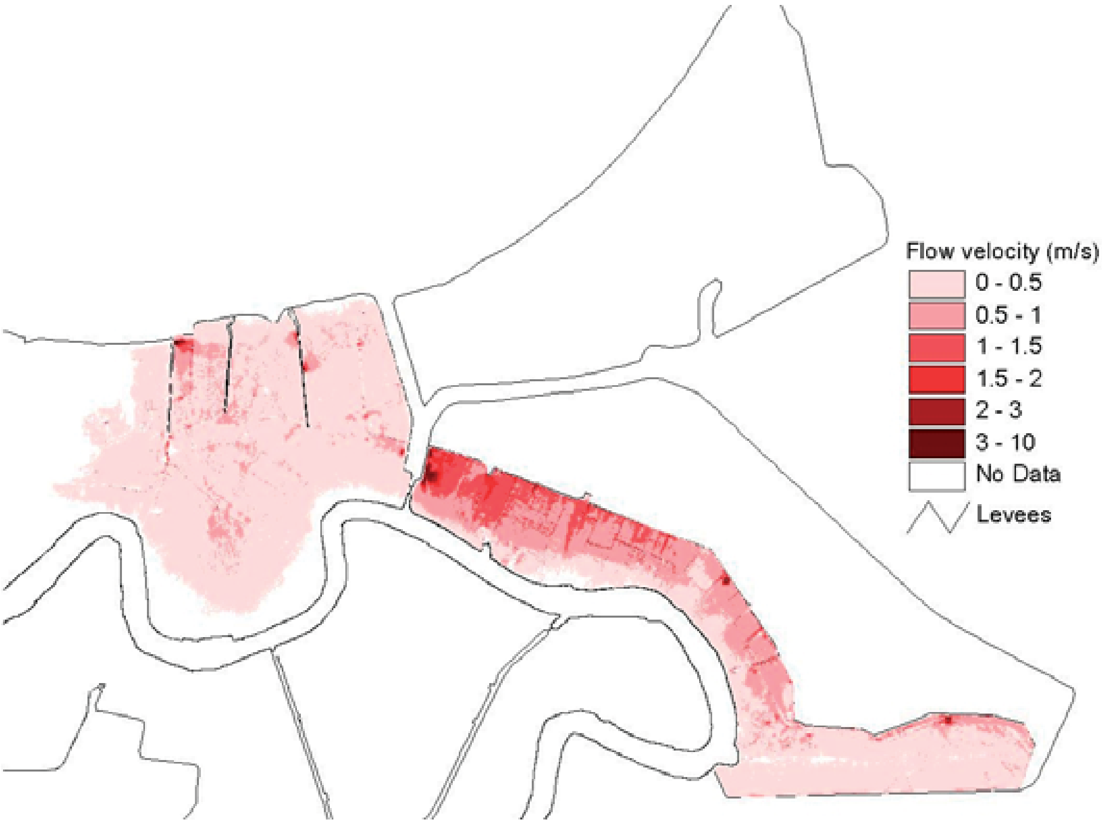


Figure 8-6: Maximum flow velocity for the Orleans and St. Bernard bowls

Figure 8-7: Product of maximum water depth and maximum flow velocity (*hv*) for the Orleans and St. Bernard bowls. (Note: These results are conservative as maximum values of depth and velocity need not have occurred simultaneously, i.e. $h_{max}v_{max} > (hv)_{max}$)

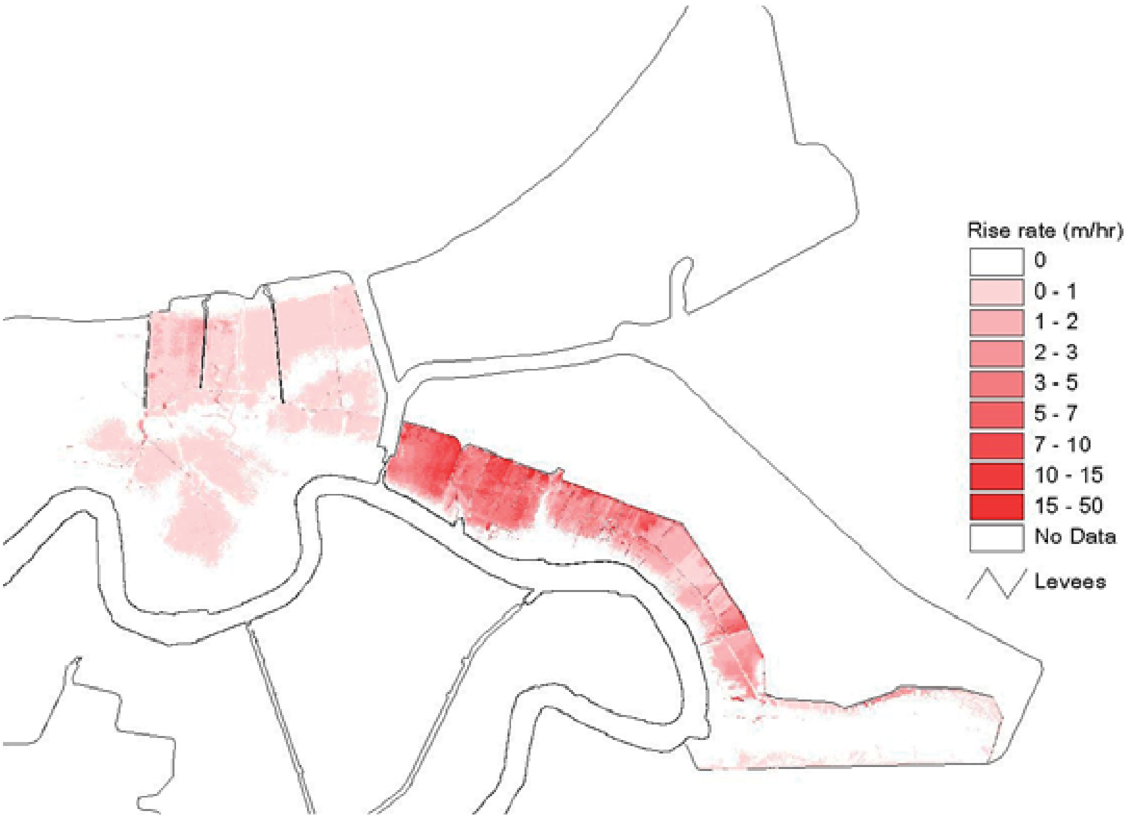


Figure 8-8: Simulated rise rate for the Orleans and St. Bernard bowls over the first 1,5m of water depth.

Figure 8-9: Simulated arrival time of the water for the Orleans and St. Bernard bowls after the initial breaches.

The simulations show that the most severe conditions occurred in the St. Bernard bowl. Very high flow velocities (3 to 10 m/s) occurred near the catastrophic breaches in the levees along the Industrial Canal. These effects caused destruction in the Lower 9th Ward (see also section 8.7). Depths in St. Bernard reached 3 to 4 metres in the deepest parts and rise rates were high (> 5 m/hr) for most of the area.

The Orleans bowl also suffered large water depths. In some locations (especially in the Lakefront area) the water depth was more than 5 metres. However, the flow velocities and rise rates were lower than in St. Bernard. Based on the simulations it is estimated that in the Orleans bowl the flow velocities were high (larger than 1 m/s to 2 m/s) only very near the breaches. For most of the area rise rates were relatively small. The highest rise rates in this area (1 to 2 m/hr) occurred in the northern part. Most of the Orleans bowl flooded within a day. In the middle of the Orleans bowl there are the Gentilly and Metairie ridges that blocked the flow from north to south for some period. These are indicated in figure 8-5 with dashed lines.

The results of the simulations have been verified with available information regarding flood characteristics. Comparison with the flood depth maps provided by LSU Hurricane Center shows that the flood depth is approximated well. Calculated arrival times of the water flow are compared with eyewitness descriptions (IPET, 2006) and these show reasonable agreement. De Bruijn (2006) and Maaskant (2007) discuss further details regarding the validation of the simulations.

8.4 Data regarding Katrina related fatalities

8.4.1 Dataset of deceased victims

In the period after Katrina deceased victims (fatalities) were recovered in a search process which involved governmental and private organisations. The buildings that were searched by rescue teams were marked by a sign that indicated the date and outcomes of the search operation, see figure 8-10. For each victim that was recovered there exists a "receipt of remains". This form includes basic information such as the date, time, and location of recovery along with the agency that recovered and the agency that transported the remains. It also includes some basic comments about the scene and sometimes lists a presumptive identification of the victim.

Figure 8-10: Signs on a home indicating the outcomes of a search operation.

The Department of Health and Hospitals (DHH) of the state Louisiana coordinated the data collection. This agency also provides the official figures on dead and missing on their "Katrina Missing" website[9]. As of August 2, 2006 this site listed **1464 deceased victims** and it is noted that the cases of an additional 135 missing have been turned over to law enforcement. Of the confirmed dead, **1118 victims perished within Louisiana**, while 346 victims perished outside of the state of Louisiana. Statistics regarding ethnicity, age and gender have been made public for 853 of the Louisiana fatalities identified at the St. Gabriel and Carville morgues, see section 8.5.1 for a further discussion.

8.4.2 Dataset of recovery locations

The LSU Hurricane Center established a collaborative effort with the Department of Health and Hospitals (DHH) and the Medical Examiner's office of the state of Louisiana. As part of this collaboration, DHH provided the LSU Hurricane Center with data on the recovery locations for the deceased victims (Boyd, 2006c). The most recent dataset, obtained on September 14, 2006, lists **771 fatalities with recovery locations** in the state of Louisiana**.** This corresponds to 69% of the victims recovered within the state. The recovery

9 http://www.dhh.louisiana.gov/offices/page.asp?ID=192&Detail=5248, accessed December 2006.

locations have been geocoded, i.e. the locations have been identified on a map and entered into a GIS layer.

The obtained dataset of recovery locations is based on the information from the receipts of remains. However, a number of these forms lack complete information, limiting the ability to map all the recovery locations. The dataset used in this section has been supplied by LSU Hurricane Center and it includes the following information: date of recovery, recovery location (Geographical coordinates, state, parish), type of facility in which the body was found and information regarding the organisations that performed recovery and transportation. Each entry in the dataset describes the recovery of one victim. In some cases, multiple victims are recovered from one location. The recovery locations dataset has been used for further analysis of the spatial distribution of the recoveries (section 8.5.3) and the relationship between flood characteristics and mortality (section 8.7).

8.4.3 Brief discussion of available data regarding Katrina related fatalities

Several issues are associated with the interpretation and analysis of the data:

- At the time of this analysis (December 2006, more than one year after the storm) the total list of deceased victims is still incomplete. Still 135 people are still missing and sporadically remains of people are found in collapsed buildings and more remote areas, such as the marshes.
- A broad operational definition has been used for a Katrina related fatality. It concerns anyone from the affected areas that died between August 28 and October 1 2005 for which the circumstances of death can be linked to hurricane Katrina (E.Boyd, personal communication).
- The recovery location of a body does not necessarily equal the location of death. Bodies could have been moved by the flood flow or by other people before final recovery. This is most relevant for recoveries in the open field[10]. A limited number of bodies has been recovered along the edge of the flood zone, possibly indicating that they have been moved by the flood. In further analysis it is assumed that the recovery location is identical to the location of the fatality.

Given these issues it is emphasized that the datasets used in this study are preliminary and not fully complete. Nevertheless it is expected that the datasets give a representative impression of loss of life caused by hurricane Katrina. Firstly, the majority of recoveries has been completed and the final number of fatalities is not expected to grow substantially. Secondly, the dataset includes the majority of recoveries inside the flooded areas and it is therefore expected that it gives a good insight in the spatial distribution of fatalities and the mortality in these areas. Overall, the recovery data includes more than two thirds of the officially reported number of fatalities in the state Louisiana. It is noted that the missing data is from specific areas (mainly non-flooded parishes) and a more complete dataset is required to draw final conclusions.

10 Analysis (reported in section 8.5.2) shows that a relatively limited parts of the recoveries (7%) were in the open field. Most of the fatalities were found in buildings, such as homes and hospitals. For these recoveries it is most likely that the recovery location equals the location of death.

8.5 Causes and circumstances of Katrina related fatalities

8.5.1 Individual characteristics of fatalities

Based on the dataset of deceased victims, the characteristics of Katrina related fatalities, such as age, gender and race are discussed. Data are available for 853 Katrina related fatalities. Information regarding other potentially important factors, such as medical cause of death, activity and behaviour during the hurricane impact, was not available.

Age

The age distribution of fatalities is given for 829 fatalities and is presented in figure 8-11. Age is unknown for 24 fatalities. The majority of victims were elderly. Out of 829 victims of whom age is known, less than one percent were children and just over fifteen percent were under 51. Older people comprise the majority of the deceased: nearly 85% are older than 51 years, 70% are over 60, and almost half are older than 75 years of age. Population statistics for Orleans and St. Bernard parish[11] show that of the pre-Katrina population about 25% were older than 50 (12% older than 65; 6% older than 75).

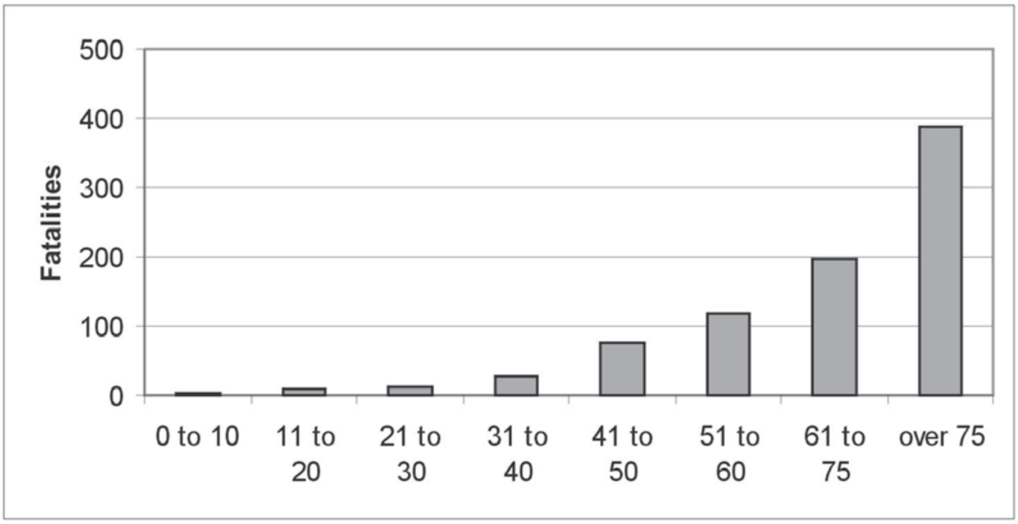


Figure 8-11: Age distribution of 829 fatalities

Gender

The available data do not indicate that gender played a dominant role in Katrina related mortality in Louisiana. For the 853 victims for which gender is known, 432 (50,6%) are male and 421 (49,4%) are female. While males are slightly over represented, this break down mostly corresponds with the gender distribution of the affected population.

Race

Of 818 fatalities for which race is listed, 451 (55%) are African American and 334 (40%) are Caucasian (white). Of the others, 18 (2%) victims are listed as Hispanic, 6 (1%) are listed as Asian-Pacific, 4 (<1%) are listed as Native American, and 5 (< 1%) are listed as Other. The race of 35 (5%) victims was unknown. In general terms this distribution corresponds to the racial distribution of the affected population. The results do not directly sup-

11 Data source: Greater New Orleans community data center, http://www.gnocdc.org/, accessed December 2006

port claims that African Americans were more likely to become a fatality, see e.g. (Sharkey, 2006). However, further investigation of the influence of race on Katrina related mortality is recommended.

8.5.2 Type of location where victims were recovered

The dataset of recovery locations provides information regarding the type of location where the body was recovered for 766 victims (for 5 recoveries the location type is unknown), see table 8-1. The majority of victims (53%) were recovered from individual residences. Ongoing fieldwork shows that many of the residential recovery locations were single story homes that were either not elevated or elevated less than three feet. Medical locations, such as hospitals and medical centers, comprise 147 (20%) of the recovery locations and nursing homes make up 76 (10%) of the recovery locations. 54 (7%) victims were recovered from open street locations. 26 (3%) victims were recovered from public shelters, 18 from the Convention Center and 8 from the Superdome. These latter two facilities served as shelters of last resort for tens of thousands of people before, during, and after the storm. 20 (3%) victims were recovered from commercial and public buildings, such as churches and schools.

Table 8-1: Recovered victims from the dataset of recovery locations by location type

Location type	Fatalities	%
Residence	404	54%
Medical	147	20%
Nursing home	76	10%
Open / street	54	7%
Morgue / coroner's office / funeral home	39	5%
Public shelter	26	3%
Public building	20	3%
Total	746	

8.5.3 Spatial distribution of recoveries

The dataset of recovery locations contains information of 771 victims. The majority of victims were recovered from parishes that suffered the direct flood impacts of Katrina, such as Orleans and St. Bernard parishes. In addition, a substantial number of fatalities occurred in parishes that did not suffer the direct impact of Katrina. In total 147 fatalities were found outside the flooded area. These fatalities were mostly evacuees and hospital patients transported from the affected area (see next section for a further discussion).

Figure 8-12 gives an overview of the spatial distribution of recoveries in and near the flooded parts of New Orleans. A distinction is made between two categories of fatalities:

1) Recoveries from residential locations such as residences, nursing homes, street locations and public buildings. In these facilities fatalities can often be directly related to the flood effects. In most cases these recoveries concerned residents of the area in which the recovery took place.
2) Recoveries from medical locations, shelters and morgues / funeral homes. These recovery locations indicate that these fatalities were not directly related to the impacts of floodwaters. For example, while the Superdome was inside the flood zone, the raised sections of this facility protected those sheltering from floodwaters. Similarly,

for hospitals in the flooded areas the ground floors were evacuated as part of storm preparations. Fatalities at these locations were often not part of the original population in the area where the recovery took place.

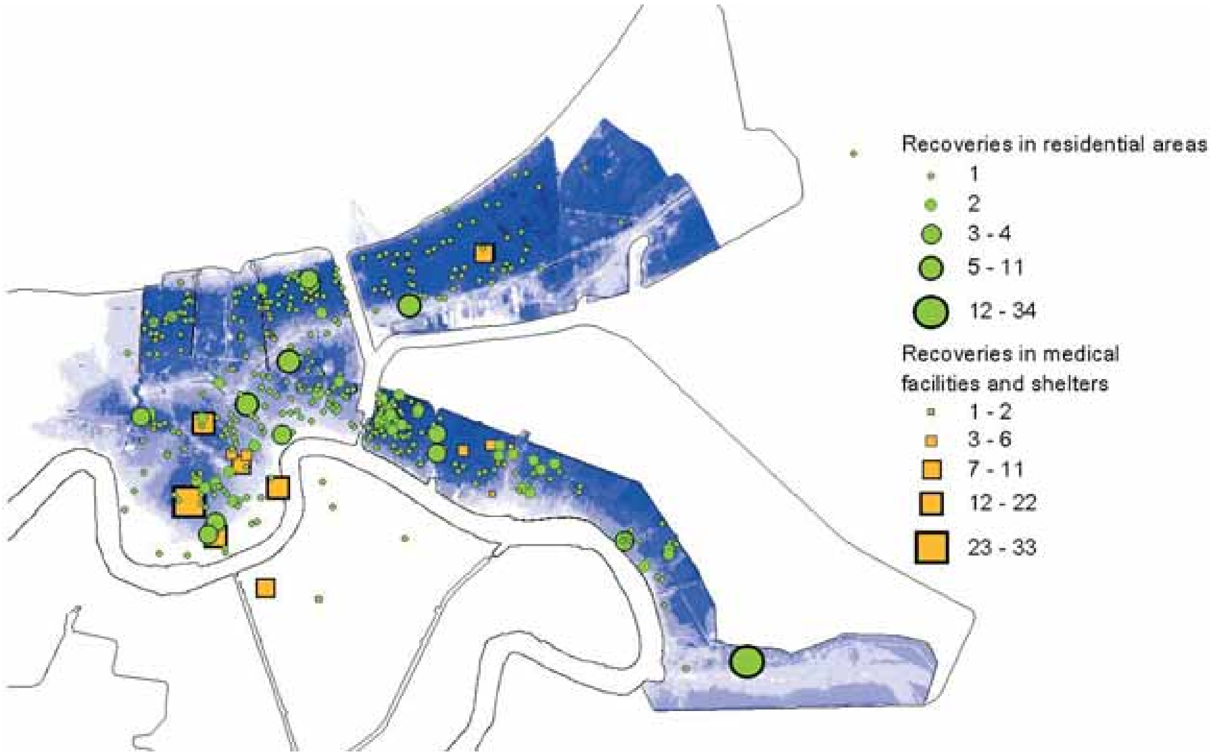


Figure 8-12: Recovery locations (source: Boyd, 2006c) and flooded area.

8.5.4 Causes and circumstances of Katrina related fatalities

A first discussion of the causes and circumstances of different groups of fatalities is presented below. It is based on the available information that has been described in the previous sections. As no data was available for a substantial number of fatalities in the state of Louisiana (31%) the findings and discussions are preliminary and not necessarily fully representative for all fatalities in Louisiana[12].

Of the 771 recovered fatalities, 147 (19%) occurred outside the flooded area in Louisiana. Most fatalities were evacuees and their occurrence is likely related to the adverse public health situation that affected those that evacuated as a result of hurricane Katrina. Likely death causes include lack of necessary medical services, chronic conditions, stress induced heart attacks or strokes, violence and suicide (see also MMWR, 2006b).

In total 624 of the 771 recovered fatalities (81%) occurred inside the flooded area. Of these, 106 were recovered from locations, such as public shelters and hospitals, that indicate that these fatalities were not directly related to the impacts of floodwaters. Most of these fatalities, about 90, occurred in hospitals. For this group of fatalities death causes are likely similar to those who died outside the flooded area, i.e. lack of necessary medical services, chronic conditions, stress induced heart attacks or strokes, violence and possibly

12 This point is emphasized here, because the missing fatality data mainly concerns fatalities from parishes outside of the flooded area (Ezra Boyd, personal communication). This implies that the estimated fraction of the total number fatalities that occurred in the flooded area could be an overestimation.

suicide. Several sources document the critical public health conditions that developed in medical facilities, see e.g (Delacroix, 2005; Berger, 2006).

This leaves 518 recovered fatalities (67% of the total recoveries) that most likely resulted from the direct exposure to the physical impacts of the flood. Typical death causes for people exposed to the floodwaters include drowning (in a building or in the street) or physical trauma due to the impacts from debris and / or building collapse, see also (Jonkman and Kelman, 2005). Many of these fatalities occurred in areas near large breaches in the Lower 9th Ward in the St. Bernard bowl. Another substantial part of the fatalities occurred in the northern part of the Orleans bowl, where large water depths occurred. The relationship between flood characteristics and mortality is further investigated in the next section. Available data indicate that a substantial number of victims (at least more than 20) were recovered from residences inside the flooded areas from attics or floors that were not flooded. This suggests that these people died due to adverse conditions associated with extended exposure in the flooded area in the days after Katrina. Typical death causes could include dehydratation / heat stroke, heart attack/ stroke, or other causes associated with lack of sustaining medical supplies. Initially thought to be a major threat to those remaining in the flooded area, disease and toxic contamination do not appear to explain many of the deaths.

Analysis of individual characteristics of victims showed that the majority of victims were elderly: nearly 85% of fatalities were over 51 years. Members of this population are the most likely to need assistance to evacuate before the storm and are the least capable to survive the physical hazards of the flood (e.g. by moving to higher floors or shelters), the delays before being rescued and the deterioration of basic public health services both inside and outside flooded area. The specific vulnerability of this group is sadly illustrated by the large numbers of fatalities in nursing homes in the flooded area, where 65 fatalities occurred in total. Thirty-one victims were recovered from St. Rita's nursing home in the south-eastern part of St. Bernard. Another factor that could have contributed to the large number of older fatalities in residential areas is that elderly might be less able or willing to evacuate before a hurricane. A past survey (Hurlbert and Beggs, 2004) indicated that there is a slight decline in the evacuation rate with age. However, no direct information is available for evacuation rates amongst different age groups for Katrina.

The above outcomes concerning the causes and circumstances of fatalities can be compared with earlier findings. Jonkman and Kelman (2005) showed that, for small-scale river floods in Europe and the United States, males are highly vulnerable to dying in floods and that unnecessary risk-taking behaviour contributes significantly to mortality. In addition, that study did not indicate that elderly were more vulnerable. The individual characteristics of Katrina related fatalities are different and likely characteristic for large-scale and more unexpected flooding. During such events survival chances will be related to individual endurance, which is generally less for elderly. In that respect the outcomes for Katrina are comparable with characteristics of the fatalities for the 1953 flood in the Netherlands (see section 5.4.1). This event also exhibited an equal distribution of fatalities over the genders and a higher vulnerability of elderly.

Further cross-analysis of individual characteristics, death causes and spatial patterns in fatality rates is recommended to gain more insight in the causes of death in different affected regions. Information regarding social factors (income, poverty, ethnicity) could be added in the analysis to gain more insight in the effects of social vulnerability factors.

8.6 Prediction and hindcast of the number of fatalities

8.6.1 Estimates of loss of life before and shortly after hurricane Katrina

This section gives a brief overview of the estimates of the loss of life due to the flooding of New Orleans before and in the first period after hurricane Katrina, see also (Reichhardt, 2005).

In the year before Katrina a large exercise was performed for a fictitious hurricane scenario named Pam that would flood the entire metropolitan area of New Orleans. The contractor IEM (2004) estimated that 60.000 people would die, most of them in New Orleans. The method that was used to obtain this estimate has not been reported publicly and it is expected that this estimate is based on expert judgment.

In the first days and weeks after the flooding of New Orleans due to hurricane Katrina there was a lot of uncertainty about the number of fatalities. In the first week after Katrina a researcher from LSU Hurricane Center estimated several thousands of fatalities due to the flooding of New Orleans. Prof. Vrijling (Delft University) used the 1% rule of thumb proposed in section 5.2.3 of this thesis. Applied to an estimated exposed population of 500.000 this resulted in 5000 estimated fatalities. If the information regarding the number of evacuated (unknown at that time) would have been taken into account (80% of the population), application of the rule of thumb would have resulted in 1000 fatalities which is very near the actual number. About two weeks after the flood a press source reported that FEMA had ordered 25.000 body bags for hurricane victims (Anon, 2005b).

8.6.2 Hindcast of the loss of life using the method proposed in this thesis

The method proposed in section 7 has been used to give an estimate in retrospect (a so-called hindcast) of the number of fatalities. The number of fatalities has been estimated based on the output of flood simulations, information regarding the population distribution and the mortality functions proposed in section 7. Results of flood simulations are available for the Orleans and St. Bernard bowls. The water depth and rise rate are averaged by tract (see also figure 8-13). When the rise rate exceeded the threshold of 0,5 m/hr the mortality function for the zone with rapidly rising waters has been used. For the New Orleans East bowl a rise rate value below this threshold value has been assumed.

Consequently the number of fatalities is determined by tract based on the exposed population in that area. It is assumed 10% of the original population was exposed to the flood effects, as 80% was evacuated and 10% found shelter in the area (see further discussion regarding this estimate in section 8.7). Based on the output of the flood simulations estimates of the numbers of fatalities near breaches have been determined[13].

Table 8-2 gives an overview of the observed and calculated numbers of fatalities for the three bowls. The applied method gives an estimate of the fatalities due to direct flood impacts. Therefore the observed fatalities in hospitals, shelters have not been included in the comparison.

Table 8-2: Observed and calculated numbers of fatalities.

Bowl	People exposed	Observed nr. of fatalities*	Calculated number of fatalities with the method from section 7			
			Total	Breach zone	Zone with rapidly rising water	Remaining zone
Orleans	25.590	260	268	10	143	115
St. Bernard	8540	190	651	131	517	3
New Orleans East	9620	68	83	0	0	83
Total flooded area	43.750	518	1002			

*: This column includes the number of recovered people in residential locations. Fatalities in special facilities, such as hospitals and shelters are not included as these are expected not to be related to flood characteristics. Reported numbers are preliminary.

Overall, the total number of fatalities that is predicted with the method proposed in section 7 is within a factor two with the observed number of recoveries so far. The total numbers of fatalities for the Orleans and Orleans East bowls are approximated well. The spatial distribution of fatalities in these bowls does not fully correspond to the observations[14]. The number of fatalities in the St. Bernard bowl is overestimated by more than a factor 3, because the numbers of fatalities in areas with higher rise rates (w>0,5m/hr) are overestimated with functions proposed in section 7. Further discussion on the influence of the different flood characteristics on mortality is included in the next section.

8.7 Analysis of the relationship between flood characteristics and mortality for New Orleans

8.7.1 General approach

Mortality functions have been derived in section 7 based on data for historical flood events. Below, the relationship between flood characteristics and mortality is investigated further based on the available data for New Orleans.

Fatalities

Information regarding fatalities from the dataset of recovery locations has been used. The analysis only includes the fatalities in the flooded area that are expected to be directly associated with the flood conditions[15], i.e. the recoveries in residential locations. Fatalities in

13 It has been determined in which areas the conditions for the breach zone are exceeded: $hv \geq 7m^2/s$ and $v \geq 2m/s$ This is only the case in areas near the 17th Street canal Breach (for a small area) and in the Lower 9th Ward, see figure 8-7. Based on the relative size of the breach area to the tract area it has been estimated how many people were exposed in the breach zone, while assuming a homogeneous population density in the tract. It has been assumed that none of the exposed people in the breach zone survives, i.e. F_D=1.

14 The calculated numbers of fatalities are over-estimated in areas with higher rise rates (w>0,5m/hr) and under-estimated in areas with lower rise rates.

15 A limited number of fatalities in the flooded area might be caused by wind effects. However, it is expected that the number of wind fatalities will be limited as a) most people found shelter during the passage of the storm; b) storms in the

medical locations and shelters are not included in the analysis because these are generally not directly related to the physical flood impacts (see also section 8.5.3). It is noted that the recovery dataset includes 69% of the total number of fatalities reported in the state Louisiana. Although most of the missing fatality data concerns fatalities from parishes outside of the flooded area, the reported mortality fractions could still be under-estimates of the eventual mortality fractions in the flood zone.

Exposed population

The population at risk is defined as the original population in the area prior to hurricane Katrina. Data from the United States Census 2000 have been used to determine the population at risk. Due to the effects of evacuation and shelter the number of exposed was reduced before the hurricane. Based on the analysis of traffic counts it is estimated 80 to 90 percent of the 'at risk' population in Southeast Louisiana evacuated the area before the storm (Wolshon, 2006a, 2006b). In this study we assume an evacuation rate of 80% for New Orleans (a number that was also stated by the mayor of New Orleans, Ray Nagin). In addition, based on available descriptions, it is assumed that another 10% found shelter in special facilities, such as the Superdome and Convention Center[16]. This results in an estimate of the exposed population in the flooded area of approximately 10% of the inhabitants, corresponding to approximately 44.000 people exposed (see also table 8-3). In this analysis it is assumed that the spatial distributions of the evacuated and shelter fractions are uniform. In practice there might have been differences in evacuation rates between neighbourhoods, but no information regarding the Katrina evacuation is available[17]. Overall, the above estimates are crude, but necessary given the limited amount of data.

Table 8-3 summarizes the number of exposed, fatalities and mortality rates for the three bowls of New Orleans. For all the three bowls the average mortality fractions are in the order of magnitude of 1%. As will be discussed further below, differences in mortality between these bowls are likely related to the severity of the flood impacts.

Table 8-3: Overview of number of inhabitants, exposed and fatalities for the three flooded bowls.

Bowl	Inhabitants (flooded area)	Exposed	Recovered nr. of fatalities*	Mortality
Orleans	255.860	25.590	260	1,02%
St. Bernard	85.420	8540	190	2,22%
New Orleans East	96.290	9620	68	0,71%
Total	437.570	43.750	518	1,18%

*: This column includes the number of recovered people in residential locations. Fatalities in special facilities, such as hospitals and shelters are not included as these are expected not to be related to flood characteristics. Reported numbers are preliminary.

past with comparable strength and no flooding have caused much less fatalities. For example, hurricane Betsy (1965) and hurricane Frederic (1979) occurred in the same area and were of similar strength (category 3). The numbers of fatalities for these storms are considerably smaller than for Katrina. Betsy caused 76 fatalities (of which a substantial part due to local flooding) and Frederic caused 5 fatalities (FEMA, 2006; pp.1-28).

16 Boyd (2006a) estimates that 72.000 people remained in the city after evacuation. This corresponds to approximately 18% of the initial population of the flooded areas. He also mentions that 26,000 people (6,3% of the population in flooded areas) found shelter in the Superdome, see also (Anon, 2005b). The estimate of a shelter percentage of 10% results when additional populations in other shelters are also included. It is noted that later estimates (mainly) in press sources give lower estimates of the sheltered population in the Superdome, so the above numbers have to be considered as preliminary.

17 A survey before Katrina (Hurlbert and Beggs, 2004) indicated differences in evacuation rates between social groups. These might relate to neighbourhoods.

Analysis of the relationship between flood characteristics and mortality

Using the approach proposed in section 7.4.1 it is investigated whether mortality can be related to flood characteristics. The dataset that has been used is included in appendix 8.I. The influence of the factors water depth, rise rate, flow velocity and arrival time of the flow has been analysed, as these are expected to be important determinants of loss of life (see also section 5). The results from the flood simulations have been used as values for flood characteristics. Another factor of relevance is the collapse of buildings. This has been analysed mainly qualitatively, using a map that indicates the level of structural damage to buildings. It is based on FEMA damage inspection reports and included in appendix 8.II. The influence of other potentially relevant factors, such as the effects of waves, the local level of warning, etc. has not been examined due to lack of data.

To analyse the relationship between mortality and flood characteristics it is necessary to distinguish different locations in the flooded area. Using existing spatial subdivisions of the city, different spatial aggregation levels of analysis can be chosen, see figure 8-13. If the spatial unit is too small the number of locations will be large relative to the number of fatalities. Then there will be many locations without fatalities and the randomness in the occurrence of fatalities will become important. If the chosen spatial unit is too large then it is no longer correct to assume constant flood conditions in one spatial unit, because spatial variations become too large. Given these considerations the neighbourhoods and tracts seem most suitable as spatial units and both are analysed below.

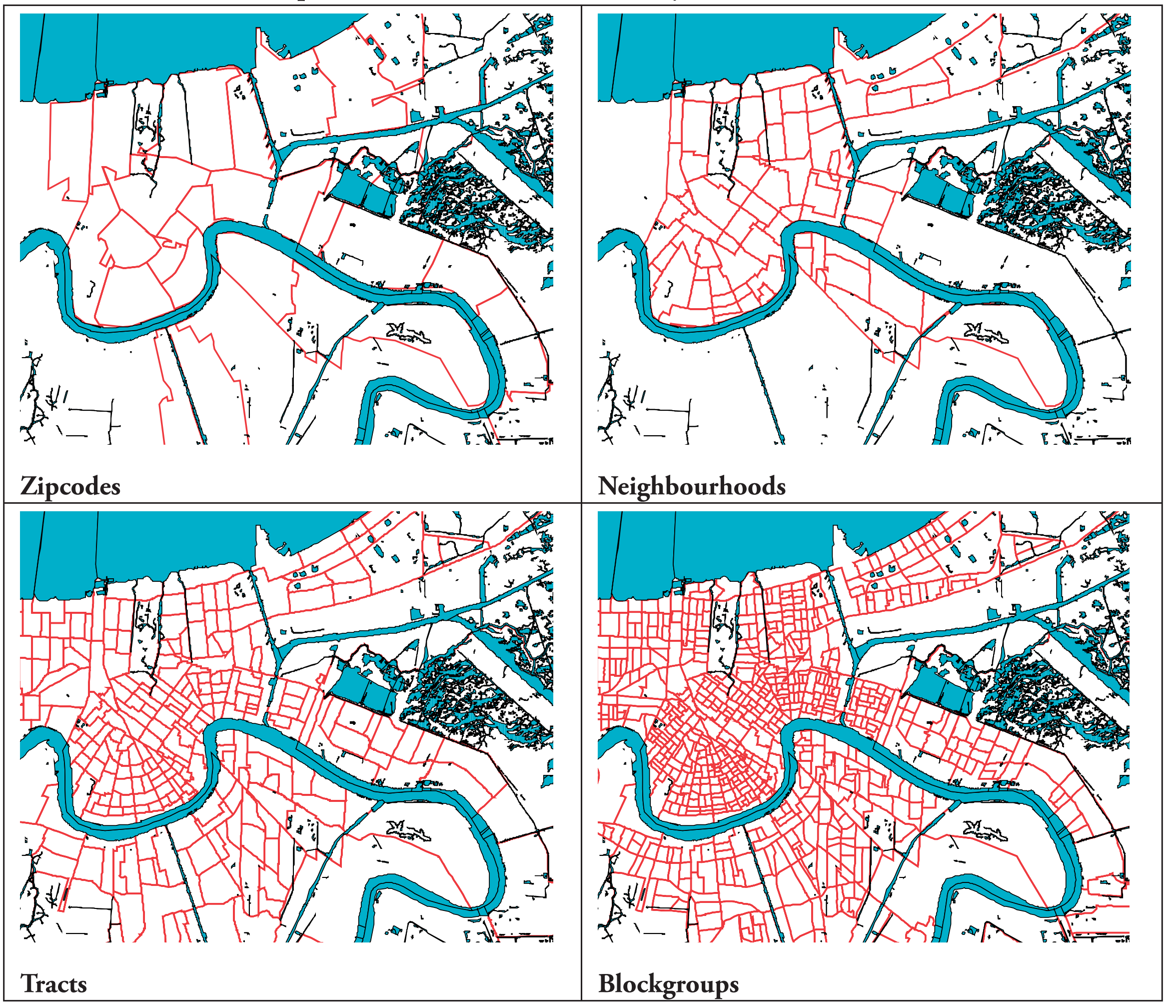


Figure 8-13: Different spatial aggregation levels for the analysis of fatalities (Maaskant, 2007)

A general overview of mortality rates by neighbourhood is included in figure 8-14. For the three bowls the relationship between mortality and flood characteristics will be discussed in the next sections.

