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The potential use of individual and societal risk criteria within the Dutch flood safety policy (part 1): Basic principles

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ABSTRACT: The Dutch government is in the process of revising its national flood safety policy. The current Dutch Flood Defense Act lays down design standards for the Dutch flood defenses. These standards have been based on/rationalized by economic optimizations in which investment costs are balanced against the discounted value of (potential) future losses. Loss of life is not considered separately. This paper presents the results of a research project that evaluated the potential roles of two risk metrics: individual and societal risk. These metrics are already used in the in the Dutch major hazards policy for the evaluation of risks to the public. Individual risk concerns the annual probability of death of an average, unprotected person. Societal risk concerns the probability of a multi-fatality event. This paper discusses technical aspects of the use of individual and societal risk metrics in flood risk management, as well as policy implications.

1 INTRODUCTION

Flood protection is of paramount importance to the low-lying Netherlands. The Dutch government is currently in the process of updating its flood risk management policy. The Flood Defense Act of 1996 lays down the exceedance probabilities of the hydraulic loading conditions that the primary flood defenses should be able to safely withstand. Policymakers increasingly voice the need for an integrated flood safety policy, in which flood probabilities (other than exceedance probabilities of loading conditions) and flood consequences are mitigated in conjunction. EU Directive 2007/60/EC, the report of the Second Dutch Delta Committee (2008), and the recently published Dutch national water plan all stress the need for evaluating flood probabilities and consequences in an integrated manner.

Flood risk is not just about probabilities, but also about the consequences of floods. The Dutch approach to the evaluation of flood safety has traditionally been to minimize the sum of the discounted investments in flood defense and the discounted expected value of future losses (Van Dantzig 1956). Various intangible losses, including loss of life, are valued in money terms and included in the financial balance.

The Dutch focus on the economics of flood safety seems understandable given the costs of flood risk mitigation and the enormous potential impact of floods. On the 29th of August 2005, Hurricane Katrina struck the US Gulf Coast. The levee system protecting New Orleans proved no match for the ensuing storm surge and large parts of the low-lying city were flooded. With damages totaling 138 billion US dollar, Katrina is the costliest natural disaster to date (Munich Re 2008). Floods on the scale of New Orleans are not unthinkable in the Netherlands, a country with broadly similar topographical characteristics as the Mississippi delta (Jonkman et al. 2005).

Apart from economic losses, floods can cause severe societal disruption and loss of life: over 1400 people lost their lives in the New Orleans flood. The Dutch government has indicated that it will explicitly consider potential loss of life when deciding on the stringency of new flood safety standards. While loss of life is monetized and included in the financial balance of cost-benefit studies, it is not evaluated separately. In another policy domain, concerned with the safety of those living in the vicinity of major industrial hazards, loss of life *is* explicitly taken into account in the evaluation of risks to the public. The Dutch government therefore commissioned a study about the opportunities for transferring the approach used in the Dutch major hazards policy to the domain of flood safety (Jonkman et al. 2008). This paper presents some key results of that research project.

The paper is organized as follows. Section two introduces the risk metrics that are used in the Dutch major hazards policy: individual and societal risk. The following section discusses how these risk metrics can be quantified for flood risks. Section four then discusses alternative ways to take fatality risks into account in a risk-informed flood safety policy. As will be shown, some uses of these risk metrics can have significant policy implications Case studies will illustrate how different types of interventions (e.g. dike strengthening, improving evacuation opportunities, compartmentalizing dike rings) influence individual and societal risks. The paper ends with a summary and discussion of the main results.

2 RISK METRICS USED WITHIN THE DUTCH MAJOR HAZARDS POLICY

The Dutch major hazards policy deals with the risks to those living in the vicinity of major industrial hazards, such as chemical plants and LPG-fuelling stations. The cornerstones of the Dutch major hazards policy are (i) quantitative risk analysis, (ii) individual and societal risk as risk-determining parameters and (iii) quantitative acceptability criteria for evaluating levels of individual and societal risk (Ale 1991, 2002; Bottelberghs 2000). Individual risk is defined as the probability of death of an average, unprotected person that is constantly present at a given location.

Individual risk criteria are reference levels for evaluating individual risks. The individual risk criteria were given a legal status in 2004 by the External Safety Decree. These limits to individual risk prevent disproportional individual exposures. Permits for property developments or plant modifications are denied if vulnerable objects would then be located within the 10^{-6} contour (Fig. 1).

An individual risk criterion alone cannot prevent the too frequent occurrence of multi-fatality accidents. As shown in Figure 1, the area affected by an accident can differ considerably from the area that is defined by

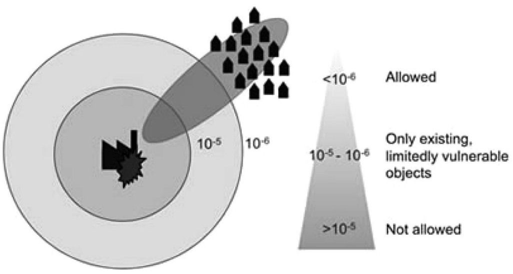

Figure 1. Individual risk contours around a hazardous establishment and the area affected by an individual accident scenario.