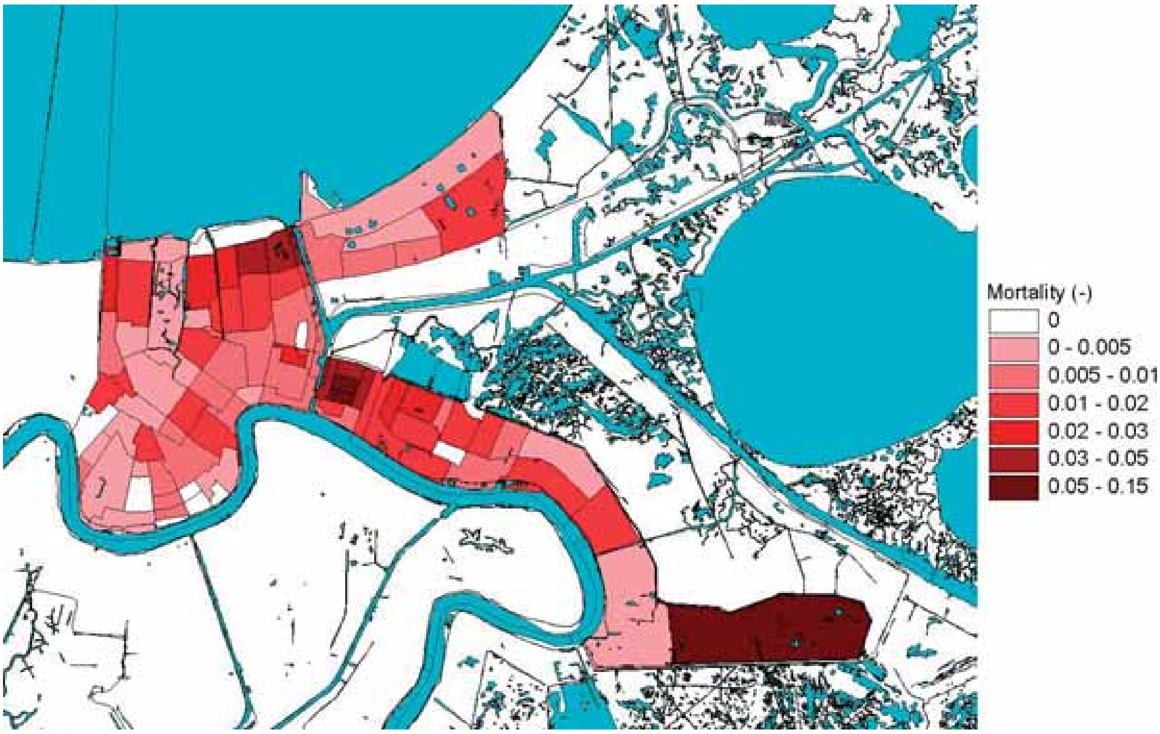


Figure 8-14: Mortality by neighbourhood (Note: A high mortality occurred in the neighborhood in the South East of the St. Bernard bowl because 30 fatalities occurred in one nursing home)

8.7.2 The Orleans bowl

The flooding of the Orleans bowl was caused by breaches along the Industrial Canal in the East and the 17th Street and London Avenue canals in the North (see figure 8-3). These resulted in the flooding of large parts of the central city. The largest water depths and fatality rates are found for the deeper parts of the bowl, mainly in the north near Lake Pontchartrain.

Figure 8-15 shows the relationship between mortality and average **water depth** by neighbourhood[18]. For the Orleans bowl there is a good relationship (R^2=0,61) between water depth and mortality, which can be described with the following lognormal function:

$$F_D(h) = \Phi_N\left(\frac{\ln(h) - \mu_N}{\sigma_N}\right) \qquad \textbf{(Eq. 8-1)}$$

$$\mu_N = 3{,}55 \qquad \sigma_N = 1{,}27$$

A slightly better fit (R^2=0,66) is found for an exponential function[19], but the lognormal function is preferred given the similarity with the earlier derived mortality functions for floods and the mortality functions used in other sectors.

18 A similar analysis has been done for tracts (smaller spatial units), but this leads to a decrease of the correlation. In this case the influence of variations in mortality between tracts with similar water depths becomes more apparent.

19 The following exponential function is found: $F_D(h)=\exp((h-6{,}89)/1{,}09)$ for $h \leq 6{,}89$m.

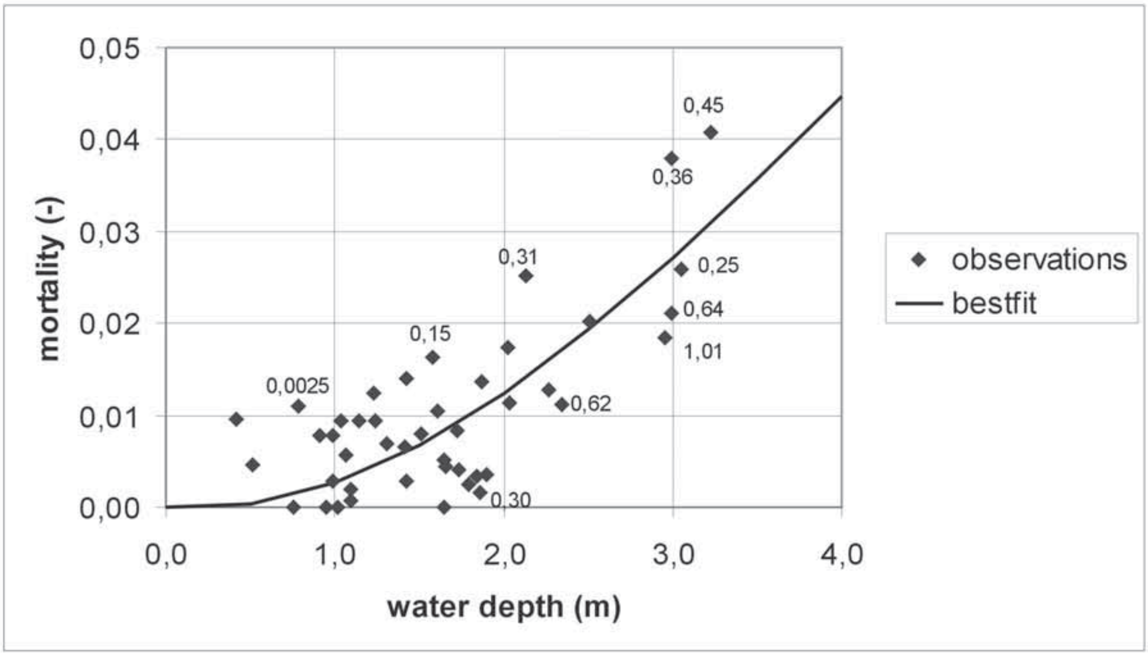


Figure 8-15: Relationship between water depth and mortality by neighbourhood for the Orleans bowl. The average value over the first 1,5m of water has been determined by neighbourhood.

The influence of the factor **rise rate** on mortality has been investigated. The average value of the rise rate by neighbourhood[20] has been determined. There does not seem to be a relationship between rise rate and mortality, see figure 8-16. Neither does the inclusion of the combined influence of rise rate and depth in the mortality function lead to an improvement of the fit of the depth-based mortality function. Figure 8-15 shows the rise rates [m/hr] for some observations. This shows that the outlying observations in that figure cannot be explained by the value of the rise rate. Observations that are far above the bestfit trendline do not have a higher rise rate than those underneath the line. It has been investigated whether the relationship between rise rate and mortality improves, when it is determined for another spatial unit (tract) or for another threshold value for water depth (1m or 2m instead of 1,5m), but this is not the case.

20 Despite relatively large variations of rise rates within a neighbourhood, the average gives an indication of the extent of rise rate, see (Maaskant, 2007) for further discussion.

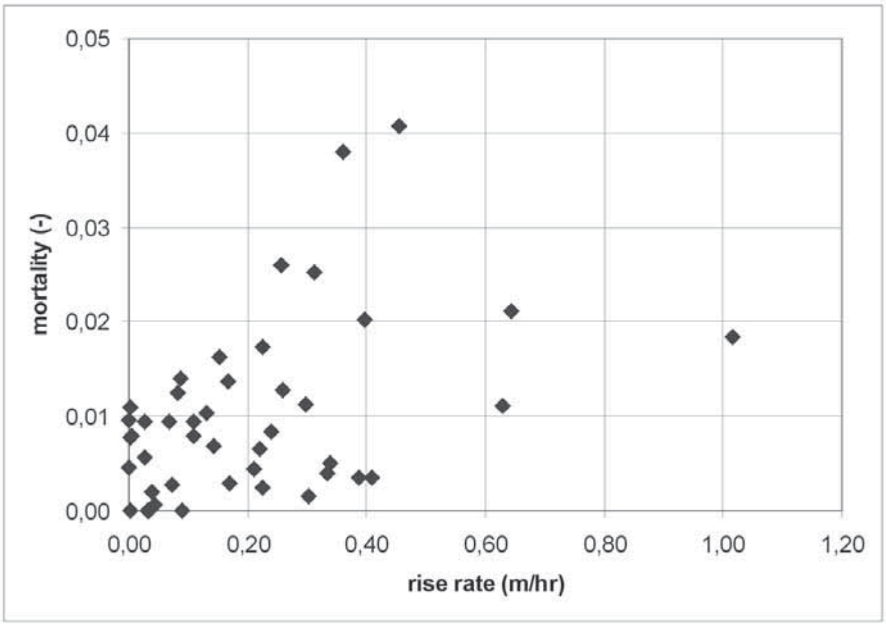


Figure 8-16: Relationship between rise rate and mortality for the neighbourhoods in the Orleans bowl.

There is a weak relationship between the arrival time of the floodwater and mortality. Arrival time is related to depth as the floodwaters that arrived first in areas near breaches that also had larger water depths.

Finally the influence of flow velocity has been examined. In the Orleans bowl higher flow velocities only occurred locally very near breaches. Comparison with the building damage map (appendix 8.II) and visual observations in the field show that hardly any buildings collapsed near the breaches in Orleans. Only near the breach in the 17th Street Canal some buildings collapsed. Comparison with the dataset of recovery locations (figure 8-9) shows that no fatalities were found in the zones near breaches. Based on these observations it is expected that the flow velocity did not have a substantial influence on mortality in the Orleans bowl.

8.7.3 The St. Bernard bowl

In total 184 fatalities were recovered in the St. Bernard bowl. Many of these fatalities (73) occurred in the neighbourhood the Lower 9th Ward. This neighbourhood is located next to the two large breaches in the Industrial Canal levees. Various eyewitness accounts tell how the floodwater entered this neighbourhood through the breaches with great force and how it caused death and destruction in the areas near the breaches. The relatively high mortality in the St. Bernard Bowl (2,2%) is mainly due to the severe flood conditions and the large number of fatalities near the breaches. For other parts of the bowl the mortality is somewhat lower (1,6%) and more similar to the mortality for the Orleans bowl (1%).

The relationship between flood characteristics and mortality is analysed further for the St. Bernard bowl. The analysis is conducted by tract because the tracts in St. Bernard have a similar surface as neighbourhoods in the Orleans bowl. The large number of fatalities near the breaches in the Lower 9th Ward appears to be related to the severe flood conditions (depth, velocity) and the large number of collapsed buildings. Areas with many fatalities and high levels of building damage are characterised by large values of the product of water depth and flow velocity(21), see figures 8-17 and 8-18. Most of the collapsed buildings and fatalities were found in the area where: $hv > 5\ m^2/s$. Observations in the field show that the area with large-scale structural damage to houses covers almost the whole Lower 9th Ward. Therefore the whole Lower 9th Ward neighbourhood is considered as the breach zone. Mortality for this neighbourhood is F_D=0,053 (or 5,3%)[22].

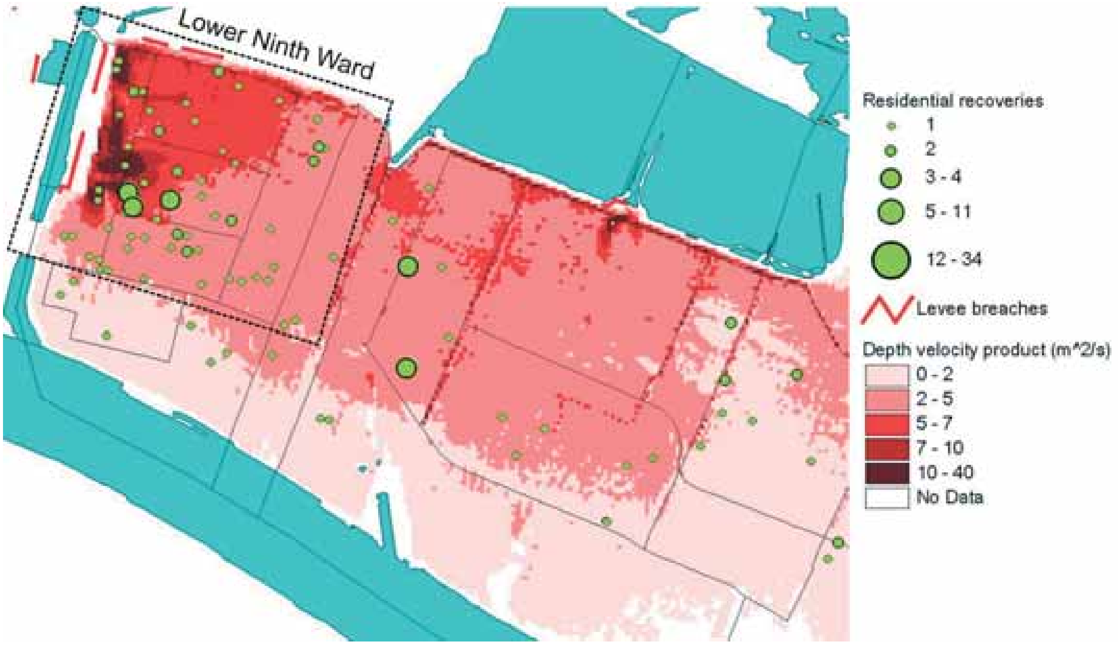


Figure 8-17: Spatial distribution of the recovered fatalities and the depth-velocity product for the north-western part of the St. Bernard bowl.

Figure 8-18: Building damage in the Lower 9th Ward (source: http://www.unifiedneworleansplan.com/home2/section/24, accessed December 2006. Damage levels determined in FEMA's post Katrina damage assessments. Note: scale differs from figure 8-17).

21 The depth – velocity product relates to the moment associated with the flow, see section 6.3.2. for further discussion.

22 The neighbourhood Lower 9th Ward covers five tracts, for which mortality varies between F_D=0,033 and F_D=0,07. However, it will be difficult to assign fatalities to a specific tract because the flow could have moved debris and bodies.

For the remaining areas in the St. Bernard bowl (i.e. all tracts apart from the Lower 9th Ward) the following relationship between mortality and water depth is found, see also figure 8-19:

$$F_D(h) = \Phi_N\left(\frac{\ln(h) - \mu_N}{\sigma_N}\right) \qquad \textbf{(Eq. 8-2)}$$

$$\mu_N = 11,23 \qquad \sigma_N = 4,67$$

The correlation between observations and the derived mortality functions is weak (R^2=0,24). It is noted that the application of the depth-based mortality function derived for Orleans gives nearly the same correlation value.

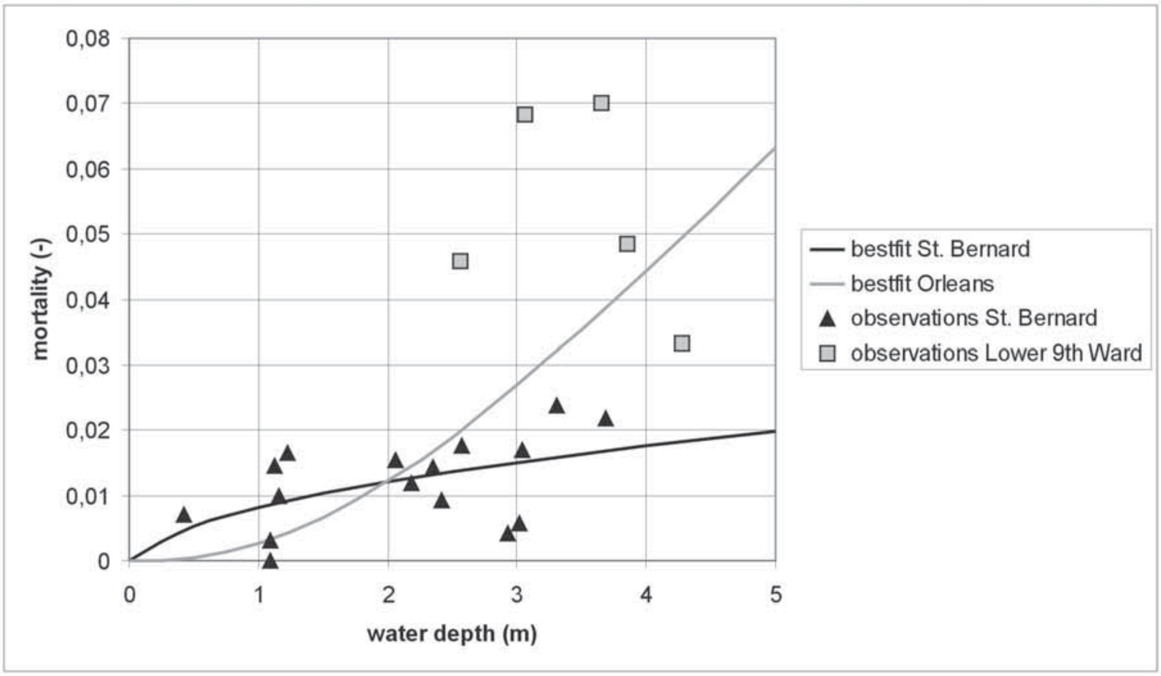


Figure 8-19: Relationship between mortality and water depth for the St. Bernard bowl.

Finally, the effects of other hydraulic characteristics have been investigated. This analysis does not reveal a relationship between rise rate and mortality (see also section 8.7.5). Neither is a good relationship found between mortality and arrival time of the floodwater after breaching.

8.7.4 The Orleans East bowl

Although the New Orleans East bowl is one of the deepest areas of the city, the number of fatalities was relatively limited (68) and the average mortality relatively low (0,71%). The flooding of New Orleans East was caused by overtopping of levees and a number of smaller breaches. It is therefore expected that the rise rates and velocities in this area were less severe than in the other areas. One other aspect could be a higher evacuation rate for this area, but no information is available to verify this. Neither are flood simulations available for this bowl to examine the flood conditions such as the rise rate and the velocity. Therefore it is only possible to investigate relationship between water depth and mortality. Figure 8-20 shows the relationship between mortality and flood depth. The lognormal trendline gives a poor fit (R^2=0,23) and it can be approximated with:

$$F_D(h) = \Phi_N\left(\frac{\ln(h) - \mu_N}{\sigma_N}\right) \qquad \text{(Eq. 8-3)}$$

$$\mu_N = 4,29 \qquad \sigma_N = 1,30$$

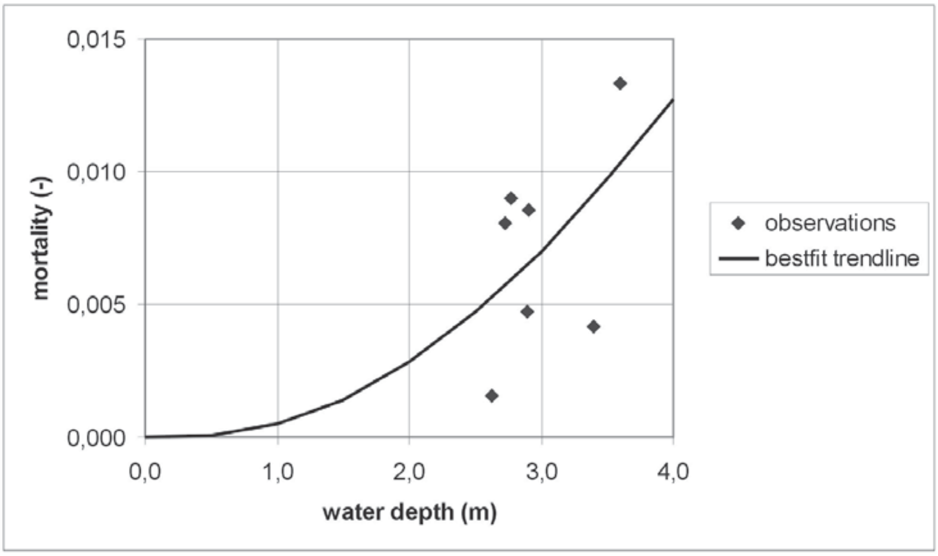


Figure 8-20: Relationship between mortality and water depth for the Orleans East bowl.

Comparison with the results for the other bowls shows that mortality rates in Orleans East are lower, although water depths were relatively high. Whether this lower mortality is associated with less severe circumstances (velocity, rise rate), higher evacuation rates or other factors[23] will have to be investigated in further research. Until that time the observations for the Orleans East bowl has not been included in the combined analysis in the next section.

8.7.5 Combined analysis for the Orleans and St. Bernard bowls

In this section the observations and analyses for the Orleans and St. Bernard bowls are combined. Firstly, it is observed that mortality was high in the breach zones characterised by high flow velocities and large numbers of severely damaged and collapsed buildings. For the St. Bernard bowl, these circumstances occurred in the Lower 9th Ward. In this area the (average) mortality was 5,3%. By approximation this breach zone was characterised by the following values of the depth velocity product: $hv > 5 m^2/s$. In the Orleans bowl these conditions did hardly appear and did not contribute to mortality.

For the remaining locations in the Orleans and St. Bernard bowls the following relationship between flood depth and mortality is obtained (see figure 8-21):

$$F_D(h) = \Phi_N\left(\frac{\ln(h) - \mu_N}{\sigma_N}\right) \qquad \text{(Eq. 8-4)}$$

$$\mu_N = 5,20 \qquad \sigma_N = 2,00$$

23 One issue to consider is the fact that a large amount of homes in New Orleans were raised, so that the actual flood depths to which people were exposed are lower than suggested by the calculated average water depths (which include relatively low street level).

The correlation between observations and predictions is R^2=0,42, which is moderate[24]. If the data of New Orleans East would be added to the analysed dataset (not shown in figure), the vertical position of the bestfit trendline would be lower and the correlation would decrease substantially.

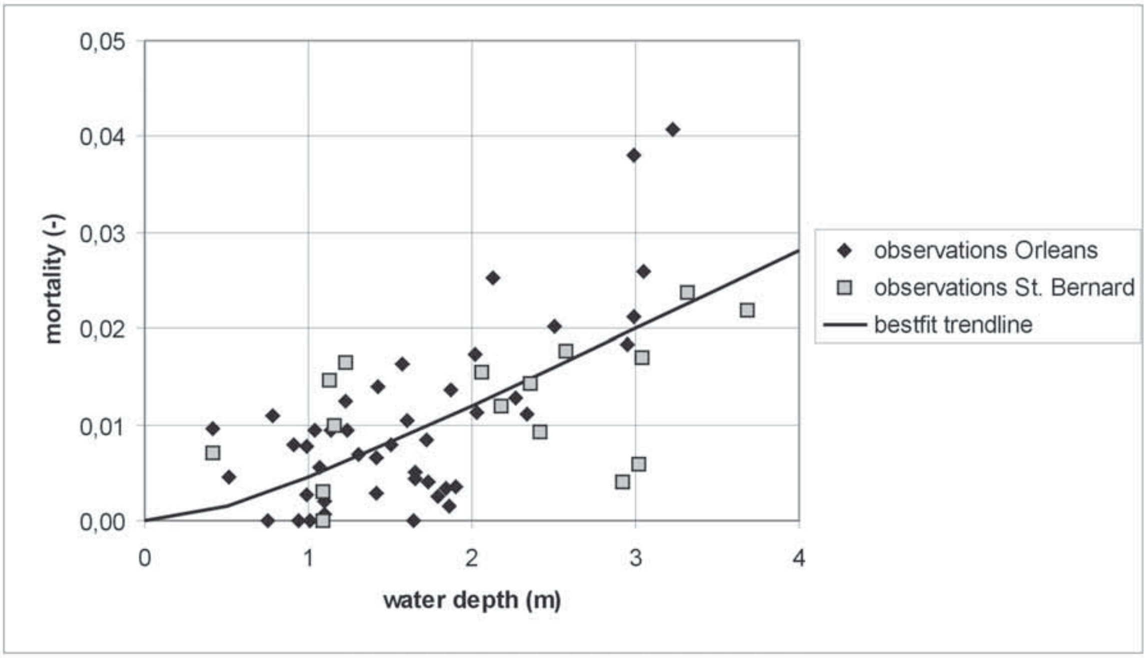


Figure 8-21: Relationship between water depth and mortality for the Orleans and St. Bernard bowls.

The available data for the Orleans and St. Bernard bowls do not indicate a clear influence of the **rise rate** on mortality. Figure 8-22 shows the mortality as a function of rise rate for the two bowls. Although the rise rates in the Orleans bowl were significantly lower than in the St. Bernard bowl, the relationships between depth and mortality are very similar for the two bowls. The inclusion of the rise rate in the depth-mortality function does not lead to a better result[25]. This is a striking result as previous analyses and anecdotal evidence from historical events suggested that rise rate was an important determinant of mortality (see sections 5 and 7.4). A further discussion regarding the influence of rise rate on mortality is given in section 8.8.2.

24 It is better than the correlation that was obtained in section 7 for the locations in the remaining zone.

25 Neither do the observations indicate the so-called threshold effect that has been assumed in section 7, where mortality suddenly increases when a certain value of the rise rate is exceeded.

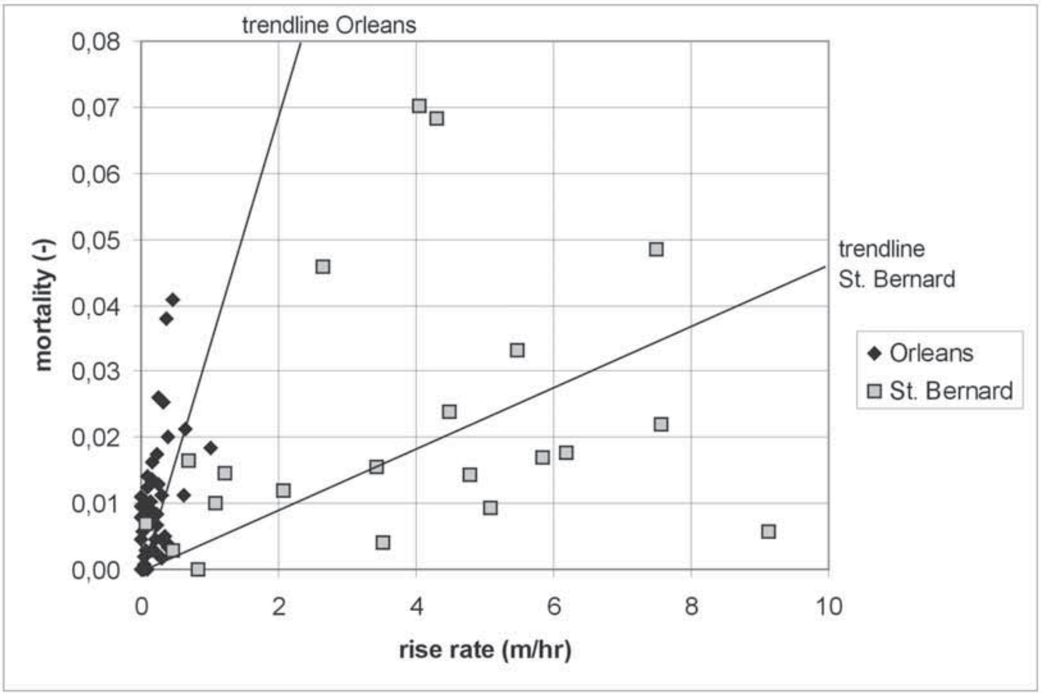
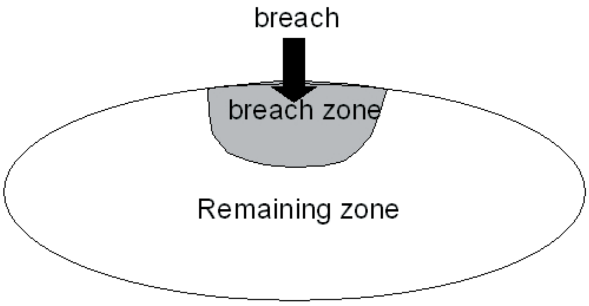


Figure 8-22: Relationship between rise rate and mortality for the Orleans and St. Bernard bowls.

Summary of findings for New Orleans

Based on the above analyses the derived mortality functions for the flooding of New Orleans are summarized in figure 8-23.



Breach zone: $hv > 5m^2/s$
⇨ F_D=0,053
Remaining zone ($hv < 5m^2/s$):
⇨ $F_D(h)=\Phi_N((\ln(h)-5,20)/2,00)$

Figure 8-23: Preliminary mortality functions derived from the data for the flooding of New Orleans.

When this approach is applied to the Orleans and St. Bernard bowls the estimated number of fatalities is 395, while the actual observed number for the considered locations is 404. There is a good correlation (R^2=0,74) between observed and calculated mortality fractions, see figure 8-24. Most of the observed mortality fractions are approximated with the proposed functions within a bandwidth of a factor 2.

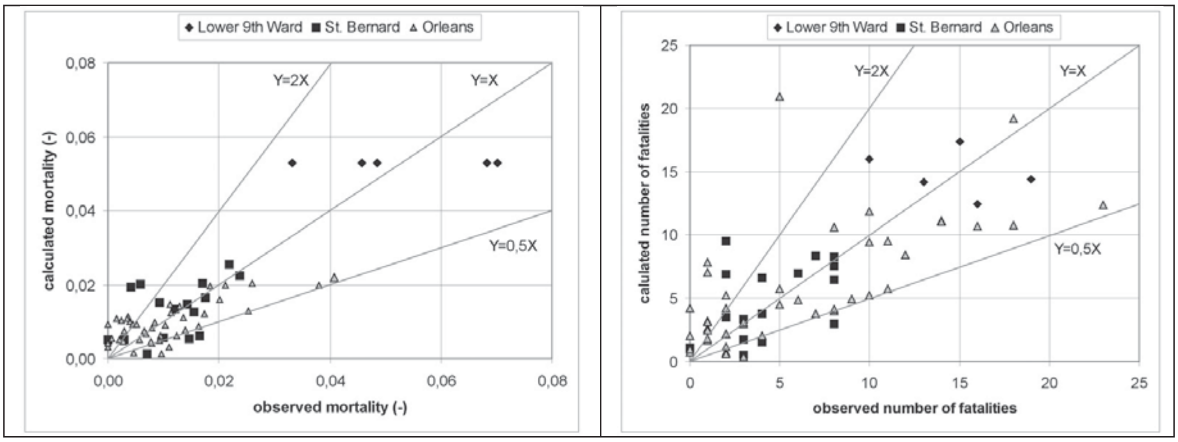


Figure 8-24: Comparison by neighbourhood between observations and calculations with the derived mortality functions for mortality (left, R^2=0,74) and number of fatalities (right, R^2=0,53)

Remarks

The proposed mortality functions are applicable to mortality associated with the physical impacts of the flood. The occurrence of fatalities associated with the adverse public health situation is not included in the proposed functions. This group of fatalities proved to be substantial, covering approximately one third of the total number of recovered.

The proposed functions are preliminary given several issues. These will be discussed in more detail in section 8.8.4. Two major issues are the following: 1) the dataset of recovery locations is incomplete as it covers 69% of all fatalities; 2) The number of exposed people cannot be estimated adequately. These factors can cause uncertainties in the mortality fractions that have been used for the derivation of the above functions. Based on estimates for the two above-mentioned deviations[26], it is expected that the absolute lower and upper bounds of mortality for one location will maximally deviate by a factor 0,5 and 2,9 from the currently reported mortality. However, because under- and over-estimates for single observations will be averaged out to some extent, the deviations in the eventually derived mortality functions will be less.

8.8 Closing discussion

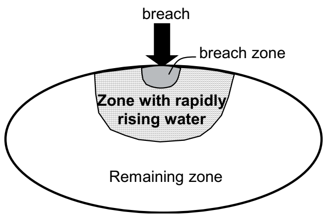
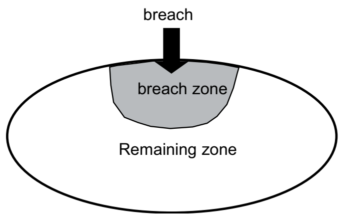
In this final section a number of issues are discussed. Section 8.8.1 gives a comparison between the mortality functions for New Orleans and those derived in section 7. The influence of the rise rate on mortality is discussed in section 8.8.2. The effects of changes in time on loss of life caused by floods are analysed in section 8.8.3. Finally, the preliminary status of the results is discussed in section 8.8.4.

26 The dataset of recovery locations is incomplete and covers 69% of all fatalities. If it is assumed that the missing recovery locations have the same spatial distribution as the known recovery locations, all the numbers of fatalities can be scaled by a factor 1,45 (or 1/0,69) for an upper bound estimate. In a lower bound estimate the originally reported numbers are used.
It is assumed that the uncertainty in the estimate of the exposed population is a factor 2. This implies that the exposed population varies between 5% and 20% of the original population. By combining these two factors the originally reported mortality fractions are scaled by a factor ½ to obtain a lower bound estimate and by a factor 1,45/0,5=2,9 to obtain an upper bound estimated.

8.8.1 Comparison with the mortality functions proposed in section 7

In this section, the derived mortality functions for Orleans and St. Bernard are compared with the mortality functions proposed in section 7. In general, the average mortality associated with the flooding of New Orleans (1,2%) is similar to the average event mortalities due to flood disasters in history (~1%). In New Orleans, many fatalities occurred in the deeper parts of the bowls, near breaches and in areas with many collapsed buildings. This is similar to the findings for historical events. Overall, the earlier proposed approach, in which different hazard zones in the flooded area are distinguished, also seems applicable to New Orleans. However, there are differences with respect to the hazard zones and the derived mortality functions. Table 8-4 gives a general comparison between the two approaches. Details are discussed below.

Table 8-4: Comparison between the earlier proposed approach for loss of life estimation and the mortality functions derived for New Orleans

Method	Section 7 of this thesis	Preliminary analysis for New Orleans
Data basis	Historical flood events (Netherlands and UK 1953, Japan 1959, etc.)	Preliminary data for New Orleans (Orleans and St. Bernard bowls)
Average event mortality	Netherlands 1953: F_D=0,007 Japan 1959: F_D=0,012	New Orleans: F_D=0,012
Approach (hazard zones for a similar breach)		
Breach zone	hv>7m²/s and v>2m/s F_D=1	hv>5m²/s F_D=0,053 (larger breach zone, lower mortality)
Zone with rapidly rising waters	Steep mortality function and high mortality fractions (F_D=0,1 to 0,4) for areas with larger water depths (4 to 5m) and high rise rates.	No apparent influence of rise rate on mortality
Remaining zone	Mortality limited. Generally below F_D=0,015 even for larger water depths	Mortality can become F_D=0,03 for larger water depths (~4m).

The depth-velocity criterion derived to determine the size of **breach zone** for New Orleans is conceptually comparable to the proposed criterion for the breach zone in section 7. However, in New Orleans the collapse of buildings occurred at a lower depth velocity product (hv>5m^2/s) than would be expected according to the criterion proposed for the breach zone in section 7 (hv>7m^2/s and v>2m/s). Clausen (1989) originally derived this latter criterion for brick and masonry houses. Many of the houses in New Orleans are made out of wood and these are more vulnerable during a flood event. Therefore it is not surprising that destruction of buildings in New Orleans was observed at lower depth-velocity products than for brick or masonry houses.

In the earlier proposed method it has been assumed that all people exposed in the breach zone do not survive, i.e. F_D=1. However, even for the most severely affected breach zones in New Orleans, observed mortality did not exceed F_D=0,1. Based on this result it is expected that the earlier assumption of 100% mortality in the breach zone is too conservative. Overall, the approach derived based on the New Orleans data results in a larger breach zone than in the earlier proposed method, but mortality in the breach zone is lower.

The derived mortality function for the remaining areas of New Orleans is compared with the mortality functions for the remaining zone and the zone with rapidly rising waters that have been derived in section 7 (see figure 8-25). For water depths below 2,5m the function for New Orleans gives a somewhat higher mortality fraction than the functions proposed in section 7. The derived function for New Orleans is in between the earlier proposed functions for larger water depths (*h*>2,5m).

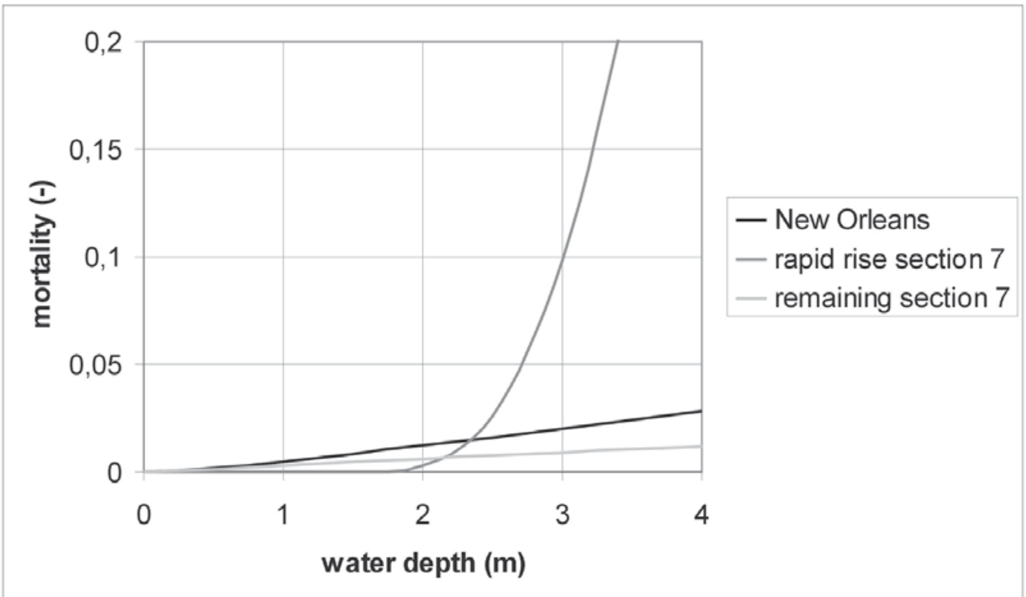


Figure 8-25: Mortality function for New Orleans and mortality functions derived in section 7.

8.8.2 Discussion on the influence of rise rate on mortality

The analysis of the data of the New Orleans disaster does not indicate an influence of the rise rate on mortality (see results in section 8.7). This is a striking result as analyses and anecdotal evidence from historical events suggested that rise rate was an important determinant of mortality (see sections 5 and 7.4). A number of possible explanations is given below for the fact that the rise rate seemed less relevant for the New Orleans floods.

- The main hazard of rapidly rising water is that people are surprised and have little time to reach higher floors or shelters. During Katrina people could have been warned and prepared before the flooding associated with the levee breaches due to the hurricane warning, the wind effects or because of the initial flooding associated with heavy rains and / or overtopping of levees. These latter effects have not been taken into account in the flood simulations from which the rise rates were determined.
- Most of the fatalities were elderly and a number of them were disabled. For these people it would have been very difficult to reach higher floors, even if the rise rate was low.
- In New Orleans, hardly any collapse of buildings has been observed outside the direct breach zones (see also appendix 8.II). So even at locations where the waters

rose rapidly, people could still have found shelter in their homes. The analysis in section 7.4.7 indicated that the zones with rapidly rising waters in historical events were characterised by large numbers of collapsed buildings. Therefore the earlier proposed mortality function could be too conservative for the New Orleans situation.

- The historical disasters studied in section 7 mainly affected rural areas (e.g. the 1953 flood in the Netherlands). The New Orleans flood affected an urban area, which may have provided more opportunities for shelter in high buildings. In addition, the New Orleans area could include more (natural) high grounds than for example the extensive low-lying areas flooded in 1953 in the Netherlands.
- The behaviour of people in the flooded regions of New Orleans could have differed from the behaviour of people during historical disasters. For example, anecdotal descriptions of the 1953 storm surge in the Netherlands (Slager, 1992) suggest that many people were overwhelmed by floodwaters during their escape. One possibility is that during the New Orleans flood disaster a larger part of the population remained in their house.
- Uncertainties in the estimates of the numbers of killed and exposed (see below) and / or inaccuracies in the flood simulations could have influenced the analysis of the relationship between the rise rate and mortality.

Based on the available data it is not yet possible to draw a final conclusion on the influence of the rise rate on mortality. One likely explanation is that (apart from areas near breaches) the number of collapsed buildings in New Orleans was less than during historical events, such as the 1953 flood in the Netherlands. Further investigation of the influence of rise rate on mortality is recommended, also involving the effects of the collapse of buildings.

8.8.3 Discussion regarding the effects of changes in time on the loss of life caused by floods

The method proposed in section 7 has been mainly derived based on events that occurred in the 1950's, while the New Orleans flood occurred in 2005. Certain circumstances that affect flood mortality could have changed over time. Some argue that these changes will have mainly reduced the loss of life caused by flood events, see e.g. (Klijn *et al.*, 2006). Potentially positive developments include improvements of prediction, transportation, building quality, communication and possibilities of evacuation, emergency response and rescue. However, there are also developments that could have a negative influence, e.g. the dependence of modern societies on technical systems, such as electricity and communication and the fact that people are less used to withstand harsh natural conditions. As a result of these developments, it can be questioned whether the method for loss of life estimation that has been proposed in section 7 is representative for a contemporary flood event and whether or not it gives a too conservative estimate of the loss of life

The New Orleans flood disaster gave insight in the limitations of evacuation and emergency response. A majority of the population (80 to 90%) evacuated before the floods and this probably saved thousands of lives. However, the consequences for the people that stayed and were exposed to the floods were still disastrous. In addition, a severe crisis situation developed amongst evacuees and the people in hospitals and shelters. The situation after the flooding illustrated the difficulties to organise a fast and effective rescue action, see also (Select Bipartisan Committee, 2006).

In many respects the New Orleans flood is very comparable to historical large-scale flood events. Similar to historical events the mortality fractions in New Orleans were the highest in areas near breaches and in areas with large water depths. The overall mortality fraction amongst those exposed for the New Orleans flood is approximately 1,2%. This is comparable to or even larger than the average event mortalities observed for historical events, such as the floods in 1953 in the Netherlands (0,7%) and the floods in 1959 in Japan (1,2%). In addition, the New Orleans flood disaster was also characterised by some circumstances that were more favourable than during historical floods. For example, most people were warned of the hurricane and the water temperature[27] was higher than during historical disasters.

The analysis in the previous sections showed that the mortality functions derived from the New Orleans event are not fully similar to the mortality functions derived in section 7. The mortality function for the zones with rapidly rising waters that has been proposed in section 7 seems too conservative for the New Orleans case. One likely explanation is that (apart from areas near breaches) the number of collapsed buildings was less than during historical events. The mortality functions for New Orleans have been applied to flood scenarios in the Netherlands, see (Maaskant, 2007) for further details. This shows that these functions give a fatality estimate that is in the same order of magnitude as the estimates obtained with the method proposed in section 7. For most of these scenarios, the functions for New Orleans even lead to a somewhat higher estimate of loss of life (~15%) than the method from section 7.

Overall, the available data for New Orleans do not support the claim that mortality amongst those exposed during a contemporary flood event is lower than during historical events. McClelland and Bowles (2002) come to a similar conclusion for dam breaks and mention that mortality patterns are consistent across the centuries.

8.8.4 Status of the results and closing remarks

This section concerns a brief discussion of the status of the analyses that have been reported in the previous sections. It is very important to stress that the results are preliminary for a number of reasons.

Firstly, the applied mortality data are still incomplete and cover approximately 70% of all fatalities. In addition, the analysis of mortality functions is limited to the Orleans and St. Bernard bowls. The Orleans East bowl is excluded from the analysis because no results of flood simulations were available for this bowl, but a different relationship between mortality and flood characteristics seems to be applicable to this area.

Secondly, various crude assumptions have been made in the analysis of the number of people exposed. For all the considered areas it has been assumed that 10% of the original

27 The water temperature during the flooding of New Orleans was high (25°C to 30°C (Pardue *et al.*, 2006)), thus hypothermia of people in the floodwater was not a likely death cause during this event. The 1953 flood disaster in the Netherlands occurred during winter time and many people drowned in the cold waters.

population was exposed. However, spatial differences in evacuation rates and exposed populations could have a very large effect on the resulting mortality values. It is recommended to investigate the spatial distribution of evacuation and shelter rates for the flooded areas of New Orleans, e.g. by means of surveys amongst evacuees.

Thirdly, results of the flood simulations have been used to estimate flood characteristics. Limitations in these simulations could influence the outcomes. Examples of limitations are the limited capabilities to model wide breaches or neglecting of the effects of rainfall, see de Bruijn (2006) and Maaskant (2007) for further discussion. Also the fact that flood characteristics (e.g. depth and rise rate) have been averaged out per neighbourhood could affect the outcomes, because substantial variations between flood characteristics within one neighbourhood could exist.

Given the above issues, the detailed results regarding the influence of flood characteristics on mortality have to be considered as indicative and preliminary. It is recommended to collect more accurate data regarding fatalities, the exposed population and the flood characteristics. One important factor that deserves further investigation is the influence of the collapse of buildings on mortality. Eventually, based on more complete analyses, an improved method for loss of life estimation may be derived from the New Orleans data in the future.

Despite the limitations, the reported results give important insight in the relationship between flood characteristics and mortality. Also, the analysis confirms that average mortality amongst the exposed population is in the order of magnitude of 1% for this type of large-scale flood event. These insights can be used for consequence and risk analyses and as input for decision-making. An application is the analysis of the effectiveness of measures to reduce the consequences of flooding. Examples of such measures are evacuation, shelter, compartment dikes and land use planning. Furthermore, estimates of loss of life are important in the context of flood risk assessment. The risk assessment can be used for decision support in the development of plans for future protection of New Orleans against flooding, see also (LACPR, 2006b). An example of the application of flood risk analysis for an area in the Netherlands is presented in next section.

9 Case study: Flood risk assessment for dike ring South Holland

Research question: How can the proposed method for loss of life estimation be applied to the quantification and evaluation of the flood risk in the Netherlands?

Keywords: flood risk, loss of life, flood defence, quantitative risk analysis, risk acceptance

In this section the flood risks are assessed for a case study area in the Netherlands, namely the dike ring area South Holland. The presented analyses are based on the methods proposed in the previous sections of this thesis and information from the project 'Flood risk and safety in the Netherlands' (FLORIS), see (Rijkswaterstaat, 2005; Melisie, 2006; Jonkman and Cappendijk, 2006) for further background. Section 9.1 gives general background information regarding flood defence in the Netherlands and the case study area, dike ring South Holland. The methods used for risk quantification are summarised in section 9.2. Results are presented in section 9.3. As a contribution to the evaluation of the acceptability of the determined risk, a comparison of the flood risk with the risks in other sectors is presented in section 9.4. The calculated flood risk levels are compared with existing criteria for the evaluation of risk acceptance (section 9.5). Concluding remarks are given in section 9.6.

9.1 Introduction

9.1.1 Flood defence in the Netherlands

Large parts of the Netherlands are below sea the level or the high water levels in the rivers and lakes. Without the protection of dikes, dunes and hydraulic structures (e.g. storm surge barriers) large parts of the country would be flooded regularly. Due to this situation the Netherlands has a long history of flood disasters (see also section 5.3). The last disastrous flood occurred in 1953. A storm surge from the North Sea flooded large parts of the Southwest of the country. More than 1800 people died during this disaster and it caused enormous economic damage.

Until 1953 dikes were constructed to withstand the highest known water level. After the 1953 flood the Delta Committee was installed to investigate the possibilities for a new approach towards flood defence. The committee proposed to reduce the vulnerability by shortening the coastline and closing off the estuaries. In addition, safety standards for flood defences were proposed. In an econometric analysis the optimal safety level was determined for the largest flood prone area, South Holland (van Dantzig, 1956). In this optimisation approach the incremental investments in more safety are balanced with the reduction of the risk. The work of the Delta Committee laid the foundations for the new safety approach, in which dikes are dimensioned based on a design water level with a certain probability of exceedance. The current design criteria and the process for safety evaluation of the flood defences are based on these design water levels. This approach to flood protection is laid down in the flood protection act of 1996.

The flood prone areas in the Netherlands are divided in so-called **dike ring areas**, i.e. areas protected against floods by a series of water defences (dikes, dunes, hydraulic structures) and high grounds. The safety standards for the various dike rings are shown in figure 9-1. The height of these standards depends on the (economic) value of the area and the source of flooding (coast or river). For coastal areas design water levels have been chosen with exceedance frequencies of 1/4000 per year and 1/10.000 per year. For the Dutch river area the safety standards were set at 1/1250 per year and 1/2000 per year. Some smaller dike ring areas bordering the river Meuse in the south of the country have a safety standard of 1/250 per year.

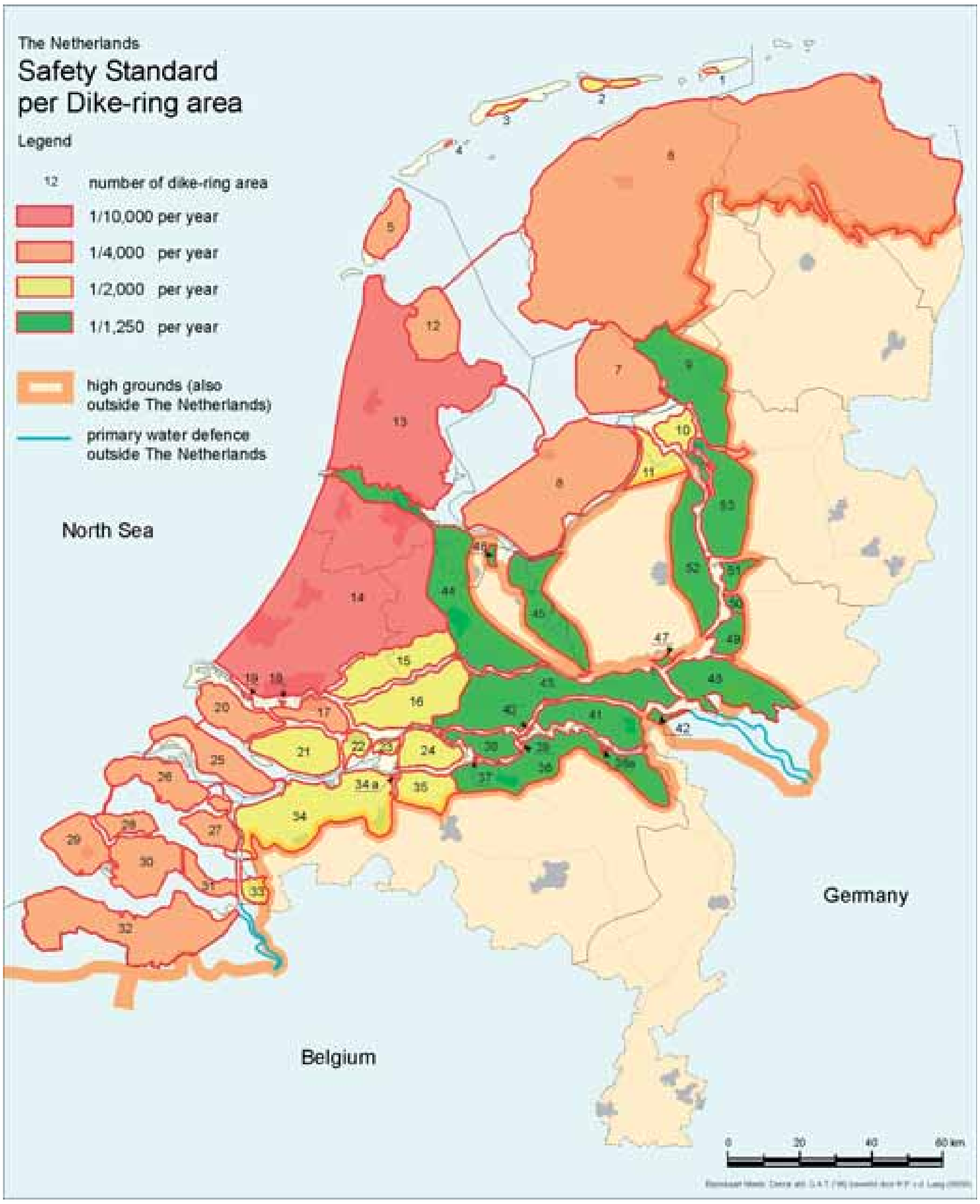


Figure 9-1: Dike ring areas in the Netherlands and safety standards (source: Rijkswaterstaat DWW). Dike ring areas along the river Meuse are not shown.

These safety standards have mostly been derived in the 1960's. Since then, the population and economic value in these dike ring areas have grown drastically. A recent investigation (RIVM, 2004) therefore concluded that these standards are no longer in proportion to economic and societal values which are protected. In the last decade the Dutch Ministry of

Transport, Public Works and Water Management has initiated projects to investigate and evaluate the flood risk, see (Rijkswaterstaat, 2005; MinVenW, 2006). Outcomes of these projects will be used to assess and evaluate the level of flood risk in the Netherlands and the need for alteration of the current policies and standards.

9.1.2 Study area: dike ring South Holland

South Holland (dike ring number 14) is the largest dike ring in the Netherlands. It is the most densely populated area in the country and it includes major cities such as Amsterdam, Rotterdam and Den Haag. The area has 3,6 million inhabitants and the total potential direct economic damage is estimated at 290 billion Euros (Melisie, 2006). Figure 9-2 gives an overview of the area and the main cities. It is noted that the area of the dike ring South Holland is nearly the same as the surface of the province of South Holland. In the remainder of this section the term South Holland is used to indicate the dike ring area.

The area is threatened by floods from the North Sea and the river system in the South (the Nieuwe Waterweg and Hollandsche IJssel). The flood defence system consists of sand dunes along the coast and earthen dikes along the rivers. As part of the Delta works, storm surge barriers have been constructed in the river system (e.g. the Maeslant barrier near Hoek van Holland and a barrier in the Hollandsche IJssel) to prevent that storm surge floods at the North Sea lead to flooding in the lower river system. Depending on the location of a breach, substantial parts of this dike ring can be flooded, as the area includes some of the deepest parts of the Netherlands. Some of these areas are almost 6 metres below mean sea level.

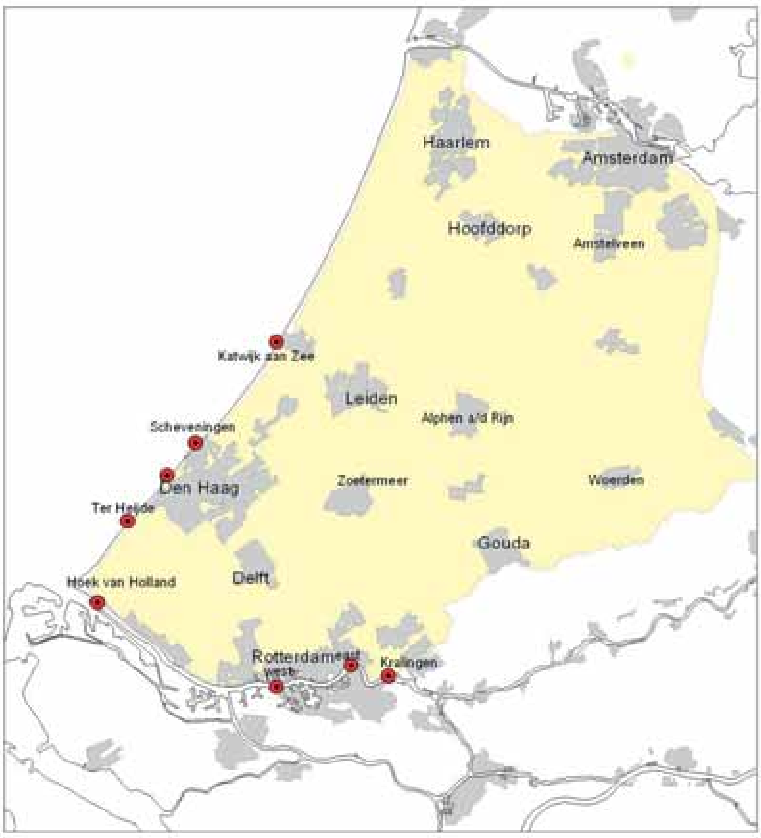


Figure 9-2: Overview of dike ring South Holland. Breach locations that are used for analysis of flood scenarios are indicated in the figure with dots.

In the remainder of this section the risks associated with a flood due to breaching of primary flood defences (dikes, dunes) have been considered[1]. Assessment of the risk for this area is of particular interest as: 1) it is the largest dike ring area in the Netherlands with the highest potential damage; 2) the first safety standard and the corresponding design water level (with a 1/10.000 year probability of exceedance) were determined for this area by the Delta Committee in the 1960's and 3) it can be flooded from the coast and rivers, leading to different damage patterns and particular challenges with respect to evacuation. Results of risk quantification for this area can be used as input for the discussion on the acceptance of the flood risk for the Netherlands.

9.2 Method for flood risk analysis

Methods for the analysis of flood risk, see e.g. (van Manen and Brinkhuis, 2005; Apel *et al.*, 2006), generally include three main steps: 1) determination of the probability of flooding; 2) simulation of flood characteristics and 3) assessment of the consequences. Below, the methods are summarised that have been used for these steps in the FLORIS project and the analyses in this study.

9.2.1 Determination of the probability of flooding

In assessing the probability of failure of a flood defence system it is necessary to take into account that failure of different elements in the system and (for each element) different failure mechanisms can lead to flooding (Vrijling, 2001). The elements in the studied system include dune and dike sections and hydraulic structures. Typical failure mechanisms for a river dike include overflowing, instability and seepage / piping. An advanced program for reliability analysis of ring dike systems has been developed: PC-RING. It considers all principal dike failure modes for the elements in a dike ring[2], see (Lassing *et al.*, 2003; Steenbergen *et al.*, 2004) for a further description. The method uses a Bayesian probability concept (see section 1.2.4) implying that large knowledge uncertainties (e.g. limited information regarding geotechnical properties of the dike) will result in a conservative estimate of the flooding probability. The method has been used to estimate the probabilities for different flood scenarios and the overall probability of flooding of South Holland. Results are present below.

9.2.2 Simulation of flood characteristics

To assess the damage of a flood it is necessary to have an understanding of its hydraulic characteristics, such as depth, velocity, rise rate and arrival time. These are determined for a so-called flood scenario. A flood scenario refers to one breach or a set of multiple breaches in the dike ring and the resulting pattern of flooding, including the flood characteristics. For South Holland several flood scenarios have been analysed to account for the differences in flood patterns and resulting consequences. For each flood scenario the location of breaching, the outside hydraulic load conditions (water level, waves) and breach growth rate have been determined.

1 Additional risks might be associated with flooding due to local rainfall or breaching of dikes along the local drainage canals in South Holland.

2 In addition, dependencies can exist between the safety of different dike rings. For example when the flooding of one dike ring reduces water levels in the river and increases the safety of a dike ring situated downstream. This is indicated as 'system behaviour', see (van Mierlo *et al.*, 2003) and (van der Wiel, 2003) for further details.

The development of the flood flow in the area has been simulated with a two dimensional hydraulic model (Sobek 1D2D). An example of the output of a flood simulation is given in figure 9-3. It is noted that the presence of line elements in the area, such as roads, railways and dikes, could influence the flood flow as they may act as compartment dikes that block the flood flow. These effects have not been taken into account in the analyses presented in this section, as line elements appeared to have limited and sometimes even negative effect on loss of life[3], see also (Jonkman and Cappendijk, 2006).

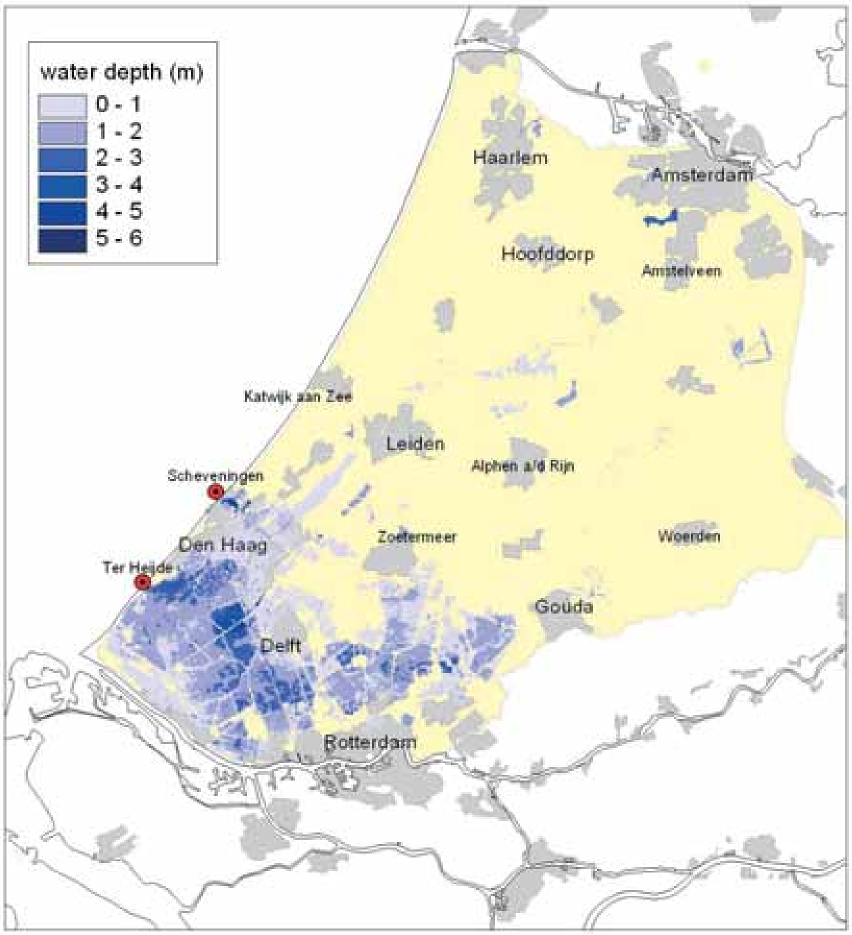


Figure 9-3: Example of output of a flood simulation showing maximum water depth for a flood scenario with breaches at Den Haag and Ter Heijde.

9.2.3 Assessment of the consequences

The consequences for different flood scenarios can be estimated based on the outputs of flood simulations and information regarding population density and spatial distribution of economic assets. The direct financial economic damages have been calculated with existing damage functions (Kok *et al.*, 2005). These relate the damage level (as fraction of total value) to the occurring water depth. Below, the proposed approach for estimation on loss of life is briefly summarised. Other damage categories, such as the number of injuries and losses of ecological and historical values, have not been analysed.

3 However, the flooded area and economic damage are expected to decrease significantly due to the presence of these line elements.

Loss of life has been determined with the method proposed in section 7. First, the exposed population for each flood scenario is analysed based on the time available before flooding and the time required for evacuation. The time available is determined by the possibilities to predict the flood, leading to different available times for coastal and river flooding. The time required is determined with an evacuation model (van Zuilekom *et al.*, 2005), also taking into account delays due to decision-making, warning and response of the population. As output, the evacuated fraction of the population in the exposed area is obtained.

The reduction of the number of exposed due to shelter is found by assuming that inhabitants of high rise buildings find shelter within the exposed area. The effects of rescue are not accounted for as it is expected that the rescue capacities will be insufficient to rescue substantial parts of the population during a large-scale flood (see also section 7.3.4).

The number of people exposed has been determined for different types of evacuation that affect the evacuation success, see figure 9-4. The type of flood mainly influences the time available, while the level of organisation of the evacuation influences the time required. Each situation results in a certain number of evacuated and people exposed.

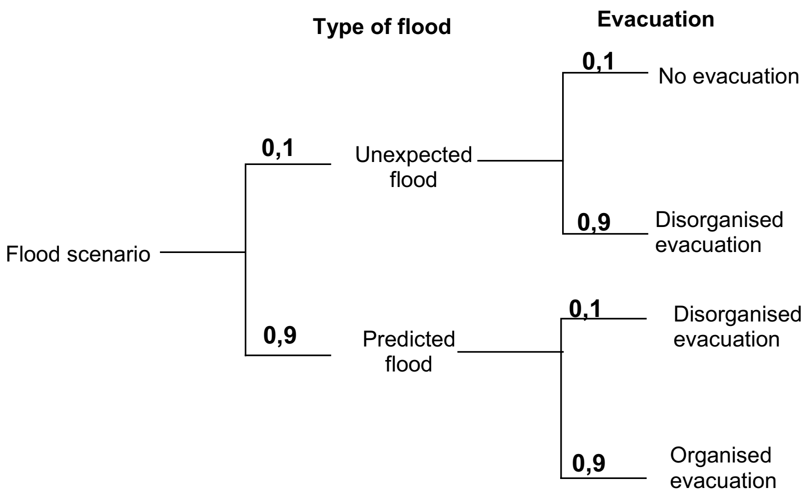


Figure 9-4: Distinguished situations with respect to evacuation and exposed population (Jonkman and Cappendijk, 2006).

For risk quantification the (conditional) probabilities for these different evacuation types that could occur within one flood scenario need to be known. Based on expert judgement, conditional probabilities for these situations have been estimated[4] (Jonkman and Cappendijk, 2006). As an example, estimates of (conditional) probabilities for different evacuation types for a coastal flood scenario in South Holland are indicated in figure 9-4. Consequently the loss of life is calculated for each situation by means of the dose response functions derived in section 7. Model uncertainties in these results are also presented by using the derived confidence intervals for the dose response functions.

4 Depending on the type of threat (coast vs. river) and the most important failure mechanism (e.g. piping which occurs often rather unexpectedly) different values for the conditional probabilities of an unexpected and predicted flood can be chosen. The level of preparation and time available will determine the likeliness of an organised evacuation. Based on analysis of these factors a better foundation of the estimates of these conditional probabilities is recommended.

9.3 Results of risk quantification

In this section the results of risk quantification are presented. First, probability and consequence estimates for different flood scenarios in South Holland are presented (section 9.3.1). These are used in section 9.3.2 to calculate the individual and societal risk.

9.3.1 Probability and consequence estimates

Probabilities have been determined for various flood scenarios. Table 9–1 shows the probabilities for the ten most likely scenarios (Melisie, 2006). It is noted that these include some flood scenarios with breaches at multiple locations. Breach locations are indicated in figure 9-2. The overall probability of flooding for dike ring South Holland is estimated at $3{,}94.10^{-4}$ per year, or approximately once in 2500 years (Rijkswaterstaat, 2005). In addition, the calculated financial-economic consequences are presented in the table.

Table 9-1: Probabilities and economic consequences for flood scenarios for dike ring South Holland, from (Melisie, 2006)

Breach location(s)	Probability (1/yr)	Economic damage (10^9 Euro)
Rotterdam – Kralingen	$1{,}36.10^{-4}$	6,8
Den Haag – Boulevard	$1{,}19.10^{-4}$	1,9
Den Haag - Scheveningen	$7{,}63.10^{-5}$	3,6
Katwijk	$2{,}44.10^{-5}$	11,3
Hoek van Holland	$1{,}15.10^{-5}$	2,0
Katwijk and Den Haag	$8{,}36.10^{-6}$	6,0
Den Haag and Ter Heijde	$7{,}23.10^{-6}$	22,8
Rotterdam West	$4{,}89.10^{-6}$	2,5
Rotterdam East	$3{,}65.10^{-6}$	5,7
Katwijk, Den Haag and Ter Heijde	$2{,}23.10^{-6}$	37,2

It is noted that the presented economic damages for the flood scenarios are substantially smaller than the absolute maximum possible economic damage for dike ring South Holland. That value, 290 billion Euros, would occur if the whole area of the dike ring South Holland was completely flooded. This indicates that the flood scenarios in South Holland are only expected to flood a limited part of the whole area. Yet, the damage values are still very large.

In order to analyse the loss of life it is necessary to investigate the effects of evacuation on the number of people exposed for different evacuation types (see figure 9-4). For South Holland the most dangerous situations are caused by coastal storm surges. For these events the time available for evacuation (i.e. expected time between prediction and dike breach) is generally limited, and estimated to be between 10 and 20 hours. Analyses with an evacuation model show that the required time for complete evacuation of (parts of) South Holland is often more than 24 hours and sometimes more than 50 hours (Van der Doef and Cappendijk, 2006). It is expected that only a small fraction of the population can be evacuated in case of a (threatening) flood of South Holland. Depending on the considered flood scenario and the type of evacuation (organised or disorganised) the evacuated fraction of the population ranges between 0,2 (for a predicted flood) and 0,01 (for an unexpected flood), results are reported in more detail in (Van der Doef and Cappendijk, 2006).

These findings imply that it is expected that only a very limited fraction of the population of South Holland can be evacuated in case of a (threatening) flood.

Based on these results the number of fatalities is determined for different scenarios and evacuation types, see table 9-2. Also, the number of people exposed in the flooded area for a situation without evacuation is presented. The number of people exposed is smaller than the population in the flooded area due to the effects of shelter. Depending on the exposed area the sheltered fraction of the population varies between 0,06 and 0,16.

Table 9-2: People at risk and numbers of fatalities for each flood scenario (rounded by decimals). A distinction is made between different evacuation types.

Flood scenario	People exposed in flooded area	Fatalities			
		Unexpected flood		Predicted flood	
		No evacuation	Disorganised evacuation	Disorganised evacuation	Organised evacuation
Rotterdam – Kralingen	180.880	1070	1060	900	860
Den Haag - Boulevard	112.140	110	100	100	100
Den Haag - Scheveningen	179.270	230	220	210	210
Katwijk	205.960	400	380	340	330
Hoek van Holland	102.690	110	100	100	100
Katwijk and Den Haag	299.280	550	530	470	460
Den Haag and Ter Heijde	706.650	3460	3290	3210	3170
Rotterdam West	107.440	190	180	170	170
Rotterdam East	187.840	600	600	510	480
Katwijk, Den Haag and Ter Heijde	1.016.560	5090	4850	4720	4670

As an example the output for the scenario with breaches at Den Haag and Ter Heijde is considered. The estimated number of fatalities is more than 3400 and without evacuation more than 700.000 people are exposed. Figure 9-5 shows the spatial distribution of the number of fatalities. The majority of fatalities, nearly 1900, occur in areas with rapidly rising waters and deep flood depths, for example South of Den Haag.

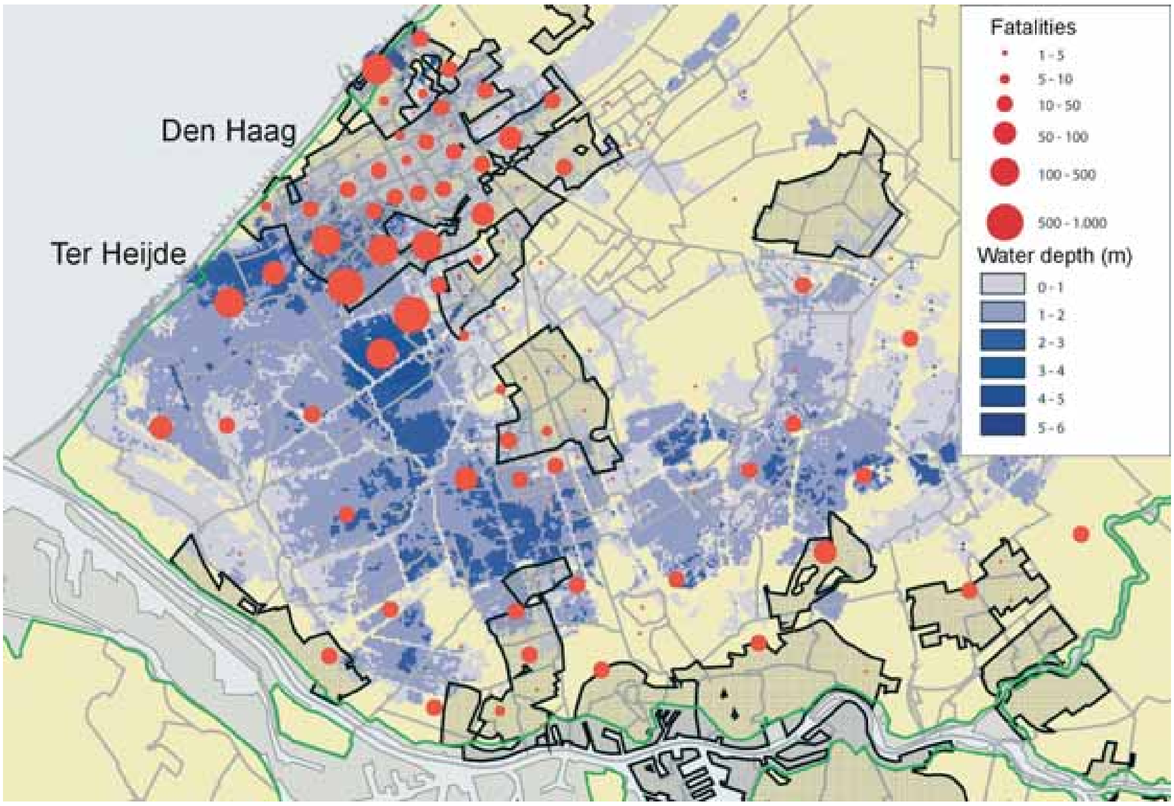


Figure 9-5: Fatalities by neighbourhood and flooded area for the scenario with breaches at Den Haag and Ter Heijde

Sensitivities and uncertainties

For the considered scenarios most fatalities occur within zones with rapidly rising water and the remaining zones. The breach zone hardly contributes[5] to the overall number of fatalities. The number of fatalities in the zones with rapidly rising waters is sensitive to the values of the rise rates used as input.

Some important sensitivities and uncertainties are discussed below. The consequences for a single scenario are strongly influenced by the choice of outside hydraulic load conditions (storm surge height and duration), and the modelling of breach growth and the course of flooding[6]. Population response and behaviour might affect evacuation success and loss of life. The number of fatalities is proportional to the number of people exposed. The number of evacuated thus has an important influence on the number of fatalities. For risk quantification the selection of the considered scenarios and the probabilities of these scenarios have an important influence on the outcomes. Above, mostly single breaches have been considered. However, if the simultaneous occurrence of multiple breaches would become more likely this would lead to the increase of consequence and risk levels. In this respect it is noted that documentation of historical coastal floods shows that these have been always characterised by multiple breaches[7].

5 For most of the scenarios 0 fatalities occur in the breach zone, as the area covered by the breach zone is relatively small and does not cover populated areas.

6 One important aspect for the course of flooding is the effect of line elements, such as roads, railways and old dikes, on the flood flow, see also (Melisie, 2006) for a discussion regarding these effects in South Holland.

7 Many historical coastal flood disasters were characterised by multiple breaches. Examples are the 1916 floods in the Netherlands (22 breaches) (Rijkswaterstaat, 1916) 1953 floods in the Netherlands (±140 breaches), the 1966 floods in Hamburg (more than 10) (Kolb, 1962) and the flooding of New Orleans after hurricane Katrina (±25 breaches).

Model uncertainties in the mortality functions and the resulting loss of life calculations have been determined by means of the confidence intervals derived in section 7. Results are reported in appendix 9.I. In addition, inherent uncertainty in the fatality estimate could arise due to variation in the outcomes of exposure of people (see section 4). For large-scale floods it is expected that this type of uncertainty has a minor influence[8] and it is therefore not analysed further.

Overall, given the above sensitivities and the lack of knowledge of the course of flood events, the presented consequence and risk numbers must be considered as indicative, but best estimates. They provide insight in the magnitude of consequences and risks of flooding. A further discussion on the use of the outcomes in decision-making is included in section 9.5.5.

Discussion of results

Results indicate that a flood of dike ring South Holland can cause hundreds to thousands of fatalities. The largest numbers[9] for the exposed population (1 million - without evacuation) and loss of life (around 5000) are found for the scenario with multiple breaches along the coast, i.e. at Katwijk, Den Haag and Ter Heijde. This flood scenario affects a large part of the western part of South Holland, yet with a small probability (~2.10^{-6} per year). Evacuation for South Holland is not very effective (see above). Therefore there are small differences between fatality number for different types of evacuation for a single flood scenario.

Mortality varies between 0,1% and 0,6% with an average of 0,3% for the considered scenarios. These rates are in the same order of magnitude as the (average) mortality fractions for global floods reported in section 5.2 ([10]). In a similar way other relationships between the reported consequence categories (i.e. fatalities, exposed and economic damage) can be investigated, see appendix 9.II for an analysis. This shows that there is a strong correlation between the following consequence categories: number of people exposed, number of fatalities and economic damage.

The results presented above can be compared with estimates of loss of life for flooding of South Holland from past studies. Asselman and Jonkman (2003) estimated that 70.000 fatalities could occur for a very extreme flood of South Holland without evacuation. A study by RIVM (2004) gives a lower limit of 2500 fatalities and an upper bound of 139.500 fatalities. In all studies it was assumed that almost the whole area of dike ring South Holland was flooded. The outcomes presented in this thesis are significantly lower, indicating that a more detailed assessment of flood pattern, evacuation and loss of life could result in a reduction of the estimated loss of life.

8 Independence of individual resistances is assumed for the studied situation. In this case a Binomial distribution can be applied to describe uncertainty in the outcomes of a flood single scenario. The number of exposed is large (N_{EXP}>100.000) and mortality relatively small ($F_D \approx 0,01$). Using equation 4-11 it can be shown for these values that the standard deviation of the Binomial distribution is very small relative to its average. In this case the Binomial distribution approximates a deterministic outcome.

9 In theory, more extreme scenarios with more fatalities might be possible. These scenarios have not been considered in this study as they have a very small probability (<< 10^{-6} per year).

10 For global coastal floods the average mortality is F_D=0,01; for river floods F_D=0,0049.

9.3.2 Risk quantification

Based on the above information regarding probabilities and consequences individual and societal risk are quantified. Based on the available data it would also be possible to determine the economic risk, e.g. in the format of an expected damage or a so-called frequency-damage or FD curve.

Individual risk

Firstly individual risk (IR) is determined for South Holland with the following formula (Jonkman, 2001)[11]:

$$IR(x,y) = \sum_i P_{f,i} F_{D|i}(x,y) \qquad \textbf{(Eq. 9-1)}$$

Where: *IR(x,y)* – Individual risk at location (x,y) [yr^{-1}]; $P_{f,i}$ – probability of occurrence of flood scenario i [yr^{-1}]; $F_{D|i}(x,y)$ – mortality at location (x,y) given flood scenario i [-]

In the elaboration of individual risk in this study, permanent and unprotected presence of people in the area is assumed and the effects of evacuation are thus neglected. This concept is thereby consistent with the definitions used in the Netherlands in the so-called external safety domain[12]. The individual risk becomes a characteristic of location and is useful for spatial planning. It is possible to take the effects of evacuation into account in the determination of individual risk, see also (Jonkman, 2001). For this case that would only lead to a very small reduction of individual risk as possibilities for evacuation in South Holland are very limited (see above).

Figure 9-6 shows the individual risk for South Holland. The highest individual risk (~10^{-4} per year) is found for deep areas exposed by scenarios with (relatively) high probabilities, e.g. in the areas Northeast of Rotterdam and South of Den Haag. This individual risk value is in the same order of magnitude as the flooding probability for the most likely flood scenario (see also section 3). For most of the areas in South Holland the individual risk is relatively low (below 10^{-6} per year), see also further discussion in section 9.5.3.

11 This formula is the discrete version of the continuous formula proposed in section 3.3.3

12 The external safety domain is concerned with (the risks) of transport and storage of dangerous goods, and airport safety in the Netherlands

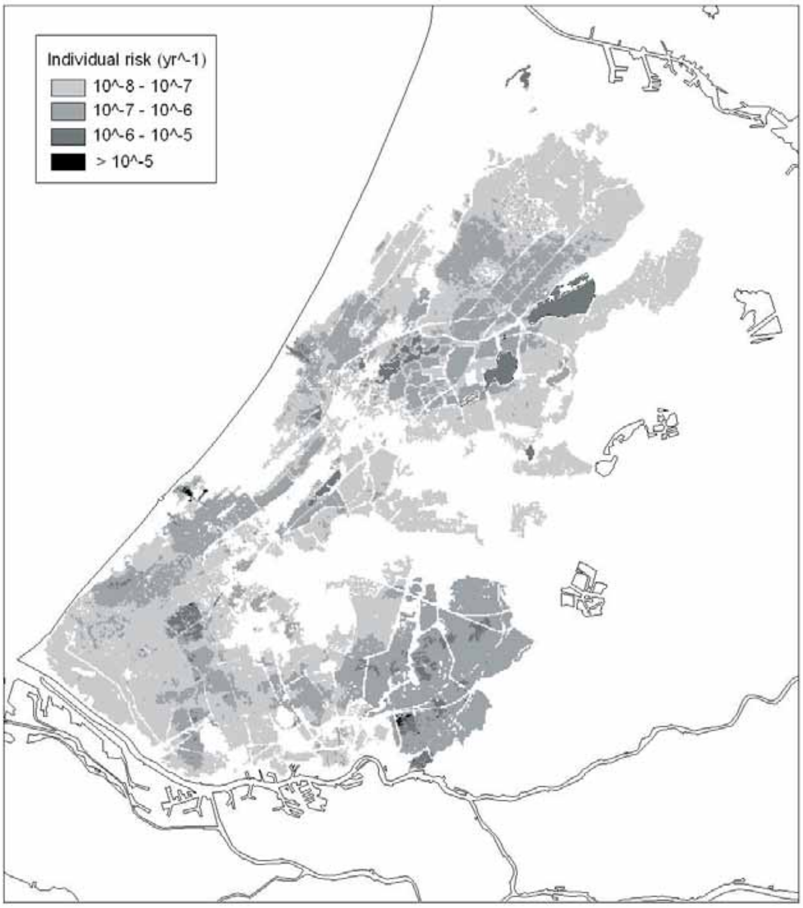


Figure 9-6: Individual risk for South Holland

Societal risk

Next, the societal risk is determined by means of an FN curve and the expected number of fatalities. In the analysis of societal risk, the effects of evacuation and the probabilities of different evacuation types have been taken into account. Figure 9-7 shows the average[13] FN curve including uncertainty bounds[14]. Only uncertainties in consequences are included here. The intersection with the vertical axis equals the flooding probability of South Holland (i.e. $3{,}94.10^{-4}$ yr^{-1}). The vertical limit at the right hand side of the curve corresponds to maximum number of fatalities (5090) and it is associated with the scenario with the largest consequences[9]. As proposed by Jongejan *et al.* (2005b), it is possible to approximate the calculated FN curve by an analytical distribution in exponential format[15]. Such an approximation could be useful for simplified analytical analyses of the risk level and risk acceptance. This approximating curve is also shown in the figure.

13 The average FN curve is based on the average dose response function derived in section 7. A symmetrical conditional distribution for model uncertainty is assumed. In that case the average and median dose response functions and the average and median FN curves are the same (see also section 4.1).

14 Due to the logarithmic scale of the horizontal axis, the 2,5% and 97,5% curves have different horizontal distances to the average FN curve.

15 Jongejan *et al.* (2005b) propose to use an exponential distribution to approximate (numerical) FN curves for different sectors. He uses the following formula: $1-F_N(n)=\frac{E(N)}{E(N\mid f)}e^{\left(-\frac{n-1}{E(N\mid f)-1}\right)}$

Where: $E(N)$ – expected number of fatalities in the system (fat / yr); $E(N|f)$ – expected number of fatalities given an accident (fat.). By using this formula an exponential approximation is found for the FN curve of flooding of South Holland (see figure 9-7).

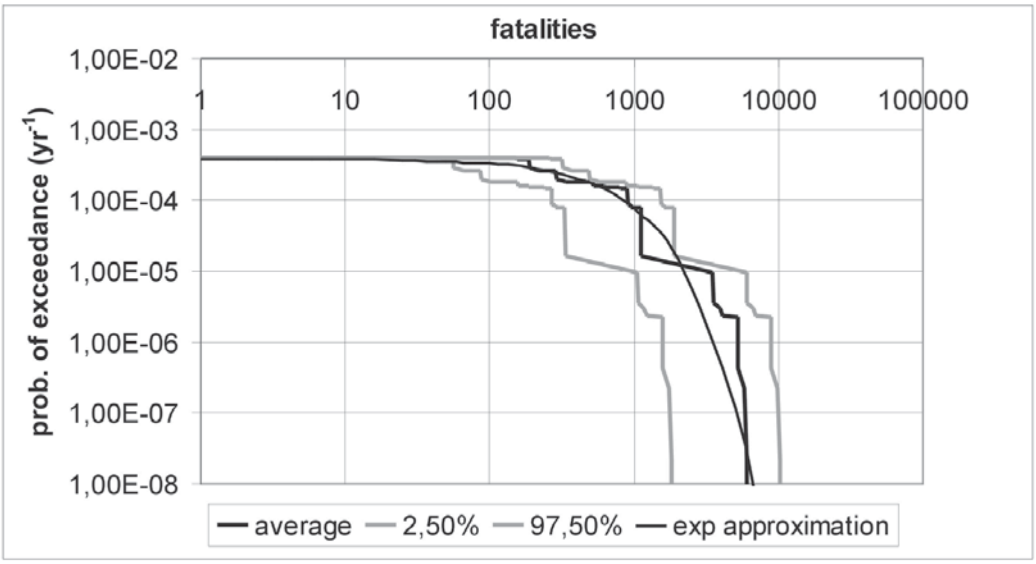


Figure 9-7: FN curve for flooding of South Holland: average FN curve, confidence intervals (2,5% and 97,5%) and exponential approximation

Figure 9-8 shows the average FN curve with the F-exposed curve. The FN and F-exposed curve are nearly parallel. Both are related via the mortality.

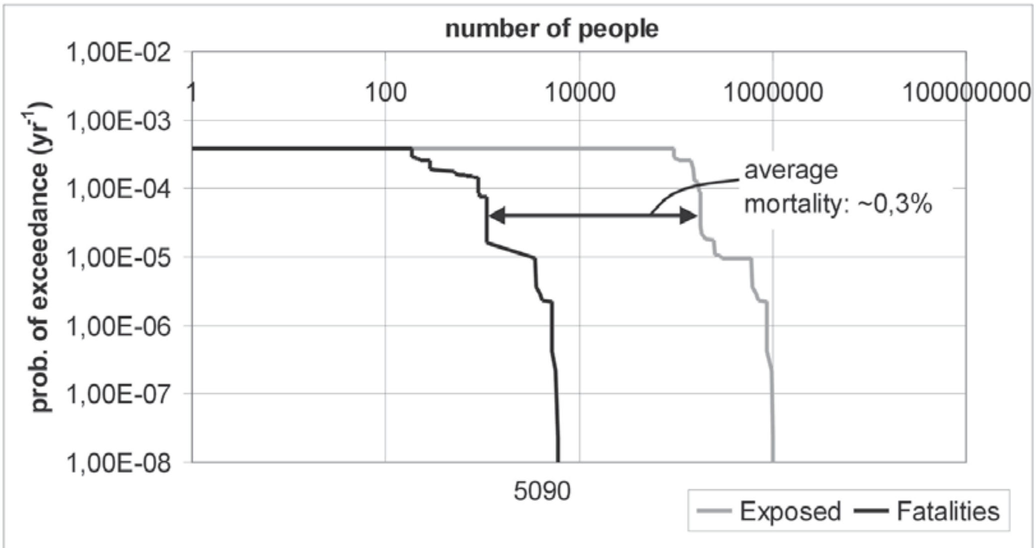


Figure 9-8: FN curve for South Holland and F-exposed curve

Based on the probabilities and fatality numbers for the scenarios, the expected number of fatalities can be determined[16]. This yields: $E(N)$=0,21 fat/yr. The standard deviation equals: $\sigma(N)$=16,1 fat/yr (see discussion below).
Based on this information the values for other risk measures can be calculated, for example for the risk integral and total risk (see also section 3.3.4). In addition, the expected number and the standard deviation of the exposed population can be determined:
$E(N_{EXP})$=62,1 pers/yr $\sigma(N_{EXP})$=3670 pers/yr

For this type of small probability – large consequence event the expected number of fatalities per year is generally relatively small. However, for this type of event the number of fa-

16 The expected value can also be found by integrating the area under the FN curve (Vrijling and van Gelder, 1997).

talities in one single event can be large, resulting in a large standard deviation. Such events have limited weight in risk neutral decision rules or risk criteria in which the expected number of fatalities is included. However, the so-called risk aversion against these large accidents can be taken into account in risk limits (see also sections 1.2.2 and 9.5).

9.4 Comparison of the societal risk for flooding with other sectors

In this section the calculated societal flood risks for South Holland are compared with those in other sectors in the Netherlands. Similar analyses have been presented by Jonkman (2001) and RIVM (2004). Figure 9-9 depicts the FN curve for traffic accidents[17] and external safety[18] in the Netherlands and the calculated FN curve for flooding of South Holland. For frequent accidents, e.g. traffic accidents, the frequency can become larger than once per year. The figure shows that deadly traffic accidents occur frequently, but that the consequences of individual events are restricted to a limited number of fatalities (<6). Accidents in external safety have a small probability but large potential consequences.

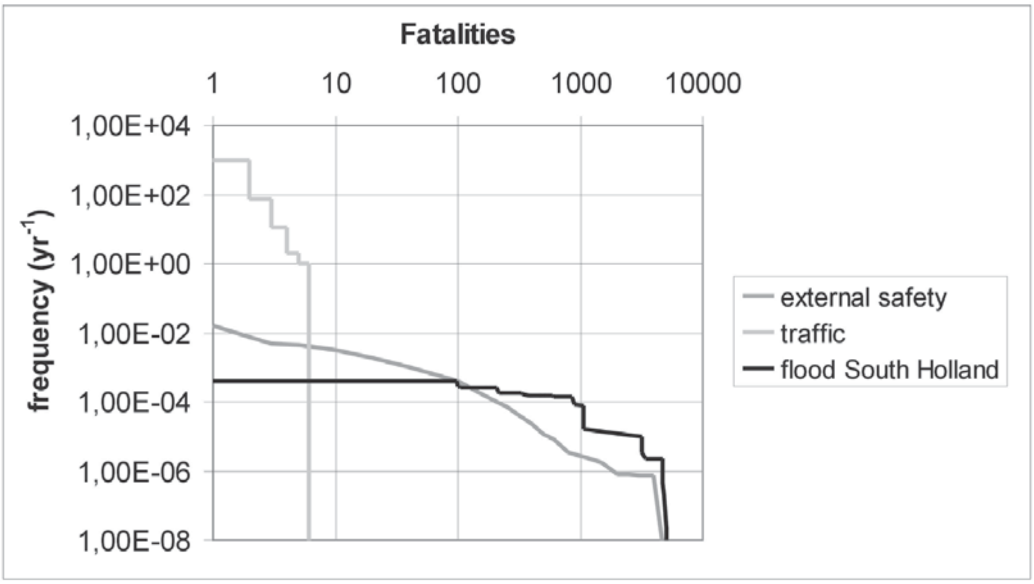


Figure 9-9: FN curve for traffic (one year), external safety at a national scale and flood risk for South Holland

The societal risk for flooding of South Holland is larger than the risk for the external safety domain (for events with more than 100 fatalities). The FN curves for other dike ring areas have to be added to obtain the societal risk for flooding at a national scale. Based on the above results, it is expected that the flood risks in the Netherlands are higher than the risks for external safety. In general, the presented results confirm the outcomes of previous studies (Jonkman, 2001; RIVM, 2004) that also concluded that the societal risk of flooding at a national scale is higher than the societal risk for the external safety domain[19].

17 Observations for the year 2003 with in total 940 fatalities; source Rijkswaterstaat AVV.

18 The external safety domain covers the risks of storage and transportation of dangerous goods and airports. Source of risk estimates: Milieu en Natuur Compendium (http://www.mnp.nl/mnc/i-nl-0303.html (31-5-06)).

19 However, the differences between external risks and flood risks are not as large as reported in previous studies, e.g. (RIVM, 2004), especially with respect to consequences. See also (Jonkman and Cappendijk, 2006) for a further discussion.

The above comparison gives insight into the relative magnitude of the risks in different domains. It is noted that other risk measures, such as the expected number of fatalities and individual risk, can be used to compare different risk domains. These types of information can be of interest for policy makers and could be used for a discussion about the necessary expenditures on risk reduction in different sectors. However, when comparing different risk sectors in decision-making it is necessary to take into account the characteristics of the activities. For example, the perception of the activity and the benefits associated with the activity are important, see also (RIVM, 2004) and (Jongejan, 2006) for a further discussion.

9.5 Evaluation of the flood risk

In this section the application of existing criteria for risk evaluation to the flood risk of the case study area is investigated. First, a previously proposed framework for risk evaluation is summarised (9.5.1). Within this framework a method is proposed for the distribution of the acceptable societal risk over installations with different sizes, such as dike rings (9.5.2). Consequently, the calculated flood risk levels are compared with the obtained risk limits in section 9.5.3.

9.5.1 Framework for risk evaluation

An important issue in the assessment of the risks is the evaluation of the acceptability of risks. Many different approaches are available for the quantitative evaluation of risk (see also section 1.3.5 for a discussion). Below, the flood risks for South Holland are compared to an existing framework for the evaluation of risks. It has been developed in previous publications (TAW, 1985; Vrijling *et al.*, 1995; Stallen *et al.*, 1996; Vrijling *et al.*, 1998). The proposed risk criteria can be seen as technical advice to policy makers. Later studies illustrated the usefulness of this approach for different fields of application, such as tunnels (Arends *et al.*, 2004) and flood protection (Jonkman, 2001). Within the framework the risks are evaluated from both an individual and a societal point of view. Moreover the societal perception of the considered activity is considered, as well as the investments in risk reduction in the context of a cost benefit framework. The three elements in the framework are briefly summarised below. For further background information and explanation reference is made to the earlier mentioned literature.

Firstly, a criterion for the limitation of individual risk is applied:

$$IR < \beta 10^{-4} \qquad \textbf{(Eq. 9-2)}$$

In this expression the value of the policy factor β[-] varies according to the degree to which participation in the activity is voluntary and with the perceived benefit. Proposed values for β are between 0,01 for involuntary activities (exposure to the risks of a hazardous installation) and 100 (e.g. for mountaineering, a voluntary activity for personal benefit), see table 9-3. The limitation of the individual risk for all citizens ensures that no one will be disproportionally exposed to the risk and it thus ensures equity.

Table 9-3: Value of policy factor β as a function of characteristics of the activity (Vrijling *et al.*, 1998)

β	Voluntary	Benefit	Example
100	Completely voluntary	Direct benefit	Mountaineering
10	Voluntary	Direct benefit	Motorbiking
1	Neutral	Direct benefit	Car driving
0,1	Involuntary	Some benefit	Factory
0,01	Involuntary	No benefit	LPG station

Secondly, a criterion for the judgement of societal risk is needed. The aggregated level of risk on a national scale could still be considered unacceptable even when the individual risks are considered acceptable. The acceptable societal risk for an installation can be limited as follows:

$$1 - F_N(n) < C_I / n^{\alpha} \qquad \textbf{(Eq. 9-3)}$$

Where: C_I – constant that determines the vertical position of he FN limit line for one installation [yr^{-1} $fat^{-\alpha}$]; α – risk aversion coefficient that determines the steepness of the FN curve.

In further analysis we assume a steepness of the limit line α=2. This steepness reflects risk aversion towards large accidents and is also used in other sectors in the Netherlands[20]. For events with small probability and large consequences it can be shown that the above criterion basically limits the standard deviation of the number of fatalities. It is proposed to decide on the acceptability of societal risk of an activity on a national scale in a societal debate first. Consequently the nationally acceptable risk can be distributed over single installations in order to obtain a constant for each installation C_I, see next section.

Finally, (aspects of) the decision problem the acceptable level of risk can be formulated as an economic decision problem. This third criterion aims at achieving an economically optimal risk level. The total costs in a system (C_{tot}) are determined by the sum of the expenditure for a safer system (I) and the expected value of the economic damage ($E(D)$).

$$C_{tot} = I + E(D) \qquad \textbf{(Eq. 9-4)}$$

In the optimal economic situation the total costs in the system are minimised. With this criterion the optimal probability of failure of a system can be determined, provided that the investments (I) and the expected economic damage[21] ($E(D)$) are a function of the probability of failure[22]. A well-known example of this approach is given by van Dantzig (1956), who derived an economically optimal level of risk for flood defence systems in the Netherlands.

Due to the combination of these three criteria a coherent framework for risk evaluation is obtained that takes into account the most important consequence types (economic damage and loss of life). It approaches the problem of acceptable risk from different points of view

20 Here, it is only noted that there is a lot of discussion in literature on the use of the FN limit lines and the appropriate steepness, see e.g. Evans and Verlander (1997) and (Ball and Floyd, 1998)

21 It is also possible to take the economic value of loss of life into account (and other consequence types) in the estimation of economic damage.

22 In a more complete analysis measures that reduce the consequences could also be included in the economic optimisation, see e.g. Jongejan and Vrijling (2006), Jonkman *et al.* (2003).

(individual and societal; equity and efficiency). In order to ensure that all three criteria are sufficiently fulfilled, the most stringent of three criteria should be applied as the limit.

9.5.2 Distribution of acceptable societal risk over objects with different sizes

In the framework discussed above it is proposed to first decide on the acceptability of societal risk for an activity on a national scale. Based on earlier work by (Vrijling *et al.*, 1995; Stallen *et al.*, 1996) the following formula can be used for the constant that determines the vertical position of the limit line at a national scale.

$$C_N = \left(\frac{\beta 100}{k} \right)^2 \qquad \textbf{(Eq. 9-5)}$$

Where: C_N – constant in formula 9-2 that determines the height of the FN limit line at a national scale; k – risk aversion factor, usually k=3; β - policy factor that determines risk acceptance (see section 9.5.1)

Consequently, the nationally acceptable societal risk needs to be distributed over single installations or objects to obtain a criterion to the acceptable risk for one object[23]. For a certain number of identical objects (N_I) the following expression has been proposed (Vrijling *et al.*, 1995):

$$C_I = \left(\frac{\beta 100}{k\sqrt{N_I}} \right)^2 \qquad \textbf{(Eq. 9-6)}$$

This equation shows that there is an inverse linear relationship between C_I and number of objects in case of objects with identical size. However, the distribution of the nationally acceptable societal risk over individual objects with different sizes has not been substantiated further in existing work. Below, first proposals concerning this distribution issue are given to stimulate further thinking and elaboration, see also (Jongejan *et al.*, 2005).

It seems reasonable to distribute the nationally acceptable risk over objects according to the relative size of an object at a national scale. A variable I_I is defined that represents the production or intensity of use of an object, e.g. the number of flights at a local airport. Then, the following formula can be used to determine the height of the FN limit line for each object:

$$C_I = \frac{I_I}{I_N} C_N = \frac{I_I}{I_N} \left(\frac{\beta 100}{k} \right)^2 \qquad \textbf{(Eq. 9-7)}$$

Where: C_N – height of FN limit line at a national scale; I_I – production of object; I_N – production at the national scale.

An object that is more intensely used would be provided with a larger part of the national risk budget than a smaller object. As larger objects generally produce more benefits for

23 The term object could refer to various objects such as airports, chemical installations, flood prone areas.

society, the acceptable risk is thereby related to the benefits of the activity[24]. To make this approach operational it is necessary to define indicators for intensity of use for different applications. Table 9-4 gives an overview of indicators that can be used to determine the relative weight of each object for different applications[25] has to be applied.

Table 9-4: Proposed objects and indicators for distributing the nationally acceptable societal risk over different objects.

Application	Installation / object	Indicators for production or intensity
Flood protection	Dike ring	Number of inhabitants
Third party risks airports	Airport	Number of flights
Storage and treatment of hazardous materials	Installation	Volume / weight of stored materials

Following this approach a large national airport with many flights can have a larger societal risk than a small local airport with a limited number of flights. A certain minimum level of protection (equity) is still ensured by application of the individual risk criterion and also the economic optimisation[26] has to be applied. Further background regarding the derivation of formula 9-7 and application of the proposed approach are discussed in appendix 9.III.

9.5.3 Evaluation of the flood risk for dike ring South Holland

In this section the application of the proposed criteria for the evaluation of individual and societal risk to the case study area is investigated. Only individual and societal risk are examined. For a more complete risk evaluation also the use of economic optimisation for this area is recommended, see e.g. (Eijgenraam, 2006; Thonus *et al.*, 2005).

Individual risk

The individual risk for South Holland is compared with existing risk limits. According to the above framework the individual risk (IR) is acceptable if $IR < \beta 10^{-4}$. For flood risk a value of β between 0,01 (involuntary activity with little benefit: $IR = 10^{-6}\ yr^{-1}$) and 0,1 (involuntary activity with some benefit: $IR=10^{-5}\ yr^{-1}$) seems reasonable. These values correspond to IR limits used in external safety. For (new) chemical installations individual risks higher than 10^{-6} per year are unacceptable, whilst the limit value is 10^{-5} per year for existing installations. Figure 9-10 shows the areas of South Holland where the risks are unacceptable according to these two proposed values. Results show that the individual risk level of 10^{-5} is exceeded only in a few areas. The 10^{-6} individual risk level is exceeded in low-lying areas south of Den Haag and east of Rotterdam.

24 The use of identical risk standards for large and small objects will lead to much higher costs for the large object to fulfill the societal risk criterion.

25 The approach presented below is mainly applicable for hazards for which separate installations or objects can be clearly distinguished. The possibilities for distribution of societal risk have to be studied further situations where no separate objects can be distinguished. An example concerns the transport of hazardous materials, where materials are transported over network of roads and railways. For such cases it is proposed to look for some practical indicator for distribution, for example a stretch of road.

26 It is noted here that that the trend that follows from the societal risk criterion (larger facilities can have a larger acceptable risk) is in contrast with the trend that follows from the economic optimisation, where better protection is given to larger areas / facilities that sustain more damage. The difference between the approaches is due to the different assumptions that have been made in formulating them. The societal risk criterion is related to benefits, the economic optimisation to the risk costs. Eventually, the most stringent of the different risk criteria will determine the acceptable risk level.

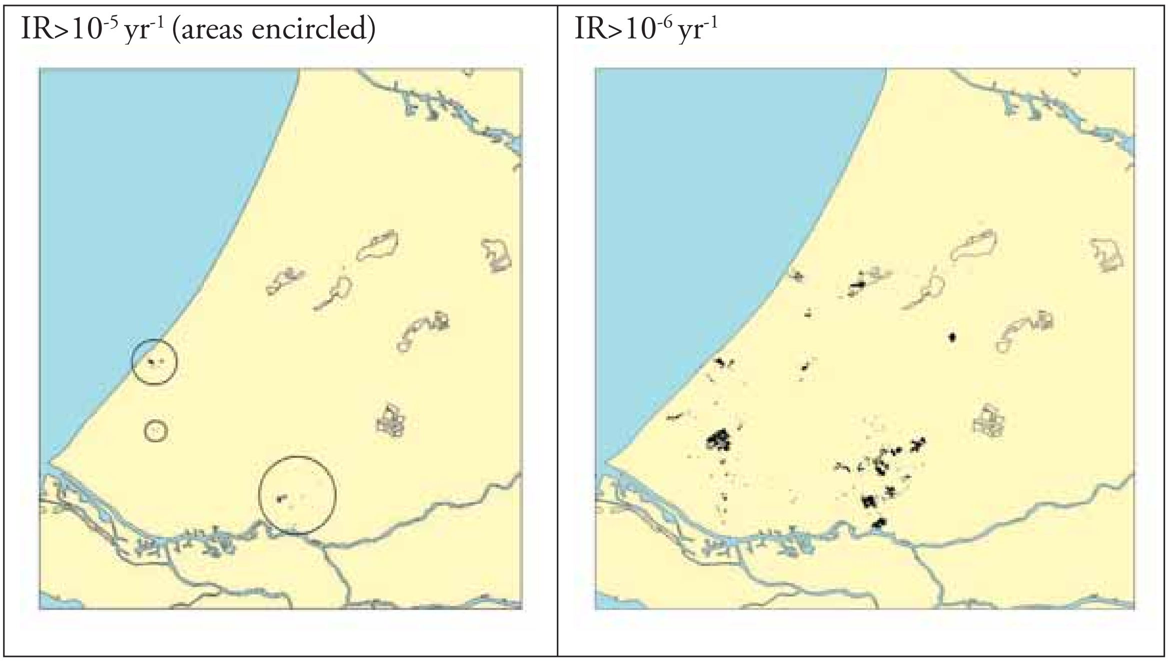


Figure 9-10: Regions in dike ring South Holland that exceed the proposed limit values for individual risk due to flooding

Societal risk

Figure 9-11 compares the FN curve for flooding of South Holland with limit lines for different values of C_I. South Holland has 3,6 million inhabitants and in the Netherlands approximately 10 million people live in flood prone areas. Application of equation 9-7 in combination with β=0,1 results in a value of C_I=4. Results show that the current flood risks would be unacceptable for this value. The flood risks would be considered acceptable for C_I≈100 and β≈0,5. This β value corresponds to activities with a neutral voluntariness and direct benefit, such as driving a car (Vrijling *et al*, 1998). A policy factor value of 0,1 seems more reasonable. It is thus found that the current societal risk for South Holland is higher than would be considered acceptable according to the existing limits proposed by Vrijling *et al.* (1995, 1998)[27].

It is noted that the chosen treatment of uncertainty could affect the height of the risks and thereby the acceptability of the situation according to risk limits. In the previous results the average FN curves and uncertainty bounds for knowledge uncertainty have been presented separately. Integration of knowledge uncertainty in the results could lead to an increase of the risk level and exceedance of the limit line (see section 4 for a more extensive discussion).

27 The standard for societal risk discussed here is based on the total risk (TR) approach. For the area the TR becomes: $TR=E(N)+k\sigma(N)$≈50 fat/yr. The proposed limiting value for TR is β100. The existing situation would be acceptable for β≈0,5, which is the same result as when the FN criterion is used.

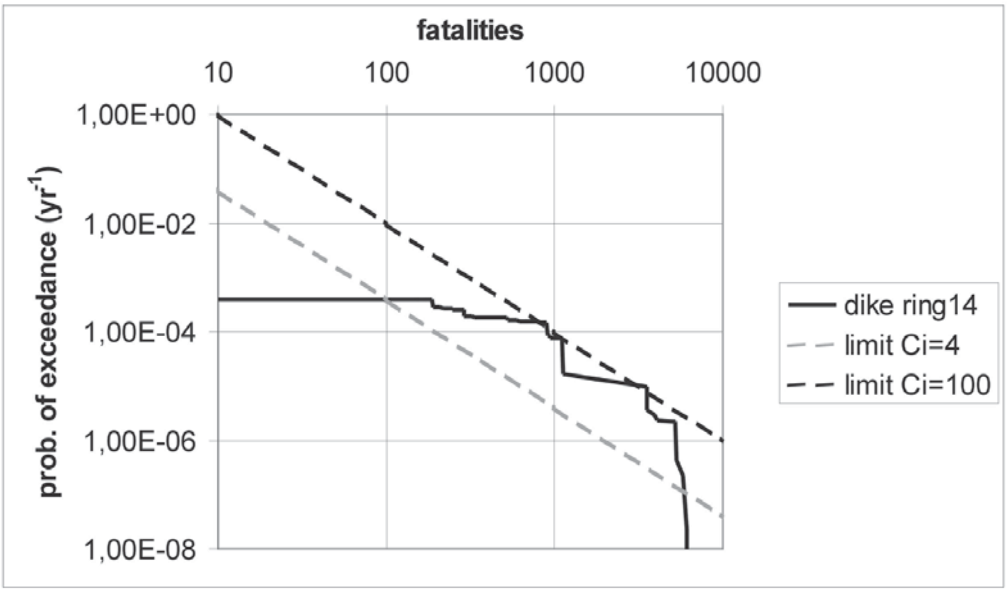


Figure 9-11: FN curve for dike ring South Holland and two limit lines or different values of C_I

9.5.4 Analysis of the effectiveness of measures to reduce the flood risk

If the determined risk levels are considered to be unacceptably high, it can be decided to reduce the risk. A distinction can be made between measures that reduce either the flooding probability or the consequences. The effects of these two types are schematically indicated in the schematic FN in figure 9-12. Measures to reduce the flooding probability could be dike strengthening or space for rivers[28]. Measures that aim at a reduction of consequences can either reduce the extent of physical effects (e.g. by construction of internal compartment dikes), the number of people exposed (e.g. by evacuation) or the mortality (e.g. by influencing the behaviour of people during the flood).

Figure 9-12: FN curve indicating the effects of two types of measures (Jonkman, 2001)

28 Dike strengthening increases the strength of the dike, space for rivers reduces the loads on the dike. Both lead to a reduction of the flooding probability.

In general, an analysis of effectiveness of measures has to be based on the required investments and the reduction of (expected) damages to economy, environment and population. A cost benefit analysis can be used to examine which (combinations of) measures are favourable. The cost effectiveness of measures can be specifically related to the reduction of loss of life by means of the evaluation of the cost of saving and extra statistical life (CSX), see section 2.6. This approach relates the investments in safety measures (I) to the reduction of the expected number of fatalities ($\Delta(E(N)$), so that $CSX = I / \Delta E(N)$. The CSX thus expresses the yearly investments needed to reduce the risk level by one expected fatality per year, so it has the unit € per fatality.

Here, cost effectiveness is analysed for a number of measures that can be taken to reduce the flood risk in South Holland. Fictitious but not unreasonable estimates are used for the investment costs and resulting reduction of flooding probability and consequences, see e.g. (Thonus *et al.*, 2005). First two dike strengthening projects are examined that reduce the probability by factors 10 and 100 respectively, with associated investment costs of 150 and 900 million Euro[29]. The construction of compartment dikes inside the flooded area can reduce the consequences, it is estimated by 50%. It is assumed that the costs of these new dikes are high (1 billion Euro)[30]. Better evacuation could reduce the number of fatalities. It is assumed that the investments in evacuation road capacity and regular drills are about 100 million Euro and that it reduces the fatalities by 30%. Finally, investments in rescue capacity (20 million euro) could lead to a limited reduction (10%) of fatalities. The initial investments are converted to an average yearly investment by assuming a discount rate of 4% and an infinite investment period.

With these data the CSX values for the measures are calculated in table 9-5. For these measures discussed above figure 9-13 displays[31] the yearly investment as a function of the reduction of the expected value of the number fatalities ($\Delta E(N)$). The CSX corresponds to the steepness in this graph. The most effective measure is the one with the smallest steepness, i.e. the expenditure that achieves largest risk reduction at lowest cost.

Table 9-5: Overview of measures to reduce the flood risk and their CSX value (Probability of flooding and consequences after measure are given as fraction of the original situation)

Measure	Initial Investment [Meuro]	Yearly investment [Meuro/yr]	Probability	Consequences	Δ E(N) [fat/yr]	CSX [10^6 Euro / fat]
Dike strengthening 1	150	6	0,1	1	0,189	32
Dike strengthening 2	900	36	0,01	1	0,208	173
Compartment dikes	1000	40	1	0,5	0,105	381
Evacuation	100	4	1	0,7	0,063	63
Rescue	20	0,8	1	0,9	0,021	38

29 These estimates of the investment costs are based on (Thonus *et al.*, 2005).

30 In some cases internal dikes might still be (partly) present in an area and investment costs could be lower.

31 Alternative presentations are possible. For example the absolute risk level after the measure at the vertical axis as a function of the investment cost at the horizontal axis, see also (Bohnenblust, 1998).

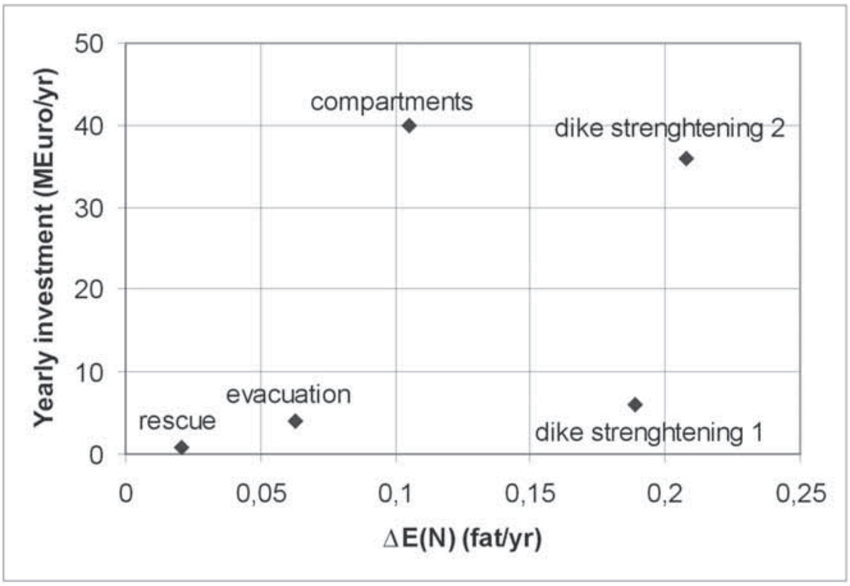


Figure 9-13: Reduction of expected number of fatalities as a function of investment costs for different measures.

For this case dike strengthening number 1 has the lowest CSX value, i.e. it gives most risk reduction at lowest cost. Another interesting measure is the improvement of rescue capacity. Although it gives limited risk reduction, costs are relatively low. Of the considered alternatives, investment in compartment dikes has the highest CSX as it gives limited risk reduction at high cost[28]. It should be noted that the last two measures (evacuation, rescue) do not reduce the economic damage caused by a flood. The first three measures have the benefit of additional (economic) damage reduction.

The calculated CSX values for investments in flood risk reduction are higher than the average CSX values derived from the study by Tengs *et al.* (1995) for investments in health care (0,76 million US$ per fatality) and traffic safety (2,2 million US$ per fatality)[32]. The CSX values for flood risk reduction are in the same order as the average CSX values reported by Tengs *et al.* for toxin control (112 million US$ per fatality). The calculated CSX value for flooding exceeds the value calculated that follows from macro economic valuation (0,5 million Euro) and the life quality method (1 to 4 million Euro), see section 2.6 for further discussion. The CSX values for flooding obtained in this study are high, due to the relatively low initial risk level and the high investment costs.

In the future, it is recommended to execute similar analyses for South Holland and other dike ring areas in the Netherlands. Using more realistic numbers for investment costs and risk reduction the effects of various measures can be assessed. In a more detailed analysis combinations of various measures could also be analysed. Such results can be presented to decision makers to support decisions regarding risk reduction measures.

32 The values reported by Tengs *et al.* (1995) are costs per life year saved. It is assumed here that 40 life years have to be saved to save one average fatality.

9.5.5 General remarks regarding the application of the results to decision-making

In this section the role of loss of life and risk estimates in the decision-making is discussed.

Decision criteria

Firstly, loss of life and risk estimates are used in various decision criteria to evaluate the acceptability of the (current) risk level in a system. In decision criteria that are based on the expected value, such as the economic optimisation, the consequence estimate has a linear influence on the resulting protection level, which is expressed as the probability of flooding. However, risk averse decision criteria, such as the limit line in the FN curve, include a quadratic relationship between the consequences and the acceptable flooding probability. For coastal areas in the Netherlands a reduction of the flooding probability by a factor 10 would require a dike heightening in the order of magnitude of 1m (and 2m heightening for a reduction of the flooding probability of a factor 100).

In the use of quantitative risk limits it is also important to consider possible variations and uncertainties in the outcomes of consequence and risk calculations (see also section 4). A less desirable situation is one in which a small change in the consequence estimate leads to exceedance of the limit and very high investment costs in risk reduction measures. Therefore it is important that a designed system is characterised by a certain extent of robustness[33].

Measures and sensitivities

Loss of life and risk estimates are sensitive to certain input parameters, such as the number of breaches, the rise rate and evacuation (see section 9.3.1). On the one hand, these sensitivities indicate the need for more research on the influence of these parameters. On the other hand, these sensitivities also indicate that decision makers should be careful with choosing measures that are associated with these parameters, because their risk reducing effects are uncertain. Small changes in the circumstances could greatly reduce the effectiveness of these measures and lead to much larger consequences. Examples of such sensitive measures are evacuation and the application of compartment dikes. The success of evacuation depends on the behaviour of people and it may not be effective for all areas and situations. The effectiveness of compartment dikes differs by flood scenario. Compartment dikes could influence the rise rate and in some cases lead to an increase of fatalities. These types of measures are thus less robust.

Decision-making based on uncertain results: more research or implementation of measures?

The presented consequence and risk analyses are aids in the decision-making process regarding flood defence strategies and protection levels. With regard to uncertainties in the outcomes there are two possible decisions. Firstly, it can be decided that the applied model is not accurate enough and that more research[34] is needed to come to a decision regarding the implementation of (physical) measures in the future. In that case it is thus decided that

33 A robust design is a design that is able to fulfill its required function throughout the entire planning period without major modifications when relatively minor changes occur (Vrijling *et al.*, 2006). These changes can concern the load conditions or the calculation models that are used to assess the risks in the systems.

34 For example the inclusion of more factors in the loss of life model.

the existing safety situation will continue to exist while additional information is gathered and analysed. In the field of flood protection the additional information to improve the risk estimates often has to come from actual disasters that we strive to avoid. Secondly, it can be decided that, despite the uncertainties, the outcomes of risk analysis justify the need for (physical) measures.

Eventually it is the task of decision makers to decide on the acceptability of the current risk levels and to evaluate the need to take (physical) measures to reduce the risk. The outcomes of consequence and risk analyses, including the uncertainties in these analyses, are input information for these decisions. Apart from loss of life estimates, the probability of an event, the economic consequences, the costs of measures and the perception (of the severity) of an event are all important factors and uncertainties will be associated with these factors as well.

9.6 Concluding remarks

In this section the results of an analysis of flood risks for dike ring South Holland have been presented. Results indicate that a flood event in South Holland is expected to expose large and densely populated areas and lead to hundreds to thousands of fatalities. The possibilities for evacuation of South Holland are very limited due to the small amount of time available and the large amount of time required[35] (Van der Doef and Cappendijk, 2006). Based on these results further investigation of the possibilities for improvement of evacuation of South Holland, and the development of alternative strategies, e.g. for shelter in place, is strongly recommended. Information regarding the elaborated flood scenarios and the number of people exposed can be used for the development of strategies for evacuation, shelter and rescue operations. It is necessary to have emergency plans prepared and practised before a serious flood occurs.

It is interesting to compare the predicted consequences of two flood scenarios for South Holland with the observed consequences of flooding of New Orleans due to hurricane Katrina in 2005, see table 9-6. For south Holland one scenario with a single breach near Rotterdam (Kralingen) and a coastal flood scenario with three breaches along the coast are considered (see figure 9-2 for breach locations). Results show that a disaster with a comparable magnitude as the flooding of New Orleans can also occur in the Netherlands. For some scenarios the estimated number of fatalities is even higher than in New Orleans. This illustrates the catastrophic potential of large-scale flooding of low-lying areas in the Dutch delta.

Table 9-6: Comparison of the consequences of flooding of New Orleans with flood scenarios of South Holland

	South Holland Rotterdam Kralingen	South Holland - Katwijk, Den Haag, Terheijde	New Orleans (2005)
Inhabitants in flooded area	180.000	1.015.000	420.000
Exposed and people in shelters	145.000 – 180.000#	984.000 – 1.015.000#	75.000*
Fatalities in flooded area	900 – 1100#	5000 – 6100#	910*
Flooded area	140 km^2	1080 km^2	260km^2
Direct economic damage (1 billion = 10^9)	€ 7 billion	€ 37 billion	US $ 30 billion
Number of breaches	1	3	±25

#: Total number of exposed and number of fatalities depend on the success of evacuation (see also above).
*: Estimates of the numbers of exposed and fatalities in the flooded area are based on the analyses in section 8. The total number of fatalities for Louisiana is 1118 and 81% of the recoveries occurred inside the flooded area.

The analysis showed that individual risk in South Holland is relatively low and mostly acceptable according to existing limit values. The individual probability of death is relatively small for flooding in comparison with the probability of death due to other activities, such as driving a car (~10^{-4} yr^{-1}) or smoking (~5.10^{-3} yr^{-1}). However, societal risk is higher than would be considered acceptable according to the limits that have been proposed in literature (Vrijling *et al.*, 1995) because large numbers of fatalities are expected in single flood

35 Evacuation will be better possible for other areas in the Netherlands. For example, for river areas prediction lead time is larger. However, several international sources document the limited effectiveness of evacuation, e.g. Ramsbottom *et al.* (2003) for the UK. Zhai *et al.* (2006) mention that for 18 recent flood evacuations in Japan, the average evacuation rate was 26%.

events. Societal risk for flooding of South Holland is high in comparison with the risk in the external safety domain the Netherlands. For a more complete comparison of external and flood risks, the flood risks for other dike ring areas in the Netherlands will have to be assessed as well.

Further discussion on the acceptability of the current level of flood risk in the Netherlands is needed, see also (MinVenW, 2006). The current standards for flood protection are mainly based on an econometric analysis and not on potential risks to people. It is proposed to take into account the individual and societal risk as additional limits for flood risks to people (see also TAW, 1985; Jonkman, 2001; RIVM, 2004; Adviescommissie Water, 2006). For the evaluation of societal risk an analysis per dike ring seems to be a suitable spatial aggregation level. A method has been proposed for the determination of the position of the limit line per dike ring. It takes into account the (relative) size of the dike ring and the acceptance of the flood risk in the Netherlands. In addition to the assessment of individual and societal risks it is also important to re-evaluate the economic foundation of the current risk limits, see e.g. (RIVM, 2004; Eijgenraam, 2006). In the evaluation of the acceptability of the flood risk it is also relevant to take into account the possible effects of climate change and the future land use developments in flood prone areas.

When the flood risks are considered unacceptable, risk reduction is necessary. An indicative analysis of the effectiveness of measures related to loss of life has been presented by means of the analysis of the Cost of Saving an Extra Life (CSX). Such results can be presented to decision makers to support decisions regarding risk reduction measures. In order to accomplish well-informed decision-making, it is important to evaluate and compare different measures for their effectiveness. Such a broad comparative analysis of the (cost) effectiveness of possible measures to reduce the flood risk in the Netherlands has not been found yet in the analyses and evaluations of the flood risk in the Netherlands. Eventually it is the task of decision makers to decide on the acceptability of the current risk levels and to evaluate the need to take (physical) measures to reduce the risk. The presented consequence and risk analyses are input information for making these decisions.

10 Conclusions and recommendations

10.1 Conclusions

This thesis concerns the estimation of loss of human life in the context of risk assessment, with a focus on applications to floods. In the first part of this thesis a general approach for loss of life estimation and risk quantification has been proposed. The second part focuses on the analysis and estimation of loss of life caused by floods.

Part one: A general approach for loss of life estimation and risk quantification
A general method has been proposed for the estimation of loss of life. It is generally applicable to 'small probability – large consequence' accidents within the engineering domain, such as floods, earthquakes and airplane crashes. An estimate of the loss of life caused by an event can be obtained based on three elements: 1) the intensity of physical effects and the extent of the exposed area; 2) the number of people exposed (sometimes reduced by evacuation, shelter and rescue) and 3) the mortality amongst the people exposed. Mortality (the number of fatalities divided by the number of people exposed) is usually determined with a so-called dose response function or mortality function. This gives the relationship between the intensity of physical effects and the mortality in the exposed population.

Using these elements, general analytical formulations for the quantification of individual risk[1] and societal risk[2] have been derived based on reliability theory. With the proposed formulations a theoretical confirmation of the relationship between individual and societal risk has been given. The formulations also give insight in the properties of the FN curve, the individual risk contours and their mutual relationship. These insights can be used to verify the consistency of individual and societal risk calculations obtained from numerical models.

Such a general and uniform set of formulations was not yet available in literature. The foundation of consequence and risk quantification has been improved with the developed general approach. It enhances the possibilities to assess the risks to people for various fields of application. It also provides insight in the effectiveness of various risk reducing measures, such as evacuation, or measures aiming at the prevention of failure.

Most existing methods for consequence and risk analysis do not explicitly account for uncertainties in loss of life estimates. In section 4 of this thesis the insight in the effects of uncertainties in loss of life estimates on the outcomes of risk quantification has been improved. It has been shown how uncertainties affect the distribution of the number of fatalities given an accident and thus the value of the standard deviation of the number of fatalities. Thereby the uncertainties can affect compliance to risk averse risk limits, for example the limit line for risk acceptance with a quadratic steepness in the FN curve. It is noted that the uncertainties do not have an effect on the expected number of fatalities.
It has been demonstrated that two types of uncertainty influence the distribution of the number of fatalities given an accident. Firstly, uncertainty arises in the consequences of

1 Individual risk: The probability (per year) of being killed at a certain location assuming permanent presence of the population.

2 Societal risk: The probability of exceedance (per year) of an accident with a certain number of fatalities.

the exposure of a group of people to physical effects due to the variation in individual responses to exposure. The resulting probability distribution of the number of fatalities is determined by dependencies between individual failures. It has been shown that typical distribution types are obtained for some characteristic situations, for example the Bernoulli distribution when all failures are fully dependent. Secondly, model uncertainty can exist in the dose response function because the underlying observations represent different circumstances and /or populations with different vulnerabilities.

Part two: Loss of life estimation and flood risk assessment

The scarcely available information regarding loss of life in historical floods has been evaluated. Analysis of global data on natural disasters shows that the impacts of floods on a global scale are enormous. Large-scale coastal and river floods that affect low-lying areas protected by flood defences can cause many fatalities. Based on available event statistics it has been shown that a first order estimate of loss of life due to coastal flood events can be obtained by assuming that 1% of the exposed population will not survive the event. This rule of thumb gives a good approximation[3] of the overall number of fatalities for some historical events, e.g. the floods in the Netherlands in 1953 and the flooding of New Orleans after hurricane Katrina in 2005.

By analysing historical flood events, the insight in the factors that influence the loss of life caused by floods of low-lying areas protected by flood defences has been improved. The number of fatalities caused by a flood event is determined by the characteristics of the flood (water depth, velocity, rise rate), the possibilities for warning, evacuation and shelter, and the loss of shelter due to the collapse of buildings. Mortality rates are the highest near breaches and in areas with a large water depth, a high rise rate and a large number of buildings collapsed.

A review of existing models for loss of life estimation from different regions and for different types of floods (e.g. for dam breaks, coastal floods, tsunamis) showed that the existing models do not take into account all of the most relevant factors (see above) and that they are often to a limited extent based on empirical data of historical flood events.

The general approach for loss of life estimation that has been proposed in part one of this thesis has been applied to develop a method for floods of low-lying areas protected by flood defences. An estimate of the loss of life due to a flood event can be given based on information regarding the flood characteristics, an analysis of the exposed population and evacuation and an estimate of the mortality amongst the exposed population. By analysing information from historical floods mortality functions have been developed. These relate the mortality amongst the exposed population to the flood characteristics for different zones in the flooded area. Thereby an improved method for loss of life estimation for floods has been developed. It is improved because a) it takes into account the most relevant event characteristics that determine loss of life and b) their influence has been quantified based on available empirical information regarding loss of life in historical flood events. Comparison of the outcomes of the proposed method with information from historical

3 Observed event mortality for the Netherlands 1953 flood: 0,7%. (Preliminary) observed mortality for the flooding of New Orleans: 1,2%. Also for other historical flood events, such as floods in Japan in 1959 (1,2%) and in the United Kingdom in 1953 (1%), the rule of thumb gives a good approximation.

flood events shows that it gives an accurate[4] approximation of the number of observed fatalities during these events. The outcomes of the proposed method are sensitive to the chosen flood scenario (especially to the number of breaches and the size of the flooded area) and the rise rate of the floodwater.

A preliminary analysis of the loss of life caused by the flooding of New Orleans after hurricane Katrina in the year 2005 has been presented. The hurricane caused more than 1100 fatalities in the state of Louisiana. Based on an analysis of a preliminary dataset that gives information on the recovery locations for 771 fatalities, the following is concluded:

- Two thirds of the analysed fatalities were most likely associated with the direct physical impacts of the flood and mostly caused by drowning. One third of the analysed fatalities occurred outside the flooded areas or in hospitals and shelters in the flooded area due to causes such as strokes, heart attacks and lack of medical services. These fatalities were due to the adverse public health situation that developed after the floods. Overall, the elderly were the most vulnerable. Nearly 85% of the fatalities was over 51 years old.
- The total number of fatalities that is predicted for the New Orleans flood with the method proposed in section 7 of this thesis is within a factor 2 with the (preliminary) number of observed recoveries in the flooded area. The number of fatalities in areas with high rise rates is overestimated with the proposed method.
- Similar to historical flood events, the mortality rates were the highest in areas near breaches and in areas with large water depths. The highest mortality fractions were observed near the severe breaches in Lower 9th Ward. The earlier proposed approach, in which mortality functions for different zones in a flooded area are distinguished, is also applicable to New Orleans. A relationship has been found between the water depth and mortality. One difference with earlier findings is that the data for New Orleans does not show an influence of the rise rate on mortality.
- The available data for New Orleans do not support the claim that mortality during a contemporary flood event is lower than during historical events. The overall mortality amongst the exposed population for this event was approximately 1%, which is similar to the mortality for historical flood events.
- The presented results and analyses are preliminary. The analysed mortality dataset is incomplete (it covers 69% of all fatalities in the state of Louisiana) and crude estimates have been used for the estimation of the size of the population exposed. Despite these limitations, the results confirm earlier findings regarding the main determinants of loss of life and they give important insight in the relationship between flood characteristics and mortality.

The risks due to flooding of the dike ring area 'South Holland' in the Netherlands have been analysed in a case study. The method developed in section 7 of this thesis has been used to estimate the loss of life for different flood scenarios. Results indicate that a flood event in this area can expose large and densely populated areas and result in hundreds to thousands of fatalities. Evacuation of South Holland before a coastal flood will be difficult due to the large amount of time required for evacuation and the limited time available, see also (Van der Doef and Cappendijk, 2006). The individual risk associated with flooding

4 For most of the considered validation cases, mortality deviates less than a factor 2 from the observed mortality.

is relatively small in most of the area (<10^{-5} yr^{-1}). The societal risk of flooding for South Holland is high in comparison with the risks in the external safety domain[5] in the Netherlands. The societal risk of flooding appears to be unacceptable according to some of the existing risk limits that have been proposed in literature. These results indicate the necessity of a further societal discussion on the acceptable level of flood risk in the Netherlands. The decision has to be made whether the current risks are acceptable or additional risk reducing measures are necessary, see also (Adviescommissie Water, 2006; MinVenW, 2006). The methods and results presented in this thesis provide the input information to make these decisions.

10.2 Recommendations

Part one: general approach for loss of life estimation and risk quantification
The following recommendations are made that are related to the proposed general approach for loss of life estimation and risk quantification:

- It is recommended to use the proposed general methods for loss of life and risk quantification to **verify the consistency and completeness** of existing methods that are used in different sectors. It can be analysed whether the factors that determine loss of life are included in the existing methods. In risk calculations it is important to check whether the expected values for the number of fatalities that are calculated from individual and societal risk are equal (see section 3).
- To achieve realistic consequence estimates for a certain field it is preferred to have some form of empirical calibration of the elements in the method. Although it is primarily desired to prevent disasters, improved **recording and storage of data on loss of life** after the occurrence of disasters is recommended.
- Estimation of loss of life requires **input information from different disciplines**. For example, toxicological knowledge is required to establish dose response functions. Analysis of the effectiveness of evacuation requires psychological insight in the response of the population to warnings. For realistic loss of life estimates it is required to transfer relevant information from these disciplines to (quantitative) input for loss of life estimates. It is recommended to further investigate how this can be done.
- The general method proposed in this study mainly concerns 'small probability – large consequences' events within the engineering domain. It is recommended to investigate **applications to related fields** that have not been specifically treated in this study, such as naval and offshore safety. In addition it could be investigated how the general formulations could be extended to **other consequence types**, such as injuries and economic damage and to **other types of events**, e.g. chronic exposure to pollutants.
- Possible uncertainties in consequence estimates are neglected in most existing applications. It is recommended to **assess and present these uncertainties** in consequence and risk estimates. This implies that guidelines for risk analysis should also prescribe whether and how uncertainties are accounted for in the risk calculation. It is also recommended to investigate the relevance of the findings regarding uncer-

5 The external safety domain is concerned with (the risks) of transport and storage of dangerous goods, and airport safety in the Netherlands.

tainties for other domains where damage models and fragility curves are used, e.g. for the assessment of hurricane and earthquake damage.

Part two: Loss of life estimation and flood risk assessment
The methods and results presented in this thesis are input information in the decision-making process regarding flood defence strategies and protection levels. As the proposed method is expected to give an accurate estimate of the loss of life for a flood event (see above), it is recommended to apply it to flood risk assessment and decision-making. More specifically, the following is recommended:

- It is recommended to use the proposed approach for loss of life estimation in the **risk assessment** that is undertaken to develop plans for the future flood protection of **New Orleans** (LACPR, 2006b).
- The societal risks of flooding of South Holland appear to be unacceptable according to the existing criteria for societal risk that have been proposed in literature. It is recommended to have a discussion on **acceptability of the flood risk in the Netherlands**. The results of (quantitative) analyses of the flood risk have to be used as input in this discussion. To enable a broad discussion on the acceptability of the flood risks in the Netherlands, the flood risks for all dike ring areas in the country need to be assessed.
- Based on the above societal discussion, it is recommended to **developed quantitative limits for individual and societal risk** for flooding in the Netherlands. It is proposed to limit the societal risk per dike ring area (see section 9.5.2). In addition, it is also important to evaluate the economic foundation of the current risk limits, see e.g. (Eijgenraam, 2006). The eventual determination of the height of the risk limits concerns a political choice.
- A general investigation on the **effectiveness of measures** that reduce the flood risk for the situation in the Netherlands is recommended. To allow a proper comparison and evaluation, the investments and risk reducing effects of different types of measures have to be compared.
- Given the possibility of a catastrophic flood in South Holland with hundreds to thousands of expected fatalities, **emergency management plans** need to be developed to ensure timely evacuation and shelter of the threatened population. The people need to know where they have to go to in case of threatening flood. It is necessary to have these plans prepared and practiced before a serious flood occurs.
- The outcomes of the fatality estimates are **sensitive** to some factors such as the number of breaches, the course of the flood scenario, the number of evacuated people and the rise rate of the floodwaters. It is recommended that decision makers are careful with the choice of the **measures** that are associated with these parameters, because their risk reducing effects are uncertain. In this case, small changes in the circumstances could greatly reduce the effectiveness of these measures and lead to much larger consequences. Examples of such sensitive measures are evacuation and compartment dikes.
- Overall, the results of consequence and risk estimates and the associated uncertainties have to be presented in a **decision context**. If the estimated risk level is considered too high, there are two possible decisions. Either physical measures are taken to reduce the risk level or research is initiated to reduce uncertainties in the outcomes.

If none of these decisions is made, the existing (unsafe) situation will continue to exist.

To gain better insight in the estimated flood risk levels the following is recommended:

- The flood characteristics are important input parameters for the estimation of loss of life. The flood characteristics are highly dependent on the choice of the flood scenario, especially the assumed number of breaches and their locations. In the current flood risk analyses in the Netherlands generally one or two breaches are assumed, see e.g. (Rijkswaterstaat, 2005). However, documentation of historical coastal floods (e.g. Netherlands 1953, New Orleans 2005) shows that these were always characterised by **multiple breaches**. It is recommended to develop a method for the **choice of flood scenarios and the number of breaches** in the context of risk analysis, so that it leads to realistic estimates of the risk level.

As has been stated above, the presented method is expected to result in accurate estimate of loss of life for a flood event. However, comparison with observations showed that for single locations within one event there are substantial deviations between the observations and the predictions with the proposed method. One likely reason is that not all factors that influence the mortality at a location are included in the method. Below a number of recommendations is given that could improve the method for the estimation of loss of life. In this context the following is important to note: When defining the need for further research it has to be considered how much the inclusion of additional factors in the model improves the accuracy of the eventual estimate of loss of life. As mortality due to a flood event will be influenced by human behaviour it is expected to remain uncertain to some extent.

- In section 8 of this thesis **a preliminary** and incomplete **dataset** with information on **Katrina related fatalities** in New Orleans has been analysed. Further completion and analysis of the dataset for New Orleans is recommended. Eventually, this could lead to an improvement of the proposed method for loss of life estimation. It is also recommended to analyse loss of life for other areas affected by Katrina, e.g. for the Mississippi Gulfcoast.
- The output of the method proposed in section 7 is sensitive to the value of the **rise rate**. In the method it is assumed that if the rise rate exceeds a predefined deterministic threshold value (0,5 m/hr) much higher mortality values are obtained. However, preliminary analysis for New Orleans did not show an influence of the rise rate on mortality. Further investigation of the influence of rise rate on mortality is recommended, also in combination with the collapse of buildings (see below).
- **The collapse of buildings** in floods proves to be an important determinant of mortality. Further insight is required in building vulnerability as a function of flood characteristics (depth, velocity, waves) and the relationship with the extent of loss of life. Empirical data on the collapse of buildings during past disasters (hurricane Katrina and Indian Ocean tsunami) could be very valuable to increase these insights.
- **Human instability** in flood flows is an important cause of drowning. It has been shown how instability can be related to two physical mechanisms: moment instability (toppling) and friction instability (sliding). Further analysis of these two mechanisms based on field observations and tests is recommended.

- The **level of warning** of people in the flooded area and consequent possibilities for **shelter** could be important for loss of life. Further analysis of these factors is recommended.
- In future research it could be attempted to include the **additional factors** in the method for loss of life estimation, e.g. the population vulnerability. However, to do this, more empirical information regarding the effects of these factors during past flood disasters is required.
- The method proposed in this thesis estimates loss of life at a relatively high spatial aggregation level, e.g. for whole villages or neighbourhoods in a city. It could be interesting for applications in the Netherlands to explore the possibilities for a more detailed and **mechanistic**[6] modelling of loss life, which simulates the individual behaviour and the causes of death.
- The studied data on the consequences of floods are the by-product of the enormous human suffering due to events that we strive to avoid. However, the data that are available could contribute to the prevention and mitigation of such disasters in the future. Standardized **collection and reporting of the available data** for flood disasters is recommended, see also (WHO, 2002; Hajat *et al.*, 2003; Jonkman and Kelman, 2006). This dissertation was finished more than one and a half year after the New Orleans flood disaster and at that time no complete and final dataset regarding the fatalities was yet available. This illustrates the difficulties in the collection of data after such disasters and the need for improvement of reporting.

6 An example of such a mechanistic loss of life model is BC Hydro Life Safety Model (Johnstone *et al.*, 2005).

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Appendices

Appendix 1.I: Categorization of event types

Different types of events can be categorized with respect to the exposure to physical effects and the occurrence of mortality after exposure, see table A1.

Table A 1: Categorisation of events with respect to exposure and occurrence of mortality

		Exposure	
		Immediate	**Chronic**
Mortality after exposure	**Direct**	floods[1], airplane crashes, earthquakes and tunnel fires	-
	Delayed	Exposure to nuclear radiation or some chemical substances	Exposure to air pollution or other noxious substances

A distinction is made between immediate and chronic exposure. For immediate exposure, the effects manifest within relatively short time period (seconds, hours) after an event. Chronic exposure concerns continuous exposure to effects over a longer period. It generally concerns small doses of physical effects for which no single source event can be identified. Another distinction is made between direct and delayed mortality after exposure. Direct fatalities are directly caused by the physical forces of the disaster and occur mostly during or shortly after the event. Direct fatalities are also indicated as immediate or early deaths (Griffith, 1994). Due to the delay in the occurrence of medical effects, fatalities occurring within the first week after the event are generally included as direct fatalities (also see Coburn and Spence, 2002). Mortality could also manifest with a delay, as a longer induction (or latency) period could exist between exposure and death (Lentz and Rackwitz, 2005; Griffith, 1994).

Based on these categories different accidents are shown in the categories in table A1. It is noted that some accident types could cover multiple categories. For example a nuclear accident could cause both direct and delayed fatalities. In addition the release of nuclear substances could lead to chronic exposure and consequent mortality. Figure A1 shows the occurrence of fatalities as a function of time for different event types.

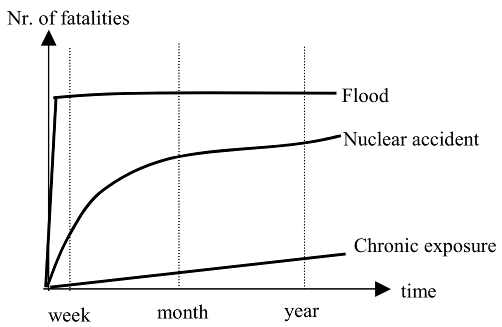


Figure A 1: Development of the number of fatalities over time for different accidents.

1 For some events characterized by immediate exposure and direct mortality, there might still be a small increase in mortality due to post event stress, see e.g. (Bennet, 1971) for floods. However, these longer-term consequences are small relative to the short-term consequences.

Appendix 2.I: Individual and population analysis of evacuation: Relationship between the x,t diagram and the distribution function of the number of evacuated people

It can be shown that the concept of the *x,t* diagram can be used to derive the distribution of the number of evacuated as a function of time in the form of figure 2-7. This is shown with a simplified one-dimensional example. Assume that the population at risk has a certain distribution over an area: *m(x)*. The exit to the safe area is located at distance x_E and the size of the population at risk (N_{PAR}) equals:

$$N_{PAR} = \int_0^{x_E} m(x)dx$$

It is assumed that all people evacuate with movement speed *v*. The people present nearest to the exit evacuate to safety first. Thus, after a certain period *t*, the people within the spatial interval $[(x_E - vt); x_E]$ will have reached the safe area, see the sketch in figure A2.

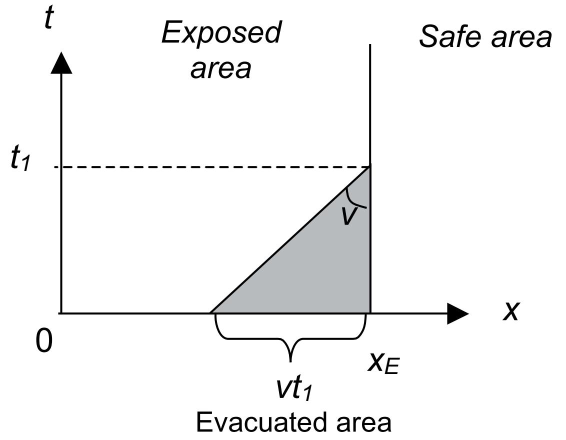


Figure A 2: x,t diagram indicating the evacuated area after t_1

Thus, for this one-dimensional situation the number of evacuated people (N_{evac}) can be determined as a function of time:

$$N_{evac}(t) = \int_{x_E - vt}^{x_E} m(x)dx = F_E(t)N_{PAR}$$

As an illustration two cases are elaborated for an identical values of N_{PAR}=100, but different distributions along an area with the exit at x_E = 100m. In the first case a homogeneous distribution of the population is assumed:

$$m(x) = 1 \qquad 0 \le x \le x_E$$

In the second case it is assumed that most people are present near the exit:

$$m(x) = 0,02x \qquad 0 \le x \le x_E$$

A walking speed of *v*=1 m/s is assumed. For both cases the population density, the *x,t* diagram and the number of evacuated people as a function of time are shown in figure A3.

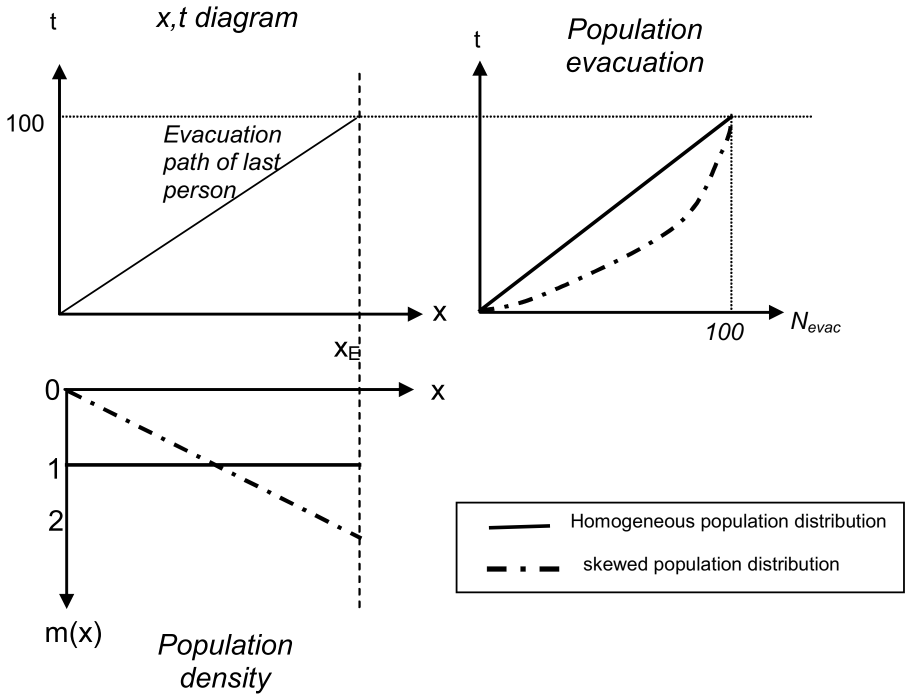


Figure A 3: Combination of population density and x,t diagram in order to obtain the number of evacuated people as a function of time

In both cases all people have evacuated after $T_{EVAC} = x_E / v = 100$s. When most people are present near the exit, the largest part of N_{PAR} evacuates in the first period. The above analysis shows that the approaches using the population's response (figure 2-7) and the *x,t* graph (Figure 2-9) are equivalent. They give different presentations of the progress of the evacuation process and can be linked via the population density.

Appendix 2.II: Discussion on the application of discrete threshold exposure limits

It is suggested in some publications to apply discrete resistance functions in safety and risk analysis, see e.g. (van der Torn, 2002). Similarly HSE (2001) advocates the use of a hypothetical person[2]. In such an approach, all the considered individuals are often assumed to have the same characteristics as the hypothetical person. Other examples of discrete resistance functions concern the threshold exposure limit and AEGL. Such threshold limits are often chosen conservatively low to account for people who are most susceptible. When this value is assigned to the whole population, this implies that a conservative resistance is assigned to the population. This is comparable to the determination of characteristic resistances in structural engineering.

As an illustration a discrete dose response function is drawn in figure A4. The threshold limit corresponds to a 50% response fraction in the actual dose response function. If the threshold exposure limit is used for loss of life estimation it is assumed that the whole exposed population will die if the limit is exceeded. It is questionable if this is a correct representation of the variation in population's response as the resistance distribution over the population is neglected. In the considered example higher resistances of certain persons in the exposed group are neglected, and consequence and risk levels might be over estimated. Similarly consequences can be under estimated, for dose values below the threshold value.

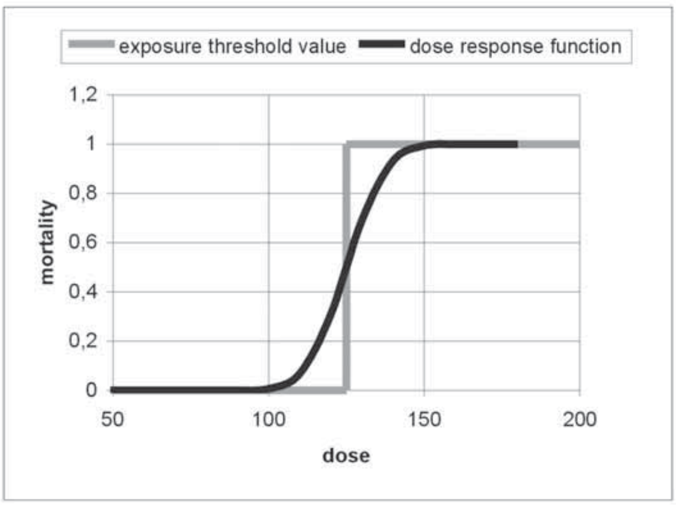


Figure A 4: Dose response function and discrete threshold value

Given these considerations it seems better to apply the resistance distribution over the population, as this will be a more appropriate representation of the variability of a population's response. The dose response function reflects the variation in individual vulnerabilities or resistances in the population. The dose response function can be considered as a composition of dose response functions of individuals or (sub)groups. The lower response fractions of the dose response function will concern the weakest elements (or people) in the population and the upper fractions the strongest. It might be possible to decompose

2 "An hypothetical person describes an individual who is in some fixed relation to the hazard, e.g. the person most exposed to it, or a person living at some fixed point or with some assumed pattern of life. (…) For example, for each population exposed to the hazard, there will usually be an hypothetical person specifically constructed for determining the control measures necessary to protect that population". HSE (2001, pp. 51)

the overall dose response function into functions for parts of the population with specific vulnerabilities (e.g. by age or gender). Ultimately, a discrete dose response function could be used if the individual resistance is exactly known. These distinctions between subpopulations (or even individuals) can only be made if epidemiological information is available on vulnerability characteristics for specific groups. Also, there has to be sufficient data to allow robust statistical analysis within the subgroups.

Proposal for the harmonisation of dose response functions and threshold exposure limits

Different formats of the dose response functions have been discussed: Continuous distribution functions such as probits can be used to estimate the loss of life and numbers of injuries in risk estimates. Discrete limits are generally used in emergency response to express concentrations at which (parts of) the general population could experience certain health effects. Various parties use these methods and underlying data differently in various fields. It suggested to harmonise these existing approaches, using available data, see also (PGS, 2003). It is recommended to develop a consistent and coherent set of functions for the analysis of mortality and incapacitation / injury, from which also threshold exposure limits can be derived for emergency response.

Firstly, distribution functions for mortality and injury / incapacitation can be derived based on available data. Table A2 gives an overview of the possibilities for determination of dose response functions.

Table A 2: Derivation of dose response functions for mortality and injury based on available data.

Phenomenon	Method / data source
Mortality	Derive dose response function based on human mortality data (e.g. observations from disasters)
	Derive dose response function based on mortality data for animals by scaling
Injury / incapacitation	Derive dose response function based on human injury data from observations from disasters or tests
	Derive dose response function based on injury data for animals by scaling
	Derive dose response function for injury from dose response function for mortality by assuming some relationship between mortality and injury ratios. It is often assumed that the injury function translates in a horizontal direction relative to the mortality function.

Based on these distributions, threshold exposure limits can be chosen that correspond to a certain response fraction (usually 0,01). In this way an optimal use of the available data is ensured and a mutually consistent set of response functions and threshold exposure limits will be obtained. An example of this approach is provided in figure A5, where a dose response function for mortality is derived based on available observations. Consequently, the dose response function for incapacitation is obtained by (horizontal) scaling. Threshold exposure limits are derived from both distribution functions.

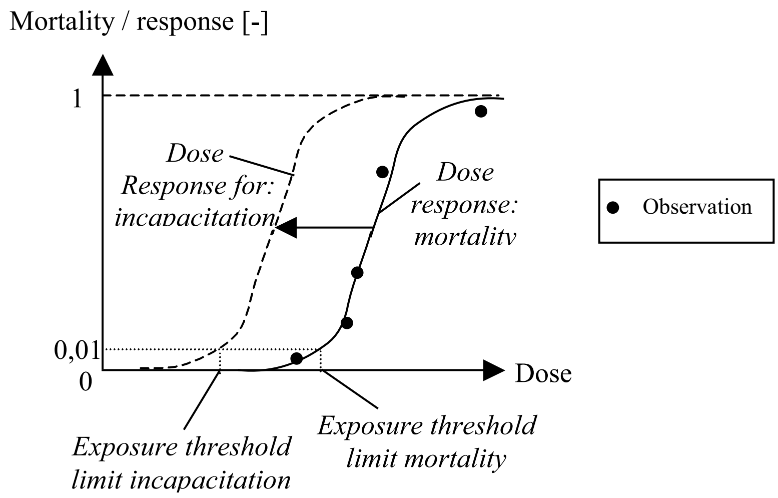


Figure A 5: Proposed harmonisation of three approaches. Based on a general dose response function for mortality, a dose response function for incapacitation, and a threshold exposure limit can be derived.

Appendix 2.III: Derivation of parameters of the lognormal distribution for different values for the probit constants

In section 2.3.4 is is shown how mortality can be approximated with a lognormal distribution. Equation 2-9 shows how the average and standard deviation of that distribution can be related to the constants in the probit function. In most[3] of the proposed probits in the Netherlands (CPR, 1990) either the value of *n* or *b* is assumed to equal 1. If *n* = 1 and exposure to a constant concentration is assumed, mortality can be expressed as a function of the sustained dose (so D=*c*t) and the following equation is obtained:

$$F_D(D) = \Phi_N\left(\frac{a + b\ln(D) - \mu_D}{\sigma_D}\right) = \Phi\left(\frac{\ln(D) - 1/b(\mu_D - a)}{\sigma_D / b}\right)$$

Thus, mortality has a lognormal distribution as a function of dose, with the following variables:

$$F_D(D) = \Phi_N\left(\frac{\ln(D) - \mu_N}{\sigma_N}\right)$$

$$\mu_N = (\mu_D - a)/b \qquad \sigma_N = \sigma_D / b$$

For other substances *b* is assumed to equal 1, but *n* is varied (see e.g. de Weger *et al.*, 1991). If a constant duration of exposure is assumed the mortality will have a lognormal distribution as a function of the concentration *c*:

$$F_D(c) = \Phi_N\left(\frac{\ln(c) - \mu_N}{\sigma_N}\right)$$

$$\mu_N = \frac{\mu_D - a - \ln t}{n} \qquad \sigma_N = \sigma_D / n$$

3 Of the 22 probits proposed for toxicants in (CPR, 1989) only for Chlorine, either *n* or *b* does not equal 1. b=1 for all 16 probits proposed in (de Weger *et al.*, 1991).

In some recently derived probits (PGS, 2003) it is assumed that *bn*=2. Note that this implies a quadratic influence of the concentration. Assuming a constant exposure duration, the following constants of the lognormal distribution are found:

$$F_D(c) = \Phi_N\left(\frac{\ln(c) - \mu_N}{\sigma_N}\right)$$

$$\mu_N = 0,5(\mu_D - a - b\ln t) \qquad \sigma_N = \sigma_D / 2$$

Appendix 2.IV: Conceptual modelling of the dynamic approach for loss of life estimation

In the so-called **dynamic** approach the spatial and temporal developments of physical effects, evacuation and the sustained injury have to be considered (see section 2.4). It is possible to schematise the dynamic approach using the previously introduced *x,t* diagram. The concentration at distance *x* from the risk source at time *t* can be plotted in a three dimensional graph (see figure A6a). The concentration is thus a function of location and time, i.e. *c(x,t)*. By integration of the concentration over time the sustained dose at location x is obtained:

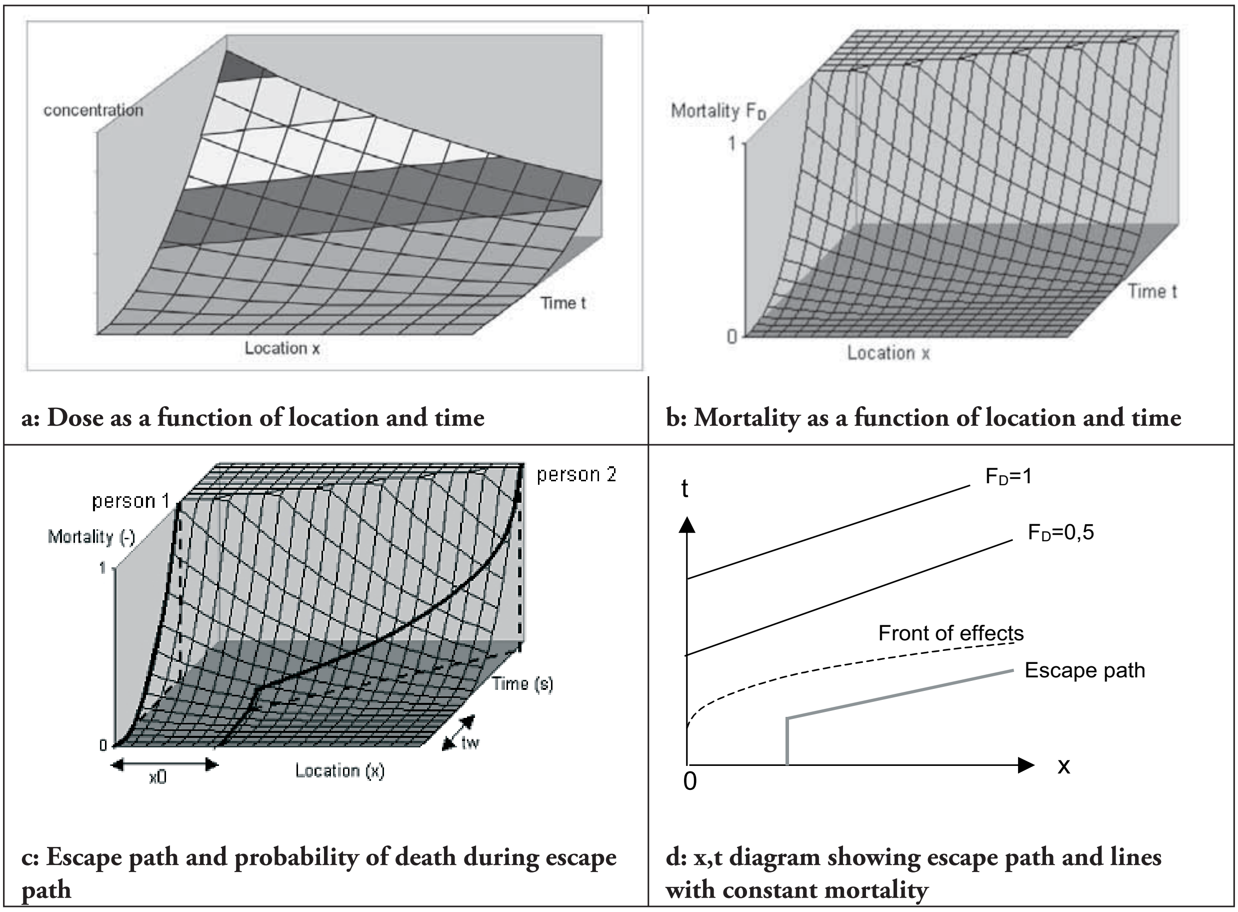
$$D(x) = \int_0^t c(x,t)dt$$

By substitution in the mortality function, mortality can be depicted as a function of location and time (see figure A6b). However, the position of an escaping person is not constant. The dose that a person sustains is obtained by integrating the exposure concentration over the escape path. The position of the person can be described as a function of the initial position (x_0), escape velocity (v), time before initiation of escape (t_w)[4] and time (t) and conceptually written as $x(x_0, v, t_w, t)$. As x_0, v_E and t_w are generally constants, the location of an escaping person at time t can be written as $x_E(t)$. By substitution, the concentration to which an escaping person is exposed along the escape path becomes $c_E(t)$. Thus, the sustained dose of an escaping person during his escape path equals:

$$D_E = \int c_E(t)dt$$

Consequently the probability of death can be estimated as a function of the sustained dose (see figure A6c). As an example the escape paths for two persons are shown in that figure. The first line shows the path of a person starting x_0=0 who does not attempt escape (v=0). The other path shows the graph for a person present at a certain distance (x_0) from the fire source who requires a certain wake up time (t_w). For both persons the mortality can be depicted as a function of location and time. Finally, based on the three dimensional mortality graph, lines with constant mortality values can be projected in the *x,t* graph (see figure A6d).

4 Time before initiation of escape is often indicates as the wake up time.



a: Dose as a function of location and time

b: Mortality as a function of location and time

c: Escape path and probability of death during escape path

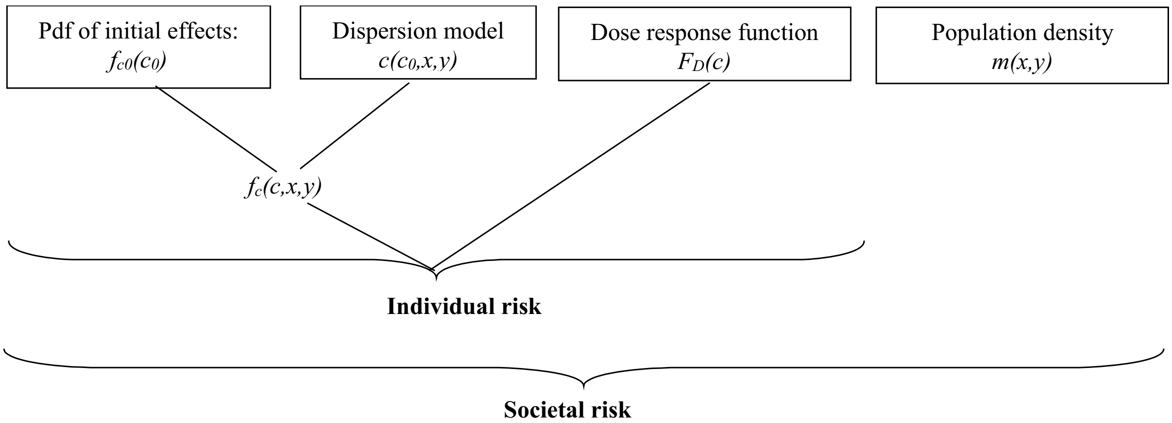
d: x,t diagram showing escape path and lines with constant mortality

Figure A 6

This concept is applicable for escape through fire smoke or other toxic substances. When analytical formulations for development of physical effects and progress of escape are available, the described analyses can be carried out analytically. In practice, such dynamic simulations will generally be implemented in (numerical) simulation models.

Appendix 3.I: Alternative approach for the determination of the individual risk

In section 3.3.2 is has been shown how the individual risk can be obtained by combining the dispersion model and the dose response function. An alternative approach is the combination of the probability density function (pdf) of initial effects and the dispersion model, see the figure below.



In this case the probability density function of effects *c* at location (x,y) (f_c(*c*,x,y))is determined from the pdf of initial release and the dispersion model. Using the Jacobian it follows:

$$f_C(c,x,y) = f_{c0}(c_0)\frac{dc_0}{dc}$$

It is noted that the influence of the location is introduced via the derivative dc_0/d*c*. The proposed formula is less suitable when the physical effects involve multiple types of hazardous effects, for example some and heat for a fire. The expression for individual risk becomes as follows:

$$IR(x,y) = P(Z(x,y) < 0) = \int_0^\infty f_C(c,x,y)F_D(c)dc$$

By substitution the following expression for the expected value is obtained.

$$E(N) = \int_0^\infty \iint_A f_C(c,x,y)F_D(c)m(x,y)dxdydc$$

By substitution of the first formula in this appendix the following expression for the expected number of fatalities is obtained:

$$E(N) = \int_0^\infty \iint_A f_C(c_0)F_D(c)m(x,y)dxdydc_0$$

As: $F_D(c) = F_D^*(c_0,x,y) \quad for \quad c(c_0,x,y)$, it follows that the derived equation for the expected number of fatalities is identical to equations 3-18 and 3-20.

Example
The above approach is used to elaborate the example for the chemical installation from section 3.6.2. For this case we use $f_{C0}(c_0)=pfa/c_0^3$ for $c_0>1$ and $c(c_0,R)=c_0e^{-\alpha R}$
The pdf of effects c at distance R follows from the Jacobian and substitution of the dispersion relation:

$$f_C(c,R)=f_{c0}(c_0)\frac{dc_0}{dc}=\frac{ap_f}{c_0^3}e^{\alpha R}=\frac{ap_f}{c^3}e^{-2\alpha R} \qquad voor \quad 1<c_0<\infty$$

The individual risk is determined by combination with the dose response function. (Note that if $c_0=1$ $c=e^{-\alpha R}$):

$$IR(R)=\int_{c_0=1}^{\infty} f_C(c,R)F_D(c)dc=\left[-2/3ap_f e^{-2\alpha R}c^{-3/2}\right]_{e^{-\alpha R}}^{\infty}=2/3abp_f e^{-0,5\alpha R}$$

This result is identical to the outcome obtained in section 3.6.2 in formula 3-46.

Appendix 3.II: Unit of the risk aversion factor *k* in the formulation of Total Risk for a Binomial distribution of the number of fatalities

Vrijling *et al.* (1995) propose the following expression for the total risk

$$TR=E(N)+k\cdot\sigma(N)$$

We assume a situation with one possible accident with probability p [yr^{-1}] and number of fatalities N. For the Binomial distribution the expressions for expected value and standard deviation are as follows:

$$E(N)=pN$$

$$\sigma(N)=\sqrt{p(1-p)N}$$

this implies that the expected value *E(N)* has unit [fatality / yr]. The standard deviation has the unit [$fatality^{0,5}$/yr]. This implies that in this case the factor *k* also must have unit [$fatality^{0,5}$] for a consistent TR expression. This issue does not exist for other distribution types, such as the normal, lognormal and exponential distribution, for which average and standard deviation have the same unit.

Appendix 3.III: Analysis of the effects on the FN curve of adding new housing developments

In section 3.4.3. the relationship between the FN curve and individual risk contours has been discussed for two typical situations (i.e. for a fixed risk source and spatially distributed accidents). Rules of thumb can be derived to assess the contribution of new housing developments to the FN curve when the IR contours are known. The ratio between the individual risk levels at distance *x* and at the origin can be written as follows:

$$\frac{IR(x)}{IR(0)} = \frac{P_E(x)F_{D|E}(x)}{P_E(0)F_{D|E}(0)}$$

Where: P_E(x) – probability of exposure at location *x*; $F_{D|E}$(x) – probability of death given exposure at location *x* (integrated over all intensities of physical effects)

For a **fixed installation** it is assumed that the probability of exposure equals the accident probability ($P_E(0) = P_f$) and that the probability of exposure is constant for all locations ($P_E(x)=P_E(0)$ for all *x*). This implies that individual risk contours will be determined by spatial variation of mortality. The ratio between mortalities at two locations will equal their individual risk ratio. The number of (additional) fatalities associated with exposing N_{EXP} people at a certain individual risk contour is calculated as follows:

$$N(x) = F_{D|E}(x)N_{EXP}(x) = \frac{IR(x)F_{D|E}(0)}{IR(0)} N_{EXP}(x)$$

Based on this equation, the increase in the number of fatalities due to the increase of the exposed population can be calculated. In many applications the mortality at the accident source equals 1 ($F_{D|E}(0)=1$), and the individual risk at the origin equals the probability of exposure and thus the probability of failure ($IR(0)=P_E(0)=P_f$).

As an example we assume an installation with a given probability of failure and given risk contours. The individual risk near the installation is IR=10^{-4} yr^{-1} and it equals the probability of failure. In the existing situation a village with N_{EXP1}=1000 inhabitants is situated at the IR=10^{-5} contour. The local government plans to add a new development with N_{EXP2}=1000 inhabitants at the IR=10^{-6} contour. The additional fatalities and the effects on the FN curve can be estimated with the above formula. This leads to a shift right in the FN curve, see figure A7.

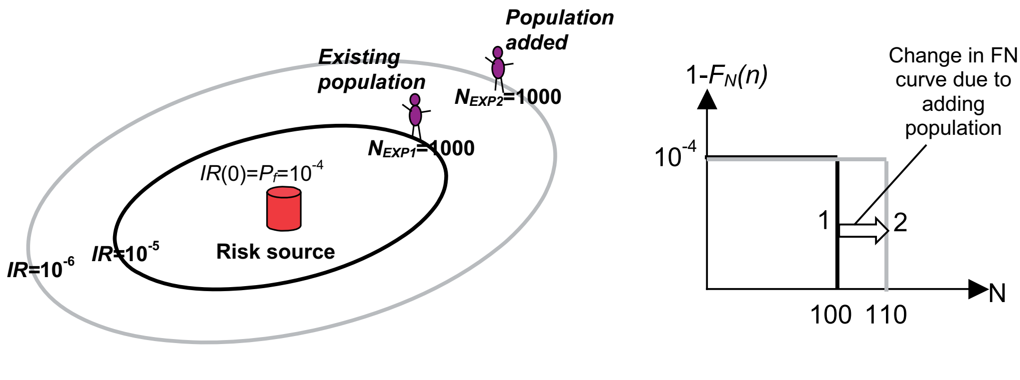


Figure A 7: Change in FN curve caused by adding exposed population at the IR=10^{-6} contour for a fixed installation

For **spatially distributed accidents** (e.g. an airport) the mortality and consequences due to exposure are the same for all locations ($F_{D|E}$(x)=$F_{D|E}$(0)). The individual risk contours will be determined by the spatial variability in the probability of an accident (e.g. an airplane crash). The probability of exposure at a location could be derived from the IR contours as follows:

$$P_E(x) = \frac{IR(x)P_E(0)}{IR(0)}$$

In a first order approximation it could be assumed that: $P_{accident}$ (x) ≈ P_E(x).Additionally, if the probability of death given an accident: $F_{D|E}$(x)=1, then P_E(x) ≈ IR(x). In this case, the points shown in the FN curve are equal to the coordinates (IR, N_{EXP})

Assume the example of an airport, where the crash probability is spatially distributed and the mortality is identical for all crash locations. We consider the same situation as in the previous example (identical IR contours, 1000 people at 10^{-5} contour and new development adding 1000 people at the 10^{-6} contour). The resulting FN curves due to addition of are shown, indicating an upward shift of the FN curve, see figure A8.

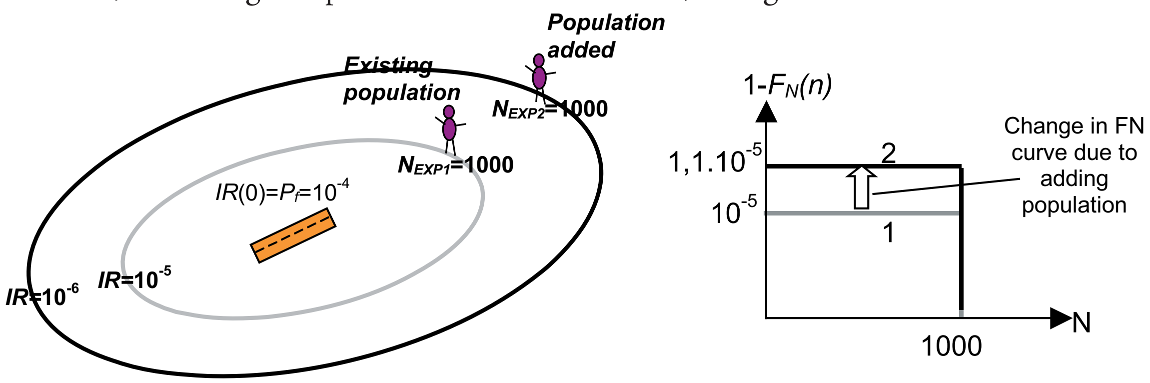


Figure A 8: Change in FN curve caused by adding exposed population at the IR=10^{-6} contour for a spatially distributed accident location

Appendix 4.I: Correlation between loads: example

Within one exposed area the loads (i.e. the level of physical effects) at two locations might be correlated via the dispersion of effects, but not identical. As an example, the water depth for a flood is schematically shown in figure A9. The water depth forms the load on the people in the polder.

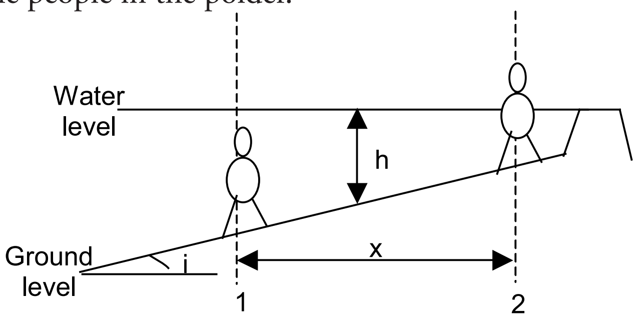


Figure A 9: Schematic view of a polder with a slope, illustrating the relationship between water depth at location 1 and 2

For the simple sloping polder the load on two persons will depend on the slope of polder surface and their mutual distance. The water depth at location 2 (h_2) can be approximated as a function of the water depth at location 1 (h_1):

$$h_2 = h_1 - ix$$

If it is assumed that $\sigma(h_1) = \sigma(h_2)$, it can be shown that $\rho_{h1,h2} = 1$

$$COV(h_1, h_2) = E\left((h_1 - \mu(h_1))(h_2 - \mu(h_2))\right) =$$

$$E\left((h_1 - \mu(h_1))(h_1 - ix - \mu(h_1) + ix)\right) =$$

$$E\left((h_1 - \mu(h_1))^2\right) = \sigma^2(h_1)$$

$$\rho_{h1,h2} = \frac{COV(h_1, h_2)}{\sigma(h_1)\sigma(h_2)} = 1$$

In this case the water depths at the two locations are based on one source of physical effects, e.g. the breach in the dike. Water depths will be fully correlated via the dispersion model. Full correlation will generally appropriate within one exposed area when loads are correlated via the dispersion model. Following the above formula correlation will also become smaller when $\sigma(h_1) << \sigma(h_2)$, i.e. when large uncertainties exist in the dispersion of physical effects. For other situations it might be more difficult to determine correlations in loads between two locations. This is for example the case when regional flood defences in a polder separate two locations.

Appendix 4.II: Influence of uncertainty on failure probability of a system

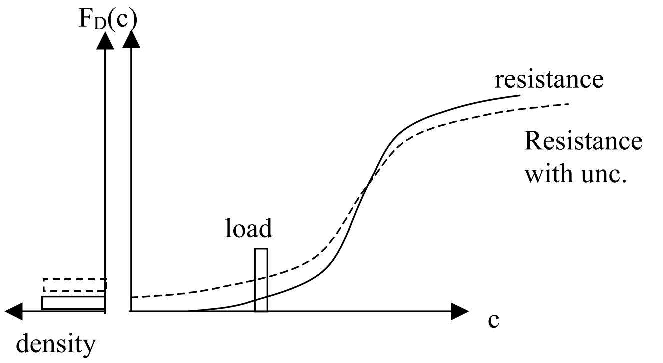
The failure probability for a given system is determined from the reliability function: $Z = R - S$. The probability of failure, P (Z<0) can be found by:

$$P(Z<0)=\int_{-\infty}^{\infty} F_R(x) f_s(x)dx$$

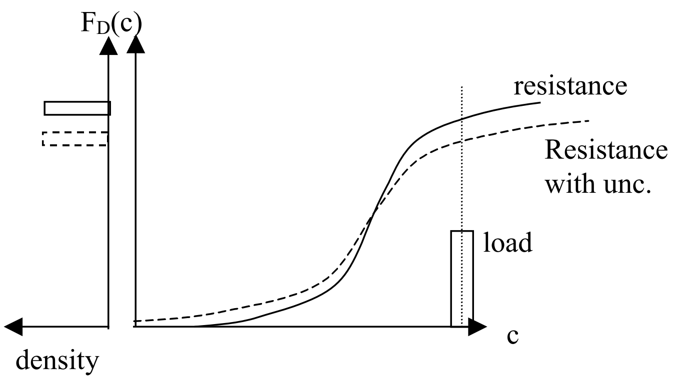
In this integral the probability density function of load ($f_S(x)$) and the distribution function of resistance ($F_R(x)$)are combined. Here, the influence of the Bayesian integration uncertainty in load and resistance is examined. Using some schematic cases, it is shown that the effects of the integration of uncertainty on the failure probability of a system will depend on the specific the distributions of load and resistance, and thus outcomes of convolution integral.

Case 1: deterministic load, variable resistance function

Case 1a: load in the lower response fractions. Due to inclusion of uncertainty, the response fraction will increase for lower loads (see section 4.5.2) and the failure probability will also increase. The response curve including uncertainty is shown with a dashed line.

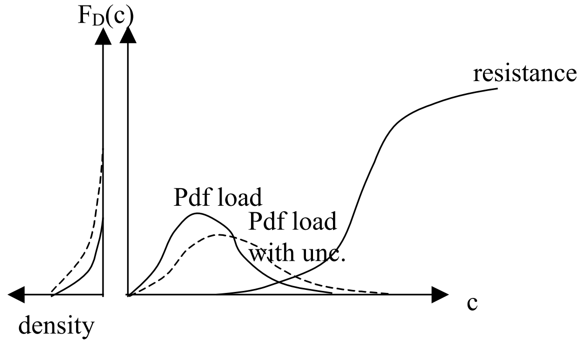


Case 1b: load in the higher response fractions. Due to inclusion of uncertainty, the response fraction will decrease for higher loads and failure probability will also decrease.



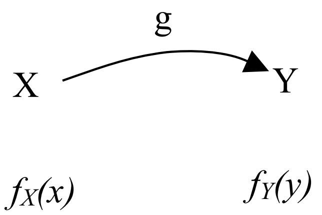
Case 2: Variable load and resistance

In most cases typical loading situation will be smaller than the resistance of a system (i.e. failure probability). Inclusion of knowledge uncertainty in loads, implies that higher loads will become more likely. For these cases the failure probability of the system will increase, as is shown below.



Appendix 4.III: Uncertainty in horizontal (*X*) and vertical (*Y*) direction

Suppose that variable Y is a function of variable X with a function g, so that $Y = g(X)$



It is assumed that the pdf of X is conditional on the value of x. Eventually we are interested in the distribution function of y conditional on a level of x:

$$F_Y(y \mid X = x) = P(Y \le y \mid X = x)$$

$$= P\left(g(X) \le y \mid X = x\right)$$

$$= P\left(X \le g^{-1}(y) \mid X = x\right)$$

$$= F_X\left(g^{-1}(y) \mid X = x\right)$$

The conditional pdf of y can be derived using the Jacobian:

$$f_Y(y \mid X = x) = f_X\left(g^{-1}(y) \mid X = x\right)\frac{dx}{dy}\bigg|_{X=x} = f_X\left(g^{-1}(y) \mid X = x\right)\frac{d}{dy}g^{-1}(y)\bigg|_{X=x}$$

So the distribution of y conditional on x is found using information on the conditional distribution of x and the function that relates x and y. In this study x could be concentration c, Y could be response fraction F_D and the function that relates the two is the dose response function $F_D(c)$.

Appendix 7.I: Summary of a literature study on flood evacuation

Given the lack of historical evacuation data, a survey of literature has been conducted to derive characteristic values for modelling of the first three phases of evacuation (namely prediction & decision-making, warning, response). The analysis focuses on the situation in the Netherlands and it is largely based on a study of literature by Frieser (2004).

Time required for decision-making

The decision-making phase includes the interpretation of signs of a threatening disaster by the responsible decision makers. The phase is concluded by a notification to the appropriate community officials in order to start spread evacuation warning.

Frieser (2004) investigated the times needed for decision-making for different kinds of (threatening) disasters. For events that could be predicted in advance, such as hurricanes in the USA, in general several days elapsed after the first signs before the decision-making process started. The actual times needed for decision-making on issuing warning and evacuation varied between 1,25 hrs and 12 hours. In the Netherlands in 1995 high river discharges on the Rhine threatened to cause flooding. The time needed to take the actual decision was approximately 4 hours. This values is proposed here as a representative decision time for preventive flood evacuation in the Netherlands.

Data on times required for decision-making <u>after</u> the occurrence of floods have not been found in literature. A survey of decisions times for toxic releases showed that these varied between 20 minutes and 3,5 hours, with a mean of 1,8 hours. It is believed that decision-making after an (unexpected) flood will need a similar decision time. The availability of procedures, instructions and information can decrease decision time.

Warning: general

The time needed to notify the population will, amongst others, depend on the level of preparedness and the availability of communication systems (Barendregt *et al.*, 2002). Wired telephone services and power are lost in almost every flood, so wide spread warning after the initiation of the flood is unlikely. Recent events have also shown that mobile telephone networks tend to be overloaded and do not function during calamities. In assessing the possibilities for warning, the speed of onset of the event is an essential variable. Unluckily the possibilities for dissemination of the warning are most limited for those floods which are most hazardous: it will be difficult to achieve a complete warning of the population if the flood suddenly occurs.

If warning is given sufficiently in advance large-scale evacuation may be achieved. Note that also warning after occurrence of the flood will affect behaviour of the population exposed to the flood, and as such it may influence flood mortality. This type of warning is investigated in section 7.4.6.

Warning effectiveness

Empirical data has been collected on the effectiveness of warning, i.e. the percentage of the threatened population that receives the warning. In 1995 very high discharges occurred in the Rhine river system. An evacuation order was issued in several parts of the Netherlands. Although, no explicit measurements of warning effectiveness were undertaken it is believed that almost all persons received the warning. Persons were already aware of the threatening situation and their "disaster-consciousness" was high. For an expected and predictable flood, for which the signs are visible in advance, it can be assumed that almost the whole population (99 to 100%) can be warned. However, active dissemination of the warning remains necessary.

Lower levels of warning effectiveness are reported for more sudden and unexpected floods. During UK river floods in 2000, only 30% of the questioned persons did receive warning prior to their house being flooded (Ramsbottom *et al.*, 2003). The floods 1953 in the Netherlands in 1953 occurred relatively suddenly and unexpected. For those 39 locations for which warning was reported, only 13 (33%) received warning prior to the flood. For the Bangladesh cyclone of 1991 the percentages of persons warned ranged between 60% (Mushtaque *et al.*, 1993) and 98 to 100% (Chowdhury *et al.*, 1993). However, as warning time was short no evacuations of persons out of the area were possible. Frieser (2004) also analysed the percentage of the persons warned for other unexpected events, namely four train derailments involving hazardous materials. This showed warning percentages ranging between 80% and 99%. Given the reported variations no first general estimate of warning effectiveness can be given, as it will depend on situational factors. Here it is assumed that it will be in the order of magnitude of 30 to 50% if no official warnings are given, and in the order of 80 to 100% if authorities are well prepared and functioning warning systems are available.

Time required for warning

This is the time needed for dissemination of the warning to a certain percentage of the population. No quantitative information was found on the warning times during the threatening floods in the Netherlands in 1995. The qualitative descriptions of the floods in 1953 in the Netherlands (Slager, 1992) suggest warning times of several hours. Frieser (2004) gave an overview of warning times for hurricanes, train derailments and hazmat accidents, see figure A10. Based on this figure, a representative warning time between 2 and 3 hours is proposed for flood evacuation for large-scale floods.

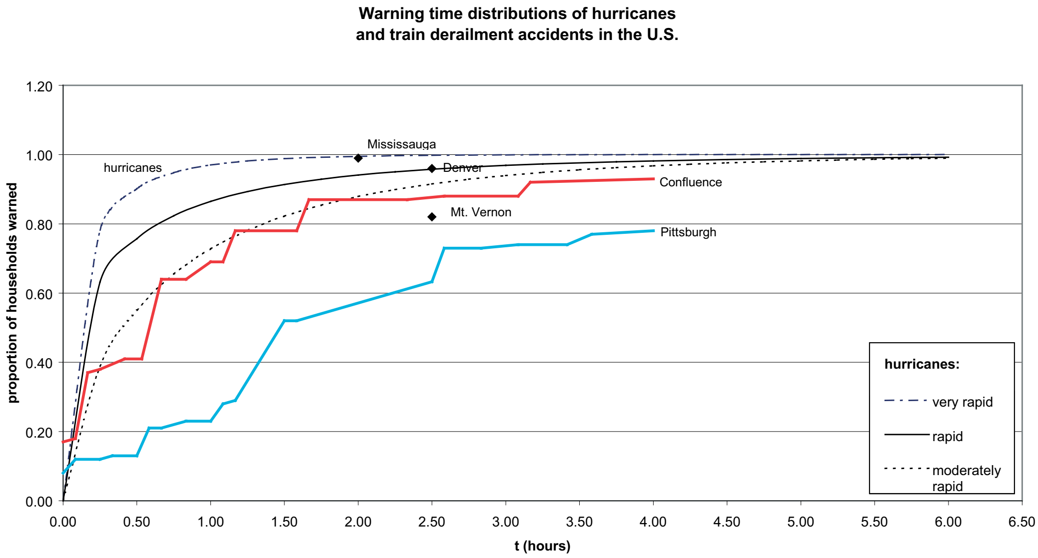


Figure A 10: Warning time distributions for some events: hurricanes (dashed lines), train derailments (dots) and accidents with hazardous materials (Frieser, 2004)

Response phase

The response phase covers the stages between warning and the response in the form of action after the warning. As is shown in section 2.2.6 several factors and barriers will influence the compliance to warning, and the time needed for response. Empirical data with respect to compliance rates and response times in past events is reviewed below.

Compliance to warnings

Several sources report non-compliance to warnings for past events. Lindell *et al.* (2002) report non-compliance rates for hurricane warnings in the United States between 35% and 64%. Rates vary from location to location and from storm to storm. For chemical accidents the range of non- evacuees was between 2 and 74% of those warned (Bellamy, 1986). Non-compliance rates to evacuation orders before potential flooding are reported to be lower. For both the floods in Prague in 2002 and the preventive evacuation in the Netherlands in 1995 non-compliance rates were low and they are estimated at 5%. In these two events almost all people were aware of the flood hazard, due to extensive media attention long before the initiation of evacuation.

In more unexpected floods with immediate warnings or events with lower disaster consciousness non-compliance rates might be higher. Pfister (2002) reports a non-compliance rate of 82% during threatening floods in Grafton (Australia), which was mainly caused by the low consciousness of the Grafton residents. For the Bangladesh 1991 cyclone a large percentage of the population received the warning in advance. However, only 19% of the families moved to safer grounds or shelters (Chowdhury *et al.*, 1993). The two most common reasons given for this passive reaction were a) the fear of burglary, and b) disbelief of the warnings. Overall, compliance will be largely determined by situational factors. The awareness of a threatening flood is essential for perception and belief of warning. As for predictable floods awareness will be high due to extensive media attention, compliance is believed to amount 95%. For more unexpected floods no general figures on non-compliance in floods can be derived from past cases. It is believed that this rate will relatively low because people will consider flood a large-scale flood in the Netherlands as a relatively unimaginable event. As a first estimate for unexpected events a compliance rate of 50% can be given. Compliance rates can be higher if additional measures are taken to convince the population of the urgency of the situation, for example the use of military troops in forcing persons to leave.

Time needed for response.
Different sources report response times for different accidents. Suetsugi (1998) gives data on for floods in the Seki River basin in Japan in 1995, for two districts (Matsumara and Tsukioka). Data on response distributions for different accidents with hazardous materials are summarized by Frieser (2004). These include accidents in Confluence and Pittsburgh, and a fire in Ephrata. Lindell *et al.* (2002) collected data on response times for hurricane evacuations. Figure A 11 shows the distributions of response times for these events.

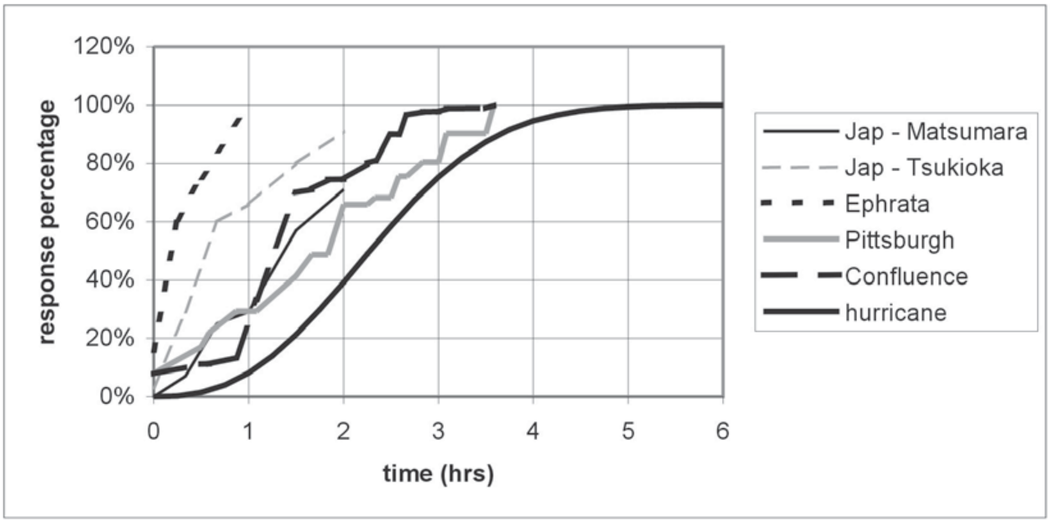


Figure A 11: Observed response time distributions for past accidents, Response times are calculated for those that actually evacuated.

Information on response times during the flood hazard in the Netherlands in 1995 is lacking. COT (1995) reported that (1) 4% of the residents at risk had already left before the evacuation warning had been issued, (2) 16% left immediately after the evacuation warning, (3) 60% made evacuation preparations and (4) 20% evacuated the next day.

Based on figure A 11 estimates of response times for floods can be made. Literature suggests that response times after a disaster will be smaller than response times in case preventive evacuation. The curve for hurricane evacuation is believed to be representative for preventive flood evacuation. A mean response time of about 2,5 hours can be assumed and the function proposed by Lindell *et al.* (2002) for residents can be used to estimate response time distribution (F_{RP}(t)). It can be written as a Weibull distribution

$$F_{RP}(t) = 1 - e^{-0.085t^{2.55}}$$

To account for response after unexpected flooding, empirical data from the other events in figure A11 will be used as a yardstick. For these cases the mean response time amounts about 1 hour, and 100% response will be achieved after about three hours.

Appendix 7.II: Analysis of spatial distribution of evacuation

Within the approach proposed in section 7.3.5 it is assumed that the available time is equal for all locations in the affected area. As a result a constant evacuation fraction is assumed for the whole area. However, the available time at a certain location will also depend on the arrival time of the floodwaters at that location. This can also be taken into account in the estimation of the fraction of evacuated, as has been shown in (Jonkman, 2001; Asselman and Jonkman, 2003). An example from (Asselman andd Jonkman, 2003) is included below. For the inundation of the province of South Holland arrival times of the flood waters are presented in figure A12. Combining this information with an evacuation model, the evacuated fraction can be estimated, see figure A13. For this case it is assumed that no time is available before the dike breach. In the areas near the dike breach there is a hardly possibility to evacuate, while areas that are affected after one day will have sufficient possibilities to evacuate.

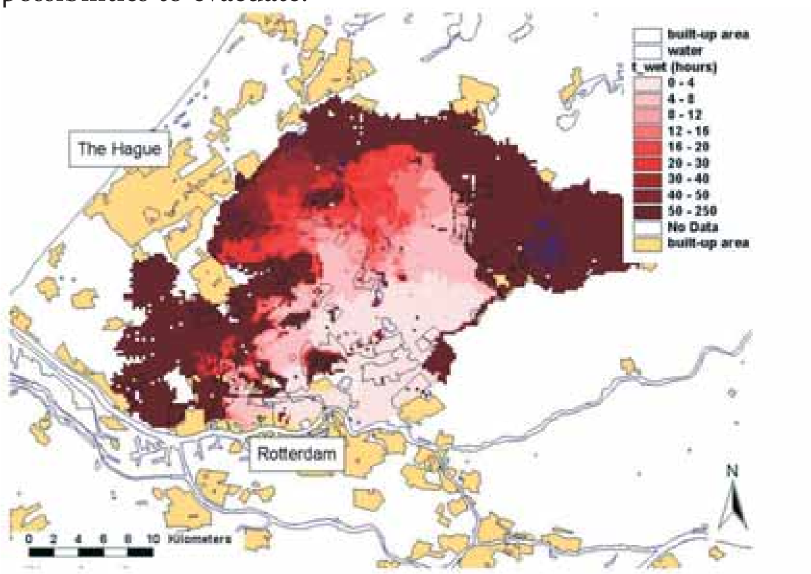


Figure A 12: Arrival time of the flood water after breaching of flood defence (Asselman and Jonkman, 2003).

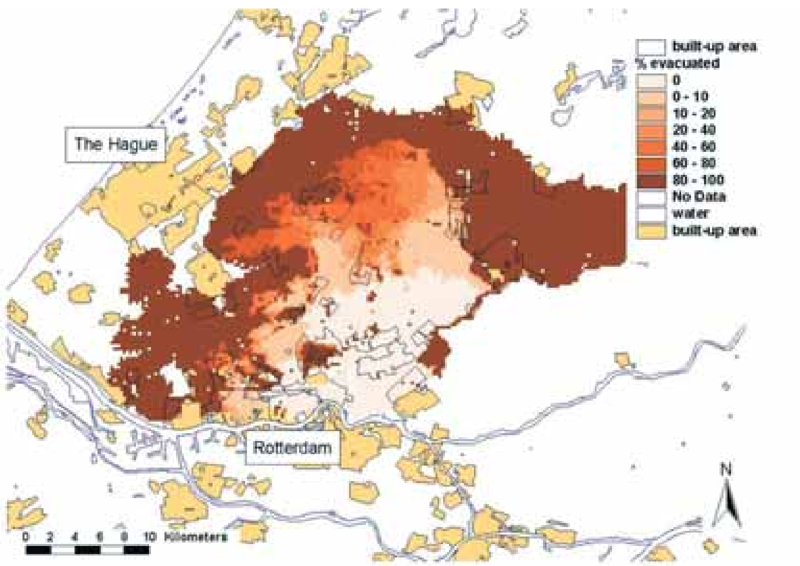


Figure A 13:Percentage of the population that has been evacuated (Asselman and Jonkman, 2003).

Appendix 7.III: Flood fatalities database

This appendix describes the variables included in the flood fatalities table. For each variable, name, symbol, unit and a description (if necessary) are given. In addition, assumptions used in inclusion of the data in the table are described for certain events in Italics.

The flood fatalities is included, the most relevant fields are displayed.

Variable	Type	Symbol	Unit	Description
Event and location				
Event code	descriptive			Abbreviation of event, indicating country and year of event
Date	date			Date of occurrence of event
Event name	descriptive			Typhoon or storm name (if appropriate)
Location	descriptive			flooded location *For NL1953: locations included are based on (Waarts, 1992). Additional locations covered in Delta 2003 have been added. As this last source gives the official death toll, these numbers have been used as reference.*
Island / region	descriptive			
Province	descriptive			
Fatalities				
Fatalities total	number	N_D	-	Total number of fatalities by location
Fatalities by zone	number		-	Fatalities by zone. By assigning fatalities to zones descriptions from sources have been used. NL 1953: Classification of fatalities by zone of Waarts (1992) has been used *Jap1959: Assumption Number of fatalities in the breach zone equals: breach ratio * N_{EXP}. Fatalities at Jyonan and Nabeta are assumed to be due to rapidly rising waters.* *UK1953: estimated based on descriptions in sources* *All: if no indicative information was available fatalities have been assigned to the remaining zone*
Number of inhabitants	number	N_{PAR}	-	Number of people in flooded area. *NL 1953: numbers of inhabitants have been abstracted from official numbers from CBS.*
Number of exposed	number	N_{EXP}	-	Is found by correcting number of inhabitants for the number of evacuated, sheltered and rescued. All events: If the whole area is flooded and no evacuation took place it has been assumed that all inhabitants were exposed. If a part of the area has been flooded, then the number exposed is assumed to equal the ratio of inundation * the number of inhabitants (thus homogenous distribution of population is assumed). If the area was not fully inundated and the number of exposed people could not be determined this has been indicated with**. *NL 1953:number of exposed has been determined based on maps of flooded areas and population distribution (van den Hengel, 2006)*
Mortality	fraction	F_D	-	Number of fatalities divided by the number of exposed people
serious injuries	number		-	Difference between serious and light injury adopted, as this has been used in (Tsuchiya and Yasuda, 1980)
light injuries	number		-	
Flood characteristics			-	

Flood depth	number	*h*	m	Water depth in the area, often determined as: water level – land level Jap 1934, Jap1950, Jap1961 given as mean inundation depth *USA1965: chosen as measured water depth closest to the population center*
Water level	number		m	
Land level	number		m	*Jap1959: Data on land levels has been derived from maps from the Japanese Geographical Survey Institute (http://mapbrowse.gsi.go.jp/mapsearch.html*
Rise rate	number	*w*	m/u	Estimation of rise rate over the first 1,5 metres of water. *NL 1953: estimations of rise rate from (Waarts, 1992)*
Rise rate	Descriptive		-	Classification of rise rate. Large if w>=0,5 m/hr Small if w<0,5 m/hr
Flow velocity	number	*v*	m/s	
Arrival time of water	number		hr	Local arrival time of flood wave after initiation of flood
Flood duration	number		hr	
Area flooded	number		ha	Extent of area flooded at location *NL 1953: data used from Waarts (1992)*
Total area	number		ha	Total area of location
Ratio of area flooded	fraction		-	Area flooded divided by total area
Breach discharge	number	Q_{breach}	m3/s	Breach discharge, indicate whether it is maximum or average
Breach width	number		m	
Embankment length	number		m	
Breach ratio	fraction		-	Fraction of total embankment length that has been breached.
Warning, shelter and evacuation				
Fraction evacuated	fraction	F_E	-	
Number of people sheltering	number	N_S	-	
Fraction of people sheltering	fraction	F_S	-	
Evacuation and shelter	Descriptive			
Warning level	Classification			Classification of warning level according to the method proposed in (Tsuchiya and Yasuda, 1980) and description in section 7.4.6
Number of people rescued	number	N_{RES}	-	
Rescue actions	Descriptive			Description of rescue actions and their effects
Building collapse				
Total number of buildings	number		-	Total number of buildings in area *For Jap1934, 1950, 1961 this is assumed to equal the number of households*
Buildings collapsed	number		-	Number of buildings to be reported to be (fully) collapsed
Fraction of buildings collapsed	fraction	FB	-	Number of buildings collapsed divided by total number of buildings
Building type	Descriptive			
Other factors				
Population vulnerability	Descriptive			Description of population vulnerability characteristics, such as a age and gender
Circumstances	Descriptive			Description of causes and circumstances of flood fatalities NL1953: mainly obtained from Slager, 1992
Sources				Sources from which recorded information has been abstracted

Appendix 7.IV: Derivation of one depth dependent mortality function for all data

In the approach proposed in section 7, three hazard zones have been distinguished based on the influence of velocity and rise rate. Depth dependent mortality functions have been proposed for these zones. One alternative application would be the derivation of one depth dependent mortality function based on all available data. The figure below shows a depth dependent mortality function derived through all data used for calibration.

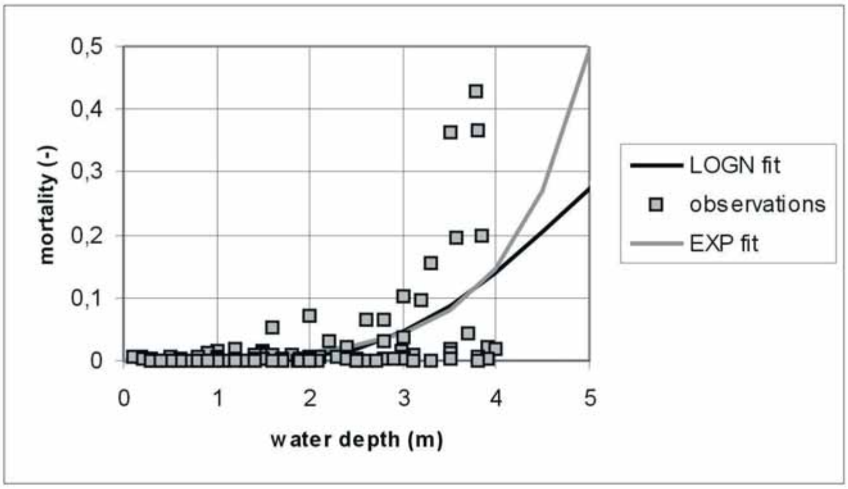


Figure A 14: Derived mortality function for the whole available dataset

The obtained functions, their parameters and correlations are summarized in the table below.

Function	Parameters	Correlation: R^2
Lognormal – all data	μ_{LN}=1,89, σ_{LN}=0,46	0,28
Exponential – all data	A=5,58; B=0,82	0,27

The use of two different mortality functions for the remaining zone and zone with rapidly rising water is shown in figure A15. It is clear that this approach leads to the best fir with available data.

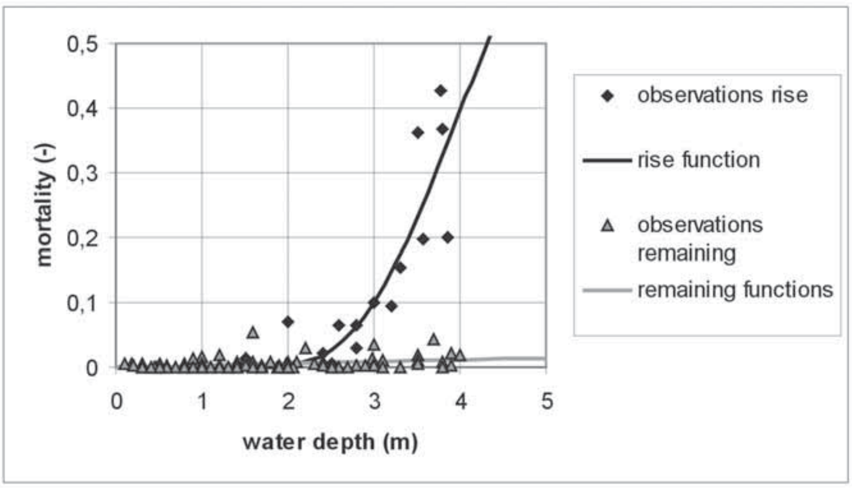


Figure A 15: Mortality functions proposed in section 7

Event and Location				Fatalities							Flood characteristics			g, Shelter and Eva	Building collapse					
					Fatalities by cause															
Event code	Date	Event Name	Location	Fatalities total N_D	Rise rate	low veloci	Remaining	Nr. of inhabitants N_{PAR}	Nr. of exposed people N_{EXP}	mortality F_D [-]	flood depth h [m]	rise rate w [m/u]	rise rate (classification)	Warning level (classification)	Number of buildings	Buildings collapsed	Fraction buildings collapsed FB [-]	Circumstances (descriptive)	Sources	
Jap1934	9-9-1934	Muroto typhoon	Higashiyodogawa-ku	32			32	216947	2169	0,01475			small		49269	205	0,00416083		Tsuchiya and Kawata, 1981	
Jap1934	9-9-1934	Muroto typhoon	Nishiyodogawa-ku	243			243	181040	74226	0,003274	1,4		small		41042	220	0,00536036		Tsuchiya and Kawata, 1981	
Jap1934	9-9-1934	Muroto typhoon	Fukushima-ku				0				0		small						Tsuchiya and Kawata, 1981	
Jap1934	9-9-1934	Muroto typhoon	Konohana-ku	256			256	207441	207441	0,001234	1,7		small		45909	490	0,01067329		Tsuchiya and Kawata, 1981	
Jap1934	9-9-1934	Muroto typhoon	Nishi-ku	2			2	130436	26087	7,67E-05	0,6		small		23908	6	0,00025096		Tsuchiya and Kawata, 1981	
Jap1934	9-9-1934	Muroto typhoon	Minato-ku	69			69	264416	264416	0,000261	1,6		small		71987	110	0,00152805		Tsuchiya and Kawata, 1981	
Jap1934	9-9-1934	Muroto typhoon	Taisho-ku	111			111	125390	125390	0,000885	1,7		small		28169	204	0,007242		Tsuchiya and Kawata, 1981	
Jap1934	9-9-1934	Muroto typhoon	Naniwa-ku	2			2	149852	20979	9,53E-05	1		small		3173	23	0,00724866		Tsuchiya and Kawata, 1981	
Jap1934	9-9-1934	Muroto typhoon	Nishinari-ku	81			81	196399	62848	0,001289	1		small		44755	232	0,00518378		Tsuchiya and Kawata, 1981	
Jap1934	9-9-1934	Muroto typhoon	Sumiyoshi-ku	47			47	265358	5307	0,008856	1,6		small		61582	295	0,00479036		Tsuchiya and Kawata, 1981	
Jap1950	3-9-1950	Typhoon Jane	Higashiyodogawa-ku	4			4	163125	22838	0,000175	1,1		small		38696	431	0,0111381		Tsuchiya and Kawata, 1981	
Jap1950	3-9-1950	Typhoon Jane	Nishiyodogawa-ku	58			58	76519	59685	0,000972	2,5		small		18438	341	0,01849441		Tsuchiya and Kawata, 1981	
Jap1950	3-9-1950	Typhoon Jane	Fukushima-ku	2			2	79475	45301	4,41E-05	1,3		small		19621	161	0,00820549		Tsuchiya and Kawata, 1981	
Jap1950	3-9-1950	Typhoon Jane	Konohana-ku	33			33	43878	35980	0,000917	2,6		small		10843	492	0,0453749		Tsuchiya and Kawata, 1981	
Jap1950	3-9-1950	Typhoon Jane	Nishi-ku	3			3	44545	42763	7,02E-05	1,4		small		11259	587	0,05213607		Tsuchiya and Kawata, 1981	
Jap1950	3-9-1950	Typhoon Jane	Minato-ku	63			63	41508	37357	0,001686	2,9		small		10398	1326	0,12752452		Tsuchiya and Kawata, 1981	
Jap1950	3-9-1950	Typhoon Jane	Taisho-ku	13			13	59784	49621	0,000262	1,9		small		15176	531	0,03498946		Tsuchiya and Kawata, 1981	
Jap1950	3-9-1950	Typhoon Jane	Naniwa-ku	2			2	43505	9571	0,000209	0,8		small		10617	475	0,04473957		Tsuchiya and Kawata, 1981	
Jap1950	3-9-1950	Typhoon Jane	Nishinari-ku	4			4	151509	46968	8,52E-05	0,9		small		37668	134	0,0035574		Tsuchiya and Kawata, 1981	
Jap1950	3-9-1950	Typhoon Jane	Sumiyoshi-ku	22			22	143505	50227	0,000438	0,8		small		34997	329	0,00940081		Tsuchiya and Kawata, 1981	
UK1953	30-1-1953	East Coast Floods	Felixstowe	39	39			550	550	0,070909	2		large						Grieve, 1959	Summers, 1978
UK1953	30-1-1953	East Coast Floods	Mablethorpe - Sutton area	16			16	6000	6000	0,002667	1,2		small						Grieve, 1959	Summers, 1978
UK1953	30-1-1953	East Coast Floods	King's Lynn	15			15	1500	1500	0,01	1,5		small					people were trapp	Grieve, 1959	Summers, 1978
UK1953	30-1-1953	East Coast Floods	Cobholm / Great Yarmouth	10			10	5000	5000	0,002	2		small					6 drowned, of whi	Grieve, 1959	Summers, 1978
UK1953	30-1-1953	East Coast Floods	Ipswich	0							1,3		small						Grieve, 1959	Summers, 1978
UK1953	30-1-1953	East Coast Floods	Harwich	8			8	3000	3000	0,002667	1,7		small					fatalities: mother -	Grieve, 1959	Summers, 1978
UK1953	30-1-1953	East Coast Floods	Jaywick	37		37	0	700	700	0,052857	2		small					whole village flood	Grieve, 1959	Summers, 1978
UK1953	30-1-1953	East Coast Floods	Wallasea island	2			2	37	37	0,054054	1,6		small					1 trapped in hous	Grieve, 1959	Summers, 1978
UK1953	30-1-1953	East Coast Floods	Foulness Island	3			3	368	368	0,008152	1,8		small						Grieve, 1959	Summers, 1978
UK1953	30-1-1953	East Coast Floods	Great Wakering	6			6	2748	2748	0,002183	1,5		small					housing estate flo	Grieve, 1959	Summers, 1978
UK1953	30-1-1953	East Coast Floods	Southend	2			2	1000	1000	0,002	1		small					(1 shock, 1 pneun	Grieve, 1959	Summers, 1978
UK1953	30-1-1953	East Coast Floods	Canvey Island - Sunken Marsh	58	?		?	11000	??		2		small					very fast rate of ri	Grieve, 1959	Summers, 1978
UK1953	30-1-1953	East Coast Floods	Tilbury	1			1	6000	6000	0,000167	1,3		small					(old lady in home)	Grieve, 1959	Summers, 1978
NL1953	1-2-1953	Watersnoodramp	Fynaart / Heinen	76	38	38	0	5141	5141	0,014783	1,5	*	large	D					Waarts, 1992	Delta 2003
NL1953	1-2-1953	Watersnoodramp	Halsteren	68	34	34	0	7894	**		3,5	*	large	D					Waarts, 1992	Delta 2003
NL1953	1-2-1953	Watersnoodramp	Nieuw-Vossemeer	50			50	1686	1686	0,029656	2,2		small	D					Waarts, 1992	Delta 2003
NL1953	1-2-1953	Watersnoodramp	Klundert	17			17	5245	5245	0,003241	2,8		small	C					Waarts, 1992	Delta 2003
NL1953	1-2-1953	Watersnoodramp	Willemstad	2			2	2067	**		0,5		small	A				1 fatality in bed, 2 in water		Delta 2003
NL1953	1-2-1953	Watersnoodramp	Dinteloord	7			7		**				small							Delta 2003
NL1953	1-2-1953	Watersnoodramp	Dussen	6			6						small						Waarts, 1992	Delta 2003
NL1953	1-2-1953	Watersnoodramp	Hoge en Lage Zwaluwe	2			2	704	704	0,002841			small							Delta 2003
NL1953	1-2-1953	Watersnoodramp	Oosterhout	0			0	21415	21415	0	0,3		small						Waarts, 1992	Delta 2003
NL1953	1-2-1953	Watersnoodramp	Raamsdonk	1			1		**				small							Delta 2003
NL1953	1-2-1953	Watersnoodramp	Sprang-Capelle	0			0	6029	6029	0			small						Waarts, 1992	Delta 2003
NL1953	1-2-1953	Watersnoodramp	Steenbergen	10			10		**				small							Delta 2003
NL1953	1-2-1953	Watersnoodramp	Terheijden	1			1	5088	**				small							Delta 2003
NL1953	1-2-1953	Watersnoodramp	Waspik	0			0	3529	**				small						Waarts, 1992	Delta 2003
NL1953	1-2-1953	Watersnoodramp	Zevenbergen	7			7	9386	**				small						Waarts, 1992	Delta 2003
NL1953	1-2-1953	Watersnoodramp	Texel	6			6		**				small							Delta 2003
NL1953	1-2-1953	Watersnoodramp	Zijpe	1			1						small							Delta 2003
NL1953	1-2-1953	Watersnoodramp	Geersdijk	5			5				2,6		small						Waarts, 1992	Delta 2003
NL1953	1-2-1953	Watersnoodramp	Kortgene	44			44	3748	3748	0,01174	3,5		small						Waarts, 1992	Delta 2003
NL1953	1-2-1953	Watersnoodramp	Wissekerke	1			1	3562	**				small							Delta 2003
NL1953	1-2-1953	Watersnoodramp	Burghsluis	10	10	0	0	50	50	0,2	3,85	16	large	D	10	3	0,3		Waarts, 1992	Delta 2003
NL1953	1-2-1953	Watersnoodramp	Nieuwerkerk	288	288		0	1858	**1871**	0,153928	3,3	*	large	D	513	314	0,61208577	many fatalities du	Waarts, 1992	Delta 2003
NL1953	1-2-1953	Watersnoodramp	Ouwerkerk buiten	66	66		0	180	180	0,366667	3,8	4	large	D	70	56	0,8		Waarts, 1992	Delta 2003
NL1953	1-2-1953	Watersnoodramp	Ouwerkerk kern	25	25		0	385	385	0,064935	2,8	4	large	D	112	41	0,36607143		Waarts, 1992	Delta 2003
NL1953	1-2-1953	Watersnoodramp	Nieuwerkerke	0			0						small	D					Waarts, 1992	Delta 2003
NL1953	1-2-1953	Watersnoodramp	Oosterland	65			65	1819	**1795**	0,036212	3		small	D	521	99	0,19001919			Delta 2003
NL1953	1-2-1953	Watersnoodramp	Brouwershaven	3	3	0	0	1198	**728**	0,004121	2,5	0,5	large	C	365	8	0,02191781	3 people drowned	Waarts, 1992	Delta 2003
NL1953	1-2-1953	Watersnoodramp	Dreischor	32	22	10	0	1020	**1037**	0,030858	2,8		large	C	343	24	0,06997085	many fatalities du	Waarts, 1992	Delta 2003
NL1953	1-2-1953	Watersnoodramp	Zierikzee	24	0	1	23	7129	5645	0,004252	3,5	*	small	C	1994	49	0,02457372	water flows throug	Waarts, 1992	Delta 2003

Event and Location				Fatalities							Flood characteristics			g, Shelter and Eva	Building collapse					
					Fatalities by cause															
Event code	Date	Event Name	Location	Fatalities total N_D	Rise rate	ow veloci	Remaining	Nr. of inhabitants N_{PAR}	Nr. of exposed people N_{EXP}	mortality F_D [-]	flood depth h [m]	rise rate w [m/u]	rise rate (classi-fication)	Warning level (classification)	Number of buildings	Buildings collapsed	Fraction buildings collapsed FB [-]	Circumstances (descriptive)	Sources	
NL1953	1-2-1953	Watersnoodramp	Serooskerke	15	15			219	227	0,066079	2,6		large	B	79	40	0,50632911		Waarts, 1992	Delta 2003
NL1953	1-2-1953	Watersnoodramp	Kerkwerve	3	0		3	801	800	0,00375	3		small	B	212	150	0,70754717	fatalities were per	Waarts, 1992	Delta 2003
NL1953	1-2-1953	Watersnoodramp	Noordwelle	0			0	455	449	0	2		small	B	133	41	0,30827068		Waarts, 1992	Delta 2003
NL1953	1-2-1953	Watersnoodramp	Zonnemaire	0			0	791	791	0	0,4		small	B	261	0	0		Waarts, 1992	Delta 2003
NL1953	1-2-1953	Watersnoodramp	Elkerzee	0			0	517	491	0	3,1		small	A	160	30	0,1875		Waarts, 1992	Delta 2003
NL1953	1-2-1953	Watersnoodramp	Haamstede	0			0	1715	532	0			small	A	483	15	0,0310559		Waarts, 1992	Delta 2003
NL1953	1-2-1953	Watersnoodramp	Bruinisse	1			1	2137	2292	0,000436			small		734	3	0,00408719		Waarts, 1992	Delta 2003
NL1953	1-2-1953	Watersnoodramp	Duivendijke	0					511	0			small		133	75	0,56390977			Delta 2003
NL1953	1-2-1953	Watersnoodramp	Ellemeet	1			1	495	493	0,002028			small		145	68	0,46896552			Delta 2003
NL1953	1-2-1953	Watersnoodramp	Looperskapelle	0			0						small						Waarts, 1992	Delta 2003
NL1953	1-2-1953	Watersnoodramp	Noordgouwe	1			1	866	866	0,001155			small							Delta 2003
NL1953	1-2-1953	Watersnoodramp	Oudendijke	0			0	464	464	0			small						Waarts, 1992	Delta 2003
NL1953	1-2-1953	Watersnoodramp	Scharendijk	0			0				3		small						Waarts, 1992	Delta 2003
NL1953	1-2-1953	Watersnoodramp	Sirjansland	0			0						small						Waarts, 1992	Delta 2003
NL1953	1-2-1953	Watersnoodramp	St.Philipsland	10			10	2136	1676	0,005967	2,3		small	C					Waarts, 1992	Delta 2003
NL1953	1-2-1953	Watersnoodramp	Stavenisse	156	156		0	1737	1645	0,094833	3,2	10	large	D	500	140	0,28		http://people.zeel	Waarts, 19 Delta 20
NL1953	1-2-1953	Watersnoodramp	St. Maartensdijk	2			2	2147	325	0,006154	1		small	C					Waarts, 1992	Delta 2003
NL1953	1-2-1953	Watersnoodramp	St. Annaland	0			0	268	1302	0	0,5		small	A/B						Delta 2003
NL1953	1-2-1953	Watersnoodramp	Poortvliet	0			0	1705	1705	0	2		small						Waarts, 1992	Delta 2003
NL1953	1-2-1953	Watersnoodramp	Veere	2			2	1055	**				small							Delta 2003
NL1953	1-2-1953	Watersnoodramp	Vlissingen	3			3	24653	**				small							Delta 2003
NL1953	1-2-1953	Watersnoodramp	Osenenisse / Hontenisse	8			8	5561	508	0,015748	1		small						Waarts, 1992	Delta 2003
NL1953	1-2-1953	Watersnoodramp	Terneuzen (omgeving)	3			3	13790	241	0,012448	1,5		small						Waarts, 1992	Delta 2003
NL1953	1-2-1953	Watersnoodramp	Kruiningen	62		1	61	4859	3152	0,01967	3,5		small	D				5 people drowned	Waarts, 1992	Delta 2003
NL1953	1-2-1953	Watersnoodramp	Oostkerke (Wolphaartsdijk)	12			12				1,3		small	C / D						Delta 2003
NL1953	1-2-1953	Watersnoodramp	Oudelande	3			3	779	621	0,004831	0,8		small	C					Waarts, 1992	Delta 2003
NL1953	1-2-1953	Watersnoodramp	Baarland	0			0	818	719	0	1,2		small	B					Waarts, 1992	Delta 2003
NL1953	1-2-1953	Watersnoodramp	Ellewoutsdijk	3			3	486	331	0,009063	1,4		small						Waarts, 1992	Delta 2003
NL1953	1-2-1953	Watersnoodramp	Hoedekenskerke	1			1		**				small							Delta 2003
NL1953	1-2-1953	Watersnoodramp	Krabbendijke Oostdijk	2			2	1148	54	0,037037			small						Waarts, 1992	Delta 2003
NL1953	1-2-1953	Watersnoodramp	Rilland	12		7	5	2253	2076	0,00578	1,7		small					2 persons drowne	Waarts, 1992	Delta 2003
NL1953	1-2-1953	Watersnoodramp	Waarde	1		1	0	1104	80	0,0125	2,5		small					1 man deceased v	Waarts, 1992	Delta 2003
NL1953	1-2-1953	Watersnoodramp	Dordrecht	2			2	73610	73610	2,72E-05	0,45		small						Waarts, 1992	Delta 2003
NL1953	1-2-1953	Watersnoodramp	Oude Tonge	305	305		0	3088	3011	0,101295	3	6	large	D	797	139	0,17440402		Waarts, 1992	Delta 2003
NL1953	1-2-1953	Watersnoodramp	Nieuwe Tonge buiten	38	38		0	105	105	0,361905	3,5	6	large	C	30	24	0,8		Waarts, 1992	Delta 2003
NL1953	1-2-1953	Watersnoodramp	Nieuwe Tonge kern	47	47		0	2081	2081	0,022585	2,4	6	large	C	578	26	0,0449827		Waarts, 1992	Delta 2003
NL1953	1-2-1953	Watersnoodramp	Goedereede	6			6	1195	780	0,007692	2,1		small	C	319	5	0,01567398		Waarts, 1992	Delta 2003
NL1953	1-2-1953	Watersnoodramp	Middelharnis / Sommelsdijk	17			17	8818	5985	0,00284	2,4		small	C	2500	1	0,0004		Waarts, 1992	Delta 2003
NL1953	1-2-1953	Watersnoodramp	Stellendam	61		61	0	1883	1804	0,033814	3,3	vloedgolf d	small	C	454	28	0,06167401	escaping people v	Waarts, 1992	Delta 2003
NL1953	1-2-1953	Watersnoodramp	Herkingen	4			4	1078	698	0,005731	0,5		small	B	274	5	0,01824818		Waarts, 1992	Delta 2003
NL1953	1-2-1953	Watersnoodramp	Ooltgensplaat	2			2	3212	2856	0,0007	2	0,4	small	B	833	6	0,00720288		Waarts, 1992	Delta 2003
NL1953	1-2-1953	Watersnoodramp	Den Bommel	9			9	1993	1264	0,00712	2	0,4	small		479	14	0,02922756		Waarts, 1992	Delta 2003
NL1953	1-2-1953	Watersnoodramp	Ouddorp	1			1	3984	2698	0,000371			small							Delta 2003
NL1953	1-2-1953	Watersnoodramp	Numansdorp	56		40	16	4473	4473	0,01252	1,5		small	D				many fatalities in	Waarts, 1992	Delta 2003
NL1953	1-2-1953	Watersnoodramp	Goudswaard	2			2	1421	1421	0,001407			small							Delta 2003
NL1953	1-2-1953	Watersnoodramp	Heinenoord	2			2	2232	2232	0,000896			small							Delta 2003
NL1953	1-2-1953	Watersnoodramp	s Gravendeel	37		30	7	5461	5461	0,006775	1,9		small					37 persons drown	Waarts, 1992	Delta 2003
NL1953	1-2-1953	Watersnoodramp	Strijen	40		29	11	5102	5102	0,00784	1,9		small					13 persons dead	Waarts, 1992	Delta 2003
NL1953	1-2-1953	Watersnoodramp	Zuid-Beijerland	0			0	2603	2603	0			small							Delta 2003
NL1953	1-2-1953	Watersnoodramp	Zuidland	21		8	13	2278	2278	0,009219	2		small	D					Waarts, 1992	Delta 2003
NL1953	1-2-1953	Watersnoodramp	Abbenbroek	1			1	735	735	0,001361	2		small						Waarts, 1992	Delta 2003
NL1953	1-2-1953	Watersnoodramp	Hellevoetsluis	5			5	1295	1295	0,003861			small							Delta 2003
NL1953	1-2-1953	Watersnoodramp	Oudenhoorn	0			0	896	896	0	2,07		small						Waarts, 1992	Delta 2003
NL1953	1-2-1953	Watersnoodramp	Tien-Gemeten	0	0		0					*	large					3 people surprise	Waarts, 1992	Delta 2003
NL1953	1-2-1953	Watersnoodramp	Krimpen a/d Ijssel	4			4	7478	**				small							Delta 2003
NL1953	1-2-1953	Watersnoodramp	Maassluis	1			1		**				small							Delta 2003
NL1953	1-2-1953	Watersnoodramp	Molenaarsgraaf	1			1	643	643	0,001555			small							Delta 2003
NL1953	1-2-1953	Watersnoodramp	Ouderkerk a/d Ijssel	2			2	4175	**				small							Delta 2003
NL1953	1-2-1953	Watersnoodramp	Papendrecht	2			2	6384	6384	0,000313			small							Delta 2003
NL1953	1-2-1953	Watersnoodramp	Poortugaal	6			6	3707	**				small							Delta 2003
NL1953	1-2-1953	Watersnoodramp	Rhoon	4			4	3017	**				small							Delta 2003
NL1953	1-2-1953	Watersnoodramp	Sliedrecht	1			1	16105	**				small							Delta 2003

Event and Location				Fatalities							Flood characteristics			g, Shelter and Eva	Building collapse				
					Fatalities by cause														
Event code	Date	Event Name	Location	Fatalities total N_D	Rise rate	low veloci	Remaining	Nr. of inhabitants N_{PAR}	Nr. of exposed people N_{EXP}	mortality F_D [-]	flood depth h [m]	rise rate w [m/u]	rise rate (classi-fication)	Warning level (classification)	Number of buildings	Buildings collapsed	Fraction buildings collapsed FB [-]	Circumstances (descriptive)	Sources
Jap1959	26-9-1959	Ise Bay typhoon	Nabeta reclamation	123	123		0	288	288	0,427083	3,78		large	D					Tsuchiya and Yasuda, 1980
Jap1959	26-9-1959	Ise Bay typhoon	chita-cho	9		0	9	31876	5545	0,001623			small	D					Tsuchiya and Yasuda, 1980
Jap1959	26-9-1959	Ise Bay typhoon	jushiyama village	36			36	4970	4960	0,007258	2,4		small	D					Tsuchiya and Yasuda, 1980
Jap1959	26-9-1959	Ise Bay typhoon	Kisozakai village	328		328	0	2993	2993	0,109589	3,8		small	D					Tsuchiya and Yasuda, 1980
Jap1959	26-9-1959	Ise Bay typhoon	tobishima village	121		30	91	4290	4290	0,028205	3,9		small	D					Tsuchiya and Yasuda, 1980
Jap1959	26-9-1959	Ise Bay typhoon	Tokoname city	12		0	12	49006	8932	0,001343	0,46		small	D					Tsuchiya and Yasuda, 1980
Jap1959	26-9-1959	Ise Bay typhoon	yatomi-cho	308		200	108	16037	15555	0,019801	3,8		small	D					Tsuchiya and Yasuda, 1980
Jap1959	26-9-1959	Ise Bay typhoon	Yokkaichi city	113		5	108	187978	23571	0,004794	1,97		small	D					Tsuchiya and Yasuda, 1980
Jap1959	26-9-1959	Ise Bay typhoon	yokosuka-cho	3		2	1	16562	4005	0,000749	0,6		small	D					Tsuchiya and Yasuda, 1980
Jap1959	26-9-1959	Ise Bay typhoon	Handa city	290		29	261	69784	19122	0,015166	0,9		small	C					Tsuchiya and Yasuda, 1980
Jap1959	26-9-1959	Ise Bay typhoon	higashiura-cho	25		1	24	19148	3661	0,006828			small	C					Tsuchiya and Yasuda, 1980
Jap1959	26-9-1959	Ise Bay typhoon	Kuwana city	184			184	66804	12991	0,014164	2,98		small	C					Tsuchiya and Yasuda, 1980
Jap1959	26-9-1959	Ise Bay typhoon	minami-ku	1417			1417	146500	130981	0,010818	3,1		small	C					Tsuchiya and Yasuda, 1980
Jap1959	26-9-1959	Ise Bay typhoon	minato-ku	375		41	334	91591	91591	0,004094	3,9		small	C					Tsuchiya and Yasuda, 1980
Jap1959	26-9-1959	Ise Bay typhoon	Nagashima-cho	363			363	8499	8499	0,042711	3,7		small	C					Tsuchiya and Yasuda, 1980
Jap1959	26-9-1959	Ise Bay typhoon	Heisaka reclamation	0			0	180	180		2,7		small	B					Tsuchiya and Yasuda, 1980
Jap1959	26-9-1959	Ise Bay typhoon	Kariya city	14		3	11	56752	9571	0,001463	0,5		small	B					Tsuchiya and Yasuda, 1980
Jap1959	26-9-1959	Ise Bay typhoon	Kawagoe village	170		27	143	7718	7718	0,022026	4		small	B					Tsuchiya and Yasuda, 1980
Jap1959	26-9-1959	Ise Bay typhoon	morozaki-cho	2			2	7018	305	0,006563	0,18		small	B					Tsuchiya and Yasuda, 1980
Jap1959	26-9-1959	Ise Bay typhoon	Nishio City	20			20	67730	18263	0,001095	0,3		small	B					Tsuchiya and Yasuda, 1980
Jap1959	26-9-1959	Ise Bay typhoon	suzuka city	10		0	10	87555	13573	0,000737	1,87		small	B					Tsuchiya and Yasuda, 1980
Jap1959	26-9-1959	Ise Bay typhoon	Hekinan City	11		4	7	49039	24268	0,000453	0,7		small	A					Tsuchiya and Yasuda, 1980
Jap1959	26-9-1959	Ise Bay typhoon	Hekinan reclamation	2		0	2	412	412		3		small	A					Tsuchiya and Yasuda, 1980
Jap1959	26-9-1959	Ise Bay typhoon	mihama-cho	4			4	18287	1790	0,002235	0,2		small	A					Tsuchiya and Yasuda, 1980
Jap1959	26-9-1959	Ise Bay typhoon	taketoyo-cho	9		1	8	16456	1952	0,004611	0,3		small	A					Tsuchiya and Yasuda, 1980
Jap1959	26-9-1959	Ise Bay typhoon	toyohama-cho	3			3	9041	539	0,005563	0,1		small	A					Tsuchiya and Yasuda, 1980
Jap1959	26-9-1959	Ise Bay typhoon	utsumi-cho	1			1	6996	431	0,00232	0,6		small	A					Tsuchiya and Yasuda, 1980
Jap1959	26-9-1959	Ise Bay typhoon	Jyonan reclamation	55	55	0	0	279	279	0,197133	3,58		large						Tsuchiya and Yasuda, 1980
Jap1959	26-9-1959	Ise Bay typhoon	Takahama - cho	4		0	4	20225	12393	0,000323	0,9		small						Tsuchiya and Yasuda, 1980
Jap1959	26-9-1959	Ise Bay typhoon	Tsushima district	2			2	44212			3,9		small						Tsuchiya and Yasuda, 1980
Jap1959	26-9-1959	Ise Bay typhoon	ueno-cho	138		70	68	16328	3807	0,036247	1,2		small						Tsuchiya and Yasuda, 1980
Jap1961	16-9-1961	Daini-Muroto typh	Higashiyodogawa-ku	0			0	269511	*				small		72895	5	6,8592E-05		Tsuchiya and Kawata, 1981
Jap1961	16-9-1961	Daini-Muroto typh	Nishiyodogawa-ku	0			0	119796	*		0,66		small		28627	500	0,01746603		Tsuchiya and Kawata, 1981
Jap1961	16-9-1961	Daini-Muroto typh	Fukushima-ku	0			0	22029	*		0,65		small		22029	78	0,00354079		Tsuchiya and Kawata, 1981
Jap1961	16-9-1961	Daini-Muroto typh	Konohana-ku	1			1	83503	*		0,93		small		20985	359	0,01710746		Tsuchiya and Kawata, 1981
Jap1961	16-9-1961	Daini-Muroto typh	Nishi-ku	0			0	73946	*		0,45		small		16648	58	0,0034839		Tsuchiya and Kawata, 1981
Jap1961	16-9-1961	Daini-Muroto typh	Minato-ku	1			1	104797	*		0,95		small		26107	1502	0,05753246		Tsuchiya and Kawata, 1981
Jap1961	16-9-1961	Daini-Muroto typh	Taisho-ku	0			0	94553	*				small		22985	28	0,00121819		Tsuchiya and Kawata, 1981
Jap1961	16-9-1961	Daini-Muroto typh	Naniwa-ku	0			0	83741	*				small		20609	26	0,00126158		Tsuchiya and Kawata, 1981
Jap1961	16-9-1961	Daini-Muroto typh	Nishinari-ku	1			1	215154	*				small		57519	24	0,00041725		Tsuchiya and Kawata, 1981
Jap1961	16-9-1961	Daini-Muroto typh	Sumiyoshi-ku	2			2	252300	*				small		60874	212	0,0034826		Tsuchiya and Kawata, 1981
US1965	8-9-1965	Hurricane Betsy	Lafourche	0			0	500	75	0	2		small						Boyd, 2005
US1965	8-9-1965	Hurricane Betsy	Orleans	41			41	141600	141600	0,00029	1,1		small						Boyd, 2005
US1965	8-9-1965	Hurricane Betsy	St Bernard	0			0	19500	3256,5	0	1,4		small						Boyd, 2005
US1965	8-9-1965	Hurricane Betsy	Plaquemines	10			10	21500	2150	0,000465	1		small						Boyd, 2005

Appendix 7.V: Information used for validation of the method for loss of life estimation

This appendix summarized the information that has been used for the validation calculations presented in section 7.5.1. The mortality fractions and loss of life estimates can be found by applying the proposed mortality functions. Table A3 summarizes the information.

Table A 3: Information used for validation calculations

Flood	Flood type	Inhabitants/exposed	Water depth	Rise rate	Source
Norwich river floods, 1912	River	1250 exposed (50% evacuation - 2500 inhabitants)	1,25m	small	Ramsbottom *et al.*, 2003
Laingsburg, South Africa, 1981	Flash	185	4m	Large	EMDAT, 2004
Shiranui Town, Japan, 1999	Coastal	200	2,6m	Large (2m/hr)	Takikawa, 2001
Gowdall river floods, 2002	River	25 exposed (90% evacuation – 250 inhabitants	1m	Small	Ramsbottom *et al.*, 2003

For the Lynmouth 1952 case specific input data has been used. Based on the descriptions in (Ramsbottom *et al.*, 2003) three zones are distinguished:

Zone	water depth	Exposed people	Rise rate
very close to river	3m	100	Large
close	2m	100	Small
nearby	1m	200	Small

Appendix 8.I: Preliminary dataset regarding Katrina related fatalities

The following tables list the data used for the analysis of the relationship between mortality and flood characteristics. Data sources for data regarding fatalities: LSU Hurricane Center (Ezra Boyd) and Louisiana Department of Health and Hospitals. The reported numbers of recoveries are recoveries in residential locations, so recoveries in hospitals and shelters are not included in these tables. Population numbers are based on the United States 2000 census. Flood characteristics are based on (de Bruijn, 2006; Maaskant, 2007) and the reported numbers are the averages by neighborhood / tract.

Orleans bowl

Neighborhood	Popu-lation	Expo-sed	Reco-veries	Morta-lity	Avg. Water depth (m)	Avg. Rise rate (m/hr)	Avg. Arrival time (hr)	Remarks
Bywater Neighborhood	5096	510	4	0,008	0,91	0,00	11,4184	partially flooded
Audubon	14870	1487	1	0,001	1,10	0,04	22,9803	partially flooded
Uptown Neighborhood	6681	668	0	0,000	0,75	0,00	24,2254	partially flooded
Leonidas	8953	895	0	0,000	1,01	0,03	20,1133	partially flooded
Touro	3140	314	3	0,010	0,42	0,00	25,6611	partially flooded
East Carrollton	4368	437	2	0,005	0,51	0,00	24,6532	partially flooded, 1 fatality outside flooded area
Central Business District	1828	183	2	0,011	0,78	0,00	20,7495	partially flooded, 1 fatality outside flooded area
Central City Neighborhood	19148	1915	18	0,009	1,14	0,11	22,9153	partially flooded, 1 fatality outside flooded area
B.W. Cooper	4361	436	3	0,007	1,31	0,14	21,3193	
Bayou St. John	5010	501	1	0,002	1,09	0,04	13,3560	
Broadmoor	7189	719	8	0,011	2,34	0,63	20,1983	
City Park	2813	281	1	0,004	1,90	0,41	8,7422	
Desire Area	3791	379	3	0,008	1,51	0,11	7,5565	
Desire Development	780	78	0	0,000	1,64	0,09	5,0352	
Dillard	6440	644	9	0,014	1,43	0,09	9,7298	
Dixon	1771	177	2	0,011	2,03	0,30	13,9654	
Fairgrounds	6426	643	8	0,012	1,23	0,08	10,7019	
Fillmore	6938	694	14	0,020	2,51	0,40	5,4758	
Florida Area	3171	317	8	0,025	2,13	0,31	4,8261	
Florida Development	1559	156	2	0,013	2,27	0,26	4,2613	
Freret	2492	249	1	0,004	1,74	0,33	21,3345	
Gentilly Terrace	10588	1059	11	0,010	1,60	0,13	9,4639	
Gentilly Woods	4387	439	6	0,014	1,87	0,17	10,5268	
Gert Town	4489	449	2	0,004	1,65	0,21	18,3073	
Hollygrove	6919	692	12	0,017	2,02	0,23	13,5883	
Iberville Development	2558	256	2	0,008	0,99	0,00	18,5330	

Lake Terrace & Oaks	2147	215	0	0,000	0,94	0,03	13,6604	
Lakeshore/Lake Vista	3630	363	1	0,003	0,99	0,07	10,3965	
Lakeview Neighborhood	9781	978	18	0,018	2,95	1,02	3,8208	
Lakewood	1973	197	1	0,005	1,65	0,34	8,4492	
Marlyville/ Fountainebleau	6844	684	2	0,003	1,42	0,17	19,9750	
Mid-City Neighborhood	20163	2016	5	0,002	1,79	0,23	14,5448	
Milan	7582	758	5	0,007	1,41	0,22	22,1289	
Milneburg	5640	564	23	0,041	3,23	0,45	5,0860	
Navarre	2905	291	1	0,003	1,84	0,39	6,4781	
Pontchartrain Park	2630	263	10	0,038	3,00	0,36	7,4500	
Seventh Ward	16955	1696	16	0,009	1,24	0,07	11,7898	
St. Anthony	5394	539	14	0,026	3,05	0,26	3,7439	
St. Bernard Area	6427	643	1	0,002	1,86	0,30	7,7074	
St. Claude	11745	1175	11	0,009	1,04	0,03	10,3043	
St. Roch	11975	1198	10	0,008	1,72	0,24	9,1056	
Treme'/Lafitte	8869	887	5	0,006	1,06	0,03	16,4404	
Tulane/Gravier	4302	430	7	0,016	1,58	0,15	16,9848	
West End	4724	472	10	0,021	2,99	0,64	2,3765	
Total	279452*	27947*	263**					

Notes: * - totals do not exactly correspond to totals presented in tables 8-2 and 8-3, because not all neighborhoods were fully flooded.
**: total does not correspond to total listed in tables 8-2 and 8-3, because 3 of the 263 fatalities occurred outside the flooded area.

St. Bernard bowl

Neighborhood / tract#	Population	Exposed	Recoveries	Mortality	Water depth (m)	Rise rate (m/hr)	Arrival time (hr)	Remarks
000701 (Lower ninth ward)	3278	328	15	0,046	2,56	2,65	1,73	
000702	3009	301	3	0,010	1,15	1,08	2,89	
000800	2498	250	3	0,012	2,18	2,06	2,62	
000901 (Lower ninth ward)	2675	268	13	0,049	3,85	7,49	2,45	
000902 (Lower ninth ward)	3005	301	10	0,033	4,28	5,46	2,08	
000903 (Lower ninth ward)	2710	271	19	0,070	3,66	4,04	2,13	
000904 (Lower ninth ward)	2340	234	16	0,068	3,06	4,29	2,41	
030103	6705	671	2	0,003	1,09	0,47	10,64	
030104##	2693	269	33	0,123	0,99	0,13	7,93	31 fatalities in St. Rita's nursing home
030203	4292	429	3	0,007	0,42	0,07	5,74	
030204	6592	659	12	0,018				
030206	4327	433	4	0,009	2,42	5,07	4,86	
030207	5597	560	8	0,014	2,35	4,79	4,54	
030208	4892	489	2	0,004	2,92	3,52	4,84	
030209	4843	484	8	0,017	1,23	0,70	5,97	

030300	2265	227	4	0,018	2,57	6,18	2,78	
030400	2731	273	4	0,015	1,13	1,21	3,75	
030500	3362	336	8	0,024	3,31	4,49	2,90	
030601	2743	274	6	0,022	3,68	7,56	3,21	
030602	4112	411	7	0,017	3,04	5,85	3,44	
030603	3441	344	2	0,006	3,02	9,13	3,58	
030700	2140	214	0	0,000	1,09	0,83	4,39	
030800	5173	517	8	0,015	2,06	3,42	4,03	
Totals	85423	8543	190					

Notes: # - tract codes for St. Bernard used; ##- This location is not included in the analysis of the relationship between flood characteristics and mortality because the 31 fatalities at one location (St. Rita's nursing home) were associated with specific conditions, i.e. lack of evacuation.

New Orleans East bowl

Neighborhood / tract	Popula-tion	Expo-sed	Reco-veries	Morta-lity	Water depth (m)	Rise rate (m/hr)	Arrival time (hr)	Remarks
Lake Catherine	1749	175	1	0,006				
Little Woods	44311	4425	21	0,005	2,89			
Pines Village	4972	497	4	0,008	2,73			
Plum Orchard	7026	703	6	0,009	2,91			
Read Blvd East	8240	824	11	0,013	3,60			
Read Blvd West	5564	556	5	0,009	2,78			
Viavant/Venetian Isles	1865	187	12	0,064				
Village de l'est	12968	1297	2	0,002	2,62			
West Lake Forest	9596	960	4	0,004	3,40			
			2					people found in the water
Total	96291	9624	68					

Appendix 8.II: Map indicating structural damage to buildings in New Orleans

Sources: Damage levels determined in FEMA's post Katrina damage assessments. Percentages indicate structural damage level. Map available at http://www.unifiedneworleansplan.com/home2/section/24, accessed January 2007.

Appendix 9.I: Model uncertainties in fatality estimates

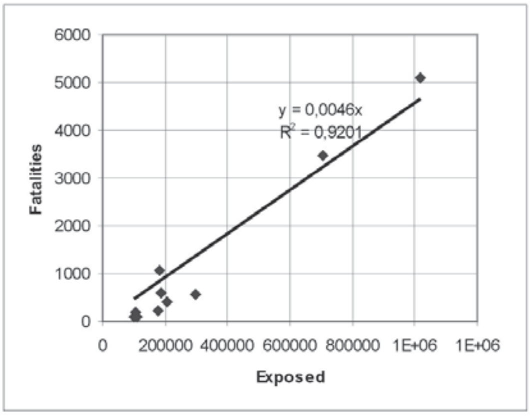
Bounds for model uncertainty in the applied dose response functions have been derived in section 7. Based on these bounds confidence intervals are reported for each flood scenario for the situation without evacuation.

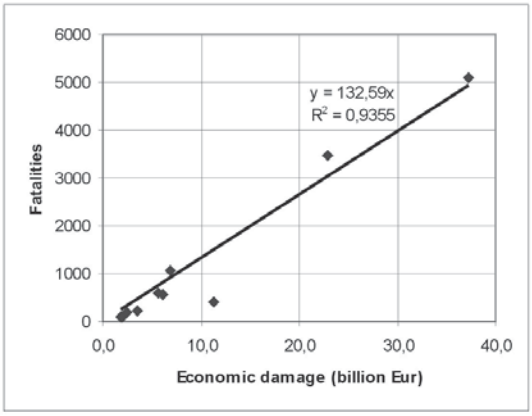
Table A 4: Confidence intervals for fatality estimates by scenario, situation without evacuation

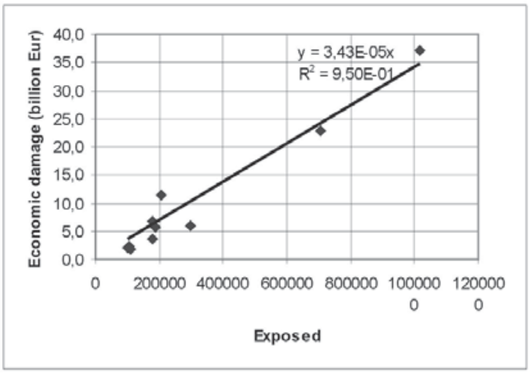
Flood scenario	5%	Average	95%
Rotterdam – Kralingen	740	1070	1930
Den Haag – Boulevard	30	110	380
Den Haag - Scheveningen	20	230	610
Katwijk	150	400	890
Hoek van Holland	10	110	330
Katwijk and Den Haag	320	550	1360
Den Haag and Ter Heijde	1820	3460	5490
Rotterdam West	30	190	430
Rotterdam East	250	600	1090
Katwijk, Den Haag and TerHeijde	3130	5090	8310

Appendix 9.II: Relationships between consequence categories

Based on the available calculation results, it is possible to investigate relationships between the magnitude three reported consequence categories: number of exposed, number of fatalities and economic damage (see also section 2.5). Figure A16 depicts the relationships between these consequence categories. The dots indicate the outcomes for different scenarios, the adjoining table summarizes the ratios between the categories.







	Fatalities	Exposed	Economic damage
Fatalities	1		
Exposed	217	1	
Economic damage	Eur 7,540,000	Eur 34,300	1
Table should be read as follows: 1 fatality is accompanied by 217 people and 7,54 million Euro damage			

Figure A 16: Relationships between numbers of fatalities, exposed and economic damage

Results show that there is a strong correlation ($R^2 \approx 0,9$) between the consequence categories. The existence of these relationships is logical. The number of exposed and fatalities are related via the dose response function. For the relationship between fatalities and exposed, the bestfit trendline is found for mortality value F_D=0,0055 ([5]). The number of exposed people in an area will be related with the economic value. Variations between scenarios in evacuation possibilities could weaken this relationship. Such proposed relationships can be used to obtain first order estimates of the impacts without a detailed assessment with consequence models. For example, if it is known that an area with a certain number of exposed people is flooded, first order estimates of loss of life and economic damage can be made. However, it should be stressed that the above relationships are based on information from model results. In addition, the presented relationships might only be applicable to a specific type of flooding. Further investigation of actual damage from past disasters is recommended to see whether similar ratios can be observed in practice.

5 This value differs from the mortality averaged over all scenarios. In the least square derivation of the bestfit trendline larger weight is given to scenarios with larger consequences.

Appendix 9.III: Distribution of acceptable societal risk over installations: background

In this appendix background information is given on the approach for the distribution of acceptable societal risk over installations proposed in section 9.5.1. Firstly, it will be shown that the application of this approach does not affect the standard deviation of the number of fatalities at a national scale for small probability – large consequence events. The approach is is thereby consistent with the total risk criterion proposed by Vrijling *et al.* (1995). Secondly, it is shown how the proposed criterion can be used in combination with an FN limit line with a linear steepness of –1. Thirdly, an example is elaborated to show how the installation size affects the acceptable failure probability of an installation for the three proposed criteria in the framework (individual risk, societal risk, economic optimisation). This indicates that especially for very large installations the societal risk criterion is expected to become most stringent.

Appendix 9.III.1: Relationship between proposed societal risk limit and standard deviation of the number of fatalities

In this appendix it is shown how the proposed rule for distribution of societal risk over installations affects the expected number and standard deviation of fatalities at a national scale. Simplified examples are elaborated to illustrate this.

We assume the application to a system of flood prone areas, so-called polders. Different configurations for the distribution of inhabitants over the polders are examined, yet the total number of (expected) fatalities and inhabitants are kept constant for the whole system. Three cases are elaborated. Failures of the considered polders are mutually exclusive, i.e. simultaneous failure is impossible. The acceptable risk at the national level is limited by the following formula:

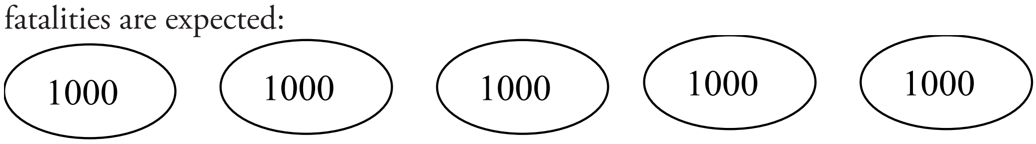
$$1 - F_N(n) < C_N / n^2$$

The acceptable probability of flooding of a single polder is determined by the value of constant C_I.

$$C_I = \frac{I_I}{I_N} C_N$$

We assume a country with I_N=500.000 inhabitants and the value of C_N =1. In case of the flooding of an area it is assumed that a fraction of F_D=0,01 of the population will be killed.

<u>Case 1: every polder the same number of inhabitants and fatalities.</u>
The first case concerns 5 polders, with 100.000 inhabitants each. In case of a flood 1000 fatalities are expected:



Constant C_I becomes:

$$C_I = \frac{I_I}{I_N} C_N = \frac{100.000}{500.000} 1 = 0,2$$

The acceptable flooding probability (p_f) becomes:

$$p_f = C_I / n^2 = 0,2/1000^2 = 2 \cdot 10^{-7}$$

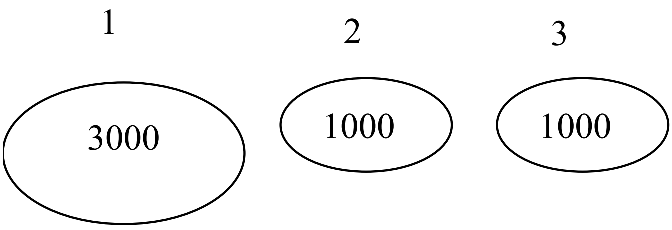
At a national scale the expected value and standard deviation become:

$$E(N) = 5 p_f n = 1 \cdot 10^{-3}\ fat/yr$$

$$\sigma(n) \approx \sqrt{5 p_f n^2} = 1\ fat/yr$$

<u>Case 2: Population distributed over unequal polders</u>

The population is distributed over three polders. Polder 1 with 300.000 inhabitants and 3000 potential fatalities. Polders 2 and 3 with 100.000 inhabitants each.



Constants become: $C_{I,1}$=0,6; $C_{I,2}$=$C_{I,3}$=0,2

The acceptable flooding probabilities become:

$$p_{f1} = C_{I1} / n_1^2 = 0,6/3000^2 = 6,66 \cdot 10^{-8}$$

$$p_{f2} = p_{f3} = C_{I2} / n_2^2 = 0,2/1000^2 = 2 \cdot 10^{-7}$$

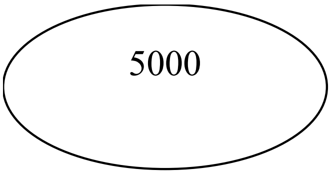
leading to:

$$E(N) = p_{f1} n_1 + 2 p_{f2} n_2 = 6 \cdot 10^{-4}\ fat/yr$$

$$\sigma(n) \approx \sqrt{p_{f1} n_1^2 + 2 p_{f2} n_2^2} = 1\ fat/yr$$

<u>Case 3: all inhabitants and fatalities in one polder</u>

In the last case all the people live in one polder, with 500.000 inhabitants, and 5000 potential fatalities.



The value of constant C_I=C_N=1. The acceptable flooding probability is:

$$p_f = C_I / n^2 = 1/5000^2 = 4 \cdot 10^{-8}$$

At a national scale the expected value and standard deviation become:

$$E(N) = p_f n = 2 \cdot 10^{-4}\ fat/yr$$

$$\sigma(n) \approx \sqrt{p_f n^2} = 1\ fat/yr$$

Discussion
The formula keeps the standard deviation of the number of fatalities constant at a national scale for installations with different sizes when $E(N) << \sigma(N)$. The three situations result in different expected values of fatalities, but expected values are negligibly small relative to the standard deviation. The approach is therefore consistent with the earlier proposed criteria for societal risk in the format of the total risk (Vrijling *et al.*, 1995).

More in general, it can be easily shown that the above approach limits the standard deviation. The standard deviation of fatalities at a national scale can be written as follows:

$$\sigma(N) \approx \sqrt{\sum_{i=1}^{n} p_i N_i^2}$$

The acceptable failure probability for each installation is found as follows:

$$p_i = C_i / N_i^2$$

Substitution yields:

$$\sigma(N) \approx \sqrt{\sum_{i=1}^{n} C_i} = \sqrt{C_N}$$

Appendix 9.III.2: General formulation for acceptable societal risk by installation

Here, it is shown how the proposed formulation for the societal risk limit can be combined with an FN limit line with a linear steepness (α=1). The general formulation for the acceptable societal risk for an installation is:

$$1 - F_N(n) < C_I / n^{\alpha}$$

Where: α – steepness of the FN limit line
The value of constant C_I can be determined with the following equation:

$$C_I = \frac{I_I}{I_N} C_N$$

We assume the example of a flood prone area (polder or dike ring) so that the number of exposed people by polder ($N_{EXP,I}$) becomes the indicator for the intensity. The number of fatalities for flooding of area I equals:

$$n = F_D N_{EXP,i}$$

It is assumed that the value of mortality F_D is identical for all areas, for example 1%. Now, the expression of acceptable societal risk by installation becomes:

$$1 - F_N(n) = \frac{C_I}{n^{\alpha}} = \frac{N_{EXP,I}}{N_{EXP,N}} \frac{C_N}{n^{\alpha}} = \frac{C_N}{N_{EXP,N} (F_D)^{\alpha} N_{EXP,I}^{(\alpha-1)}}$$

Where: $N_{EXP,N}$ - total number of exposed people at a national scale

This equation shows that for an FN limit line with a linear steepness (α =1) the acceptable failure probability becomes independent of the area size (represented by $N_{EXP,I}$). This can be explained as follows: When the installation size becomes smaller (and thus $N_{EXP,I}$) the FN limit line will translate downwards vertically. At the same time the number of fatalities will reduce because it is linearly dependent on the number of exposed people ($N_{EXP,I}$). Because a linear FN limit line is chosen, these two effects will compensate each other, and the acceptable failure probability becomes independent of the installation size. This proves that the acceptable failure probability per installation becomes independent of the installation size for a limit line with linear steepness and a constant mortality.

Appendix 9.III.3 Effect of installation size on acceptable failure probability: example[6]

With the framework presented in section 9.5.1 an acceptable or optimal failure probability per installation is obtained for three criteria (individual and societal risk and economic optimisation). Following TAW (1984) it is proposed to use the most stringent of these three criteria as a standard for the installation. In this earlier work it has been investigated how these criteria work out jointly for an object or installation with a fixed size. It is interesting to investigate how the acceptable probability for all three criteria changes with the installation size. This is investigated conceptually for all three criteria for a simple and schematic case study for a flood prone area or dike ring.

Example: dike ring area
A circular and horizontal dike ring is assumed with radius R [m] (see figure A17).

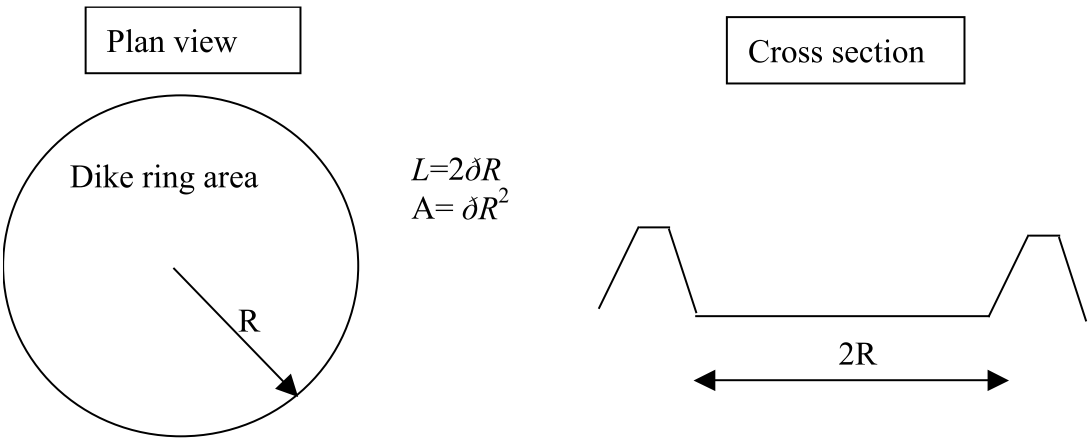


Figure A 17: Schematic dike ring

It is assumed that:

- The population density (m_0 - [pers/m^2]) and density of economic value (d_0 – [€/m^2]) are constant over the whole area and independent of dike ring size;
- The area will flood due to dike breach if the outside water level exceeds the dike height;
- In case of dike breach the whole area is flooded regardless of the size of the area and location of breaching;
- In case of flooding all economic values are lost leading to damage value $D=d_0\pi R^2$ [€]
- In case of flooding the mortality fraction equals F_D, leading to the following number of fatalities $N=F_D m_0 \pi R^2$
- The only measure considered is the reduction of flooding probability. This can be achieved by integral strengthening of the dike around area.

6 The contents of this section are based on discussions with Ruben Jongejan (TU Delft).

In the example the total number of inhabitants and damage value are kept constant at a national scale. It is investigated how the acceptable flooding can be expressed as a function of varying size of the dike ring using the three risk criteria discussed in section 9.5.1.

The acceptable failure probability according to the **individual risk** standard becomes:

$$P_f \leq \frac{\beta 10^{-4}}{F_D}$$

It is <u>independent</u> of the dike ring size.

The acceptable failure probability for one installation according to the **societal risk** criterion is:

$$P_f \leq \frac{C_I}{N^2} \quad \Rightarrow \quad P_f \leq \frac{C_I}{(F_D \pi m_0)^2 R^4}$$

A value for the constant C_I can be chosen based on the method presented in section 9.5.2. The value of C_I is determined based on the number of inhabitants of a dike ring relative to the total number of inhabitants in the country. The value of constant C_N is determined at a national scale:

$$C_I = \frac{N_I}{N_N} C_N = \frac{m_0 \pi R^2}{N_N} C_N$$

Where: N_N – number of inhabitants in flood prone areas in the country [person]; C_N – constant indicating the height of the acceptable societal risk at a national scale.

Substitution yields the following expression for acceptable failure probability for one installation:

$$P_f \leq \frac{C_N}{N_I m_0 F_D^{\,2} \pi R^2}$$

The acceptable failure probability <u>decreases linearly</u> with the area size ($A=\pi R^2$).
Finally, the acceptable (or optimal) failure probability according to the **economic optimisation** is considered. The investment costs and damage are formulated as a function of the dike ring size:

$$C_{tot} = I'Lh + P_f D / r'$$

$$C_{tot} = I'2\pi Rh + P_f d_0 \pi R^2 / r'$$

Where: I' – variable cost of dike improvement per unit of length [€/m] ; h – dike height [m]; r' – reduced interest rate [-]

An exponential distribution of the water level outside the area is considered. The economic optimum can be determined as follows:

$$P_f = e^{-\frac{h}{B}}$$

$$\frac{dC_{tot}}{dh} = 0 \quad \Rightarrow \quad P_{f,opt} = \frac{I'LBr'}{D} = \frac{I'LBr'}{d_0 A} = \frac{I'2\pi RBr'}{d_0 \pi R^2} = \frac{I'B2r'}{d_0 R}$$

Where: B – constant in the exponential distribution [m]
The above equation for the optimal flooding probability illustrates that the optimal probability will be linearly dependent on length / damage. Eijgenraam (2005) also found this result for actual (but highly schematised) dike rings in the Netherlands. Other versions of the equation show that the optimal flooding probability will be proportional with length / area size, 1/radius or 1/(area size)$^{0.5}$.
It is possible to take the economic value of loss of life into account in the optimisation (see e.g. TAW, 1984 and section 2.6). Because both damage and loss of life are dependent on dike ring size, the expression for the optimal flooding probability becomes:

$$P_{f,opt} = \frac{I'LBr'}{(D + Nd_N)} = \frac{I'B2r'}{(d_0 + d_N F_D m_0)R}$$

Where: d_N – economic value of loss of life

Numerical example
An example is given for the circular dike ring using the numerical values shown in table A5. Figure A18 indicates the acceptable flooding probability for an individual dike ring as a function of the area size. The total number of inhabitants in the country is kept constant. Because area size has a linear relationship with fatalities and economic damage, these indicators can also be displayed at the horizontal axis, leading to the same figure.

Table A 5: Values for variables used in the example

Variable	Value	unit		variable	value	Unit
m_0	0,0005	pers/m2		I'	10	€/m
F_D	0,001	-		B	4	-
N_N	1,00E+07	persons		r'	0,04	-
C_N	1	-		β	0,01	-
D_0	0,1	€/m2		d_N	1,00e6	€

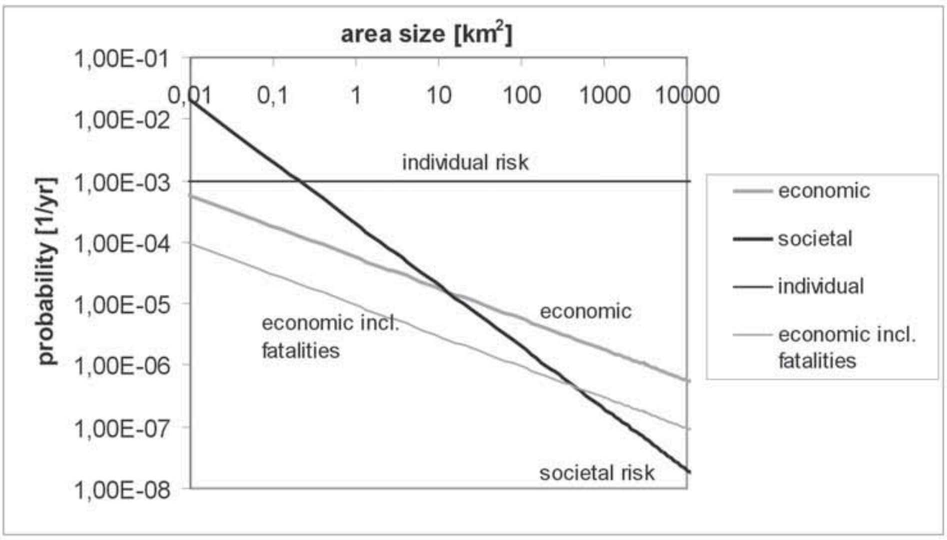


Figure A 18: Acceptable flooding probability for a single dike ring as a function of dike ring size according to different risk criteria

Discussion
Results show that acceptable for three criteria have a different dependence on dike ring size. Acceptable probability from individual risk is independent of dike ring size. The limit line from the economic analysis has a steepness of –0,5. Inclusion of the economic value of loss of life in the economic optimisation leads to a vertical shift of the line. The acceptable probability following from societal risk decreases linearly with the area size.

The analysis showed that the variation of area sizes does not affect the expected values of damage and fatalities at a national scale. However, it will affect the standard deviations of the number of fatalities and damages at a national scale. This difference is reflected in the different steepnesses of the limit lines for following from economic optimisation (which includes the expected value) and societal risk (which is based on the standard deviation). For very small dike rings the individual risk criterion could become relevant. Especially for larger dike rings it is expected that the societal risk criterion will become the most stringent. In practice this effect might be less strong than in the example, as the assumption that the whole area will floods is less appropriate for very large dike rings[7]. It is noted that the outcomes of the above example change substantially when a linear steepness is chosen for the FN limit (instead of a quadratic steepness), see previous part of this appendix. Overall, it is recommended to investigate the combined application of the three risk criteria further for actual dike rings in the Netherlands to further develop risk standards.

7 For example this was shown in the FLORIS project (Rijkswaterstaat, 2005) where it was shown that the largest polder in the Netherlands (South Holland) will not completely flood in case of a dike breach. This would lead to a reduction of damage and loss of life and thereby to higher acceptable probabilities following from the analysis of economic and societal risk.

List of symbols

The following list summarises the main symbols that have been used in this thesis. The list includes the main symbols. The following types of symbols have not been included:

- Distribution functions and probability density functions of already defined symbols, e.g. $f_N(n)$ or $F_N(n)$.
- Expected values and standard deviations of already defined symbols, e.g. E(N)
- Logical combinations and specific variations in notations of already defined symbols, e.g. σ_R (standard deviation of resistance) $N|f$ (number of fatalities given failure) and IR_{AV} – average individual risk.
- Abbreviations only used in the text and in graphs, e.g. *PLL* – potential loss of life.

All individual symbols have been defined in the text of this thesis.

Roman symbols

A	parameter of the exponential distribution [m] (section 2)
A	exposed area due to a certain accident [m^2] (section 3)
B	parameter of the exponential distribution [m] (section 2)
B	width of exposed area in polar coordinate system [rad] (section 3)
B	The average body width exposed normal to the flow [m] (section 6)
C	constant in disutility function [-]
C_C	constant in determination of size of breach zone [s/m^2]
C_D	Drag coefficient [-]
C_F	constant in the equation for friction instability [m^3/(kg s^2)]
C_I	constant that determines the vertical position of the FN limit line for an installation [yr^{-1} $fat^{-\alpha}$]
C_N	constant that determines the vertical position of the FN limit line at a national scale [yr^{-1} $fat^{-\alpha}$]
C_S	constant in the equation for moment instability [m^2/(s $kg^{0.5}$)]
CSX	cost of saving an extra statistical life [€/person]
CSXY	cost of saving an extra life year [€/yr]
C_{tot}	totals costs [€]
D	economic damage [€]
DF	debris factor [m^2/s]
F_B	fraction of buildings collapsed [-]
F_D	mortality (= number of fatalities / people exposed) [-]
F_E	fraction of the population that is able to evacuate [-]
F_I	injured fraction of the surviving exposed population [-]
F_I^*	injured fraction of the original exposed population [-]
F_O	fraction of fatalities due to other factors [-]
F_R	fraction of fatalities near the breach [-]
F_S	fraction of the population that is able to find shelter [-]
F_{buoy}	buoyancy force [N]
F_{flow}	the horizontal force of the flow on an object in the flow [N]
F_{person}	the person's weight [N]
FED	fractional effective dose [-]
I	investment in safety measures [€] (sections 2 and 9)
I	variable in the limit state function that represents the knowledge uncertainty (section 4)
I_I	production of object (can have various units, see table 9-4)
I_N	production at a national scale (can have various units, see table 9-4)
IR	individual risk [yr^{-1}]

IR_{AV} average individual risk [yr^{-1}]
IR_{MAX} maximum individual risk [yr^{-1}]
IR_T individual risk for tunnels [yr^{-1}]
K_0 constant in limit state function for human instability in flood flows [$kg^{-1/2}\ m^2\ s^{-1}$]
L a person's height [m]
N number of fatalities
N_B number of collapsed buildings
N_{EXP} number of people exposed
N_I number of injuries (section 2)
N_I number of installations (section 9)
N_{PAR} number of people at risk
N_{RES} number of people rescued
P_B probability of dike breach nearby a residential area [-]
P_E probability of exposure [-]
P_S probability of a storm [-]
Pr Probit value [-]
PV present value factor [-]
Q discharge [m^3/s]
R number of respondents [person] (section 2)
R resistance in limit state function [-] (sections 3 and 4)
R radius in polar coordinate system (section 3)
$R_{1\%}$ effect distance [m]
R_C radius of breach zone [m]
R_P number of travels per year for a specific user through a tunnel
R_{RES} rescue capacity [persons/hr]
R_T total number of travels per year through a tunnel
RI Risk integral [fat^2/yr^2]
S load in limit state function [-]
T_A time available for evacuation [can have various units, e.g. seconds or hours]
T_{DD} time required for detection and decision making before evacuation [can have various units, e.g. seconds or hours]
T_{EVAC} time required for actual evacuation [can have various units, e.g. seconds or hours]
T_R time required for evacuation [can have various units, e.g. seconds or hours]
TR Total risk [fat/yr]
T_{RESP} time required for response to evacuation warning [can have various units, e.g. seconds or hours]
T_{WARN} time required for warning for evacuation [can have various units, e.g. seconds or hours]
U disutility [-]
VoSL Value of a Statistical Life [€/person]
WTP willingness to pay [€/yr]
Z limit state function

a constant in the probit function [-] (section 2 and 7)
a constant used in probability density function of intensity of initial effects (section 3)
b constant in the probit function [-](section 2 and 7)
b constant used in the dose response function (section 3)
c intensity of physical effects [can have various units, e.g. mg/m^3]
c_0 initial intensity of physical effects at a risk source [can have various units, e.g. mg/m^3]
c_{cr} critical threshold level of physical effects [can have various units, e.g. mg/m^3]
c_R lethal resistance intensity of physical effects [can have various units, e.g. mg/m^3]
c_S load of physical effects to which people are exposed [can have various units, e.g. mg/m^3]
d_1 Distance from person's pivot point to their centre of mass [m]

d_2	Distance from person's pivot point to the mass centre of mass of the submerged part of the body [m]
g	Acceleration due to gravity [m/s^2]
h	water depth [m]
h_{ts}	tsunami wave height [m]
hv_c	critical depth velocity product for instability [m^2/s]
k	risk aversion coefficient [-]
m	population density [person/m^2] (section 3)
m	a person's mass [kg] (section 6)
m_0	constant for population density [person/m^2]
n	constant in the probit function [-]
n_v	number of vehicles per year [1/yr]
p_f	probability of failure [1/yr]
$p_{f,0}$	initial probability of failure [1/yr]
$p_{f,opt}$	optimal probability of failure following from an economic optimisation [1/yr]
q	constant mortality value that occurs if the intensity c_{cr} is exceeded [-]
t	time [s]
t_I	time span until rescue actions reach their maximum capacity [s]
v	movement speed of an evacuating person [m/s] (section 2)
v	flow velocity of water [m/s] (sections 5-9)
$v_{effects}$	dispersion velocity of physical effects [m/s]
w	rise rate of floodwater [m/hr]
x	horizontal coordinate [m]
x_A	horizontal dimension of the crash area of an airplane [m]
x'	accident location [m]
x_E	distance from the origin to a safe area [m]
y	second horizontal coordinate [m]
y_A	second horizontal dimension of the crash area of an airplane [m]
z	vertical coordinate [m]

Greek symbols

Φ_N	Cumulative normal distribution
α	risk aversion coefficient [-]
α^*	constant determining decrease of effects as a function of distance [m^{-1}]
β	policy factor used to characterise the severity of an activity [-]
θ	angle in polar coordinate system [rad]
θ_W	wind direction [rad]
λ_f	failure intensity [1/m]
μ	average (sections 4, 7 and 8)
μ	coefficient of static friction (section 6)
μ_D	average used in the conversion of a probit value to a probability (μ_D=5)
μ_N	average of the normal distribution
ρ	correlation coefficient [-] (section 4)
ρ	density of the flowing fluid [kg m^{-3}] (section 6)
σ	standard deviation
σ_C	standard deviation of the crash location relative to the flightpath centre line [m]
σ_D	standard deviation used in the conversion of a probit value to a probability (σ_D=1)
σ_N	standard deviation of the normal distribution

Curriculum Vitae

Bas Jonkman was born on April 6th, 1977 in 's-Gravenhage. After spending his youth in the town of Voorschoten, he received his school diploma from the Stedelijk Gymnasium in Leiden in 1995. In the same year he started his studies in civil engineering at Delft University, from which he graduated in March 2001 on an Msc. thesis that dealt with the quantification of flood risks in the Netherlands.

After his graduation he started to work for the Road and Hydraulic Engineering Institute of Rijkswaterstaat in Delft. Within the flood protection section he contributed to the development and application of methods for the analysis of damage, loss of life and flood risks. Since 2002 he has combined his work at Rijkswaterstaat with a position as a researcher at Delft University. During 2002 and 2003 he also worked for the Centre of Tunnel Safety (Civil Engineering Division, Rijkswaterstaat) where he was involved in the development of methods for the analysis of tunnel safety. During 2004 and 2005 Jonkman was a member of the board of young professionals at the Ministry of Transport, Public Works and Water Management.

After the tragic event of hurricane Katrina in the year 2005 the author was involved in research and advisory activities that followed this disaster. During February and March 2006 Jonkman worked in Southeast Louisiana with the Hurricane Centre of the Louisiana State University to analyse the levee failures and the consequences of the flooding of New Orleans. He participated in several workshops regarding the future planning of hurricane protection for South East Louisiana and he reviewed and contributed to reports of the United States Army Corps of Engineers on this topic. In the year 2006 he was involved in the initiation of the 'Dutch perspective for coastal Louisiana flood risk reduction and landscape stabilization', a project by the Dutch water sector. Within this project he has worked on the application of the Dutch experiences with risk-based design of flood defences to Southeast Louisiana.

The author has published his research in both academic and popular publications. In December 2006 the results of his study on the catastrophic consequences of a flooding of South Holland received national media attention in both newspapers and on national radio and television.

Nawoord

Alleen door het met eigen ogen te zien kan iemand zich een voorstelling maken van de schade die een overstromingsramp veroorzaakt. De verwoestingen in en rondom New Orleans hebben diepe indruk op mij gemaakt. De nog herkenbare persoonlijke bezittingen die je tegenkomt in het veld, zoals het fotoboek op de omslag, en de gesprekken met getroffen mensen geven een indruk van het menselijk leed. De ervaringen uit New Orleans geven aan dat het belangrijk is om te blijven werken aan onze kennis over overstromingen, en juist ook aan het voorkomen van deze rampen. Ik hoop dan ook dat de kennis uit dit proefschrift zal bijdragen tot het nemen van goede en verstandige beslissingen over de beveiliging tegen overstromingen.

In de eerste plaats wil ik mijn werkgever Rijkswaterstaat bedanken voor de geboden mogelijkheid om mijn promotie onderzoek te kunnen combineren met werkzaamheden als adviseur / specialist binnen het werkveld veiligheid hoogwater.

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One of the attractive elements of life as a researcher concerns the opportunities for travel and international collaboration. First of all I want to acknowledge the people of the LSU Hurricane Center, especially Marc Levitan, Bruce Sharky and Ivor van Heerden, for their hospitability and openness. In particular I want to thank Ezra Boyd for taking all the time to share his first-hand knowledge of New Orleans with me, both in the office and (probably even more importantly) in the field. I also want to thank Ilan Kelman and Fuminori Kato for the pleasant cooperation. I acknowledge the international members of my examination committee, Edmund Penning-Rowsell and Michael Faber, for their involvement and suggestions.

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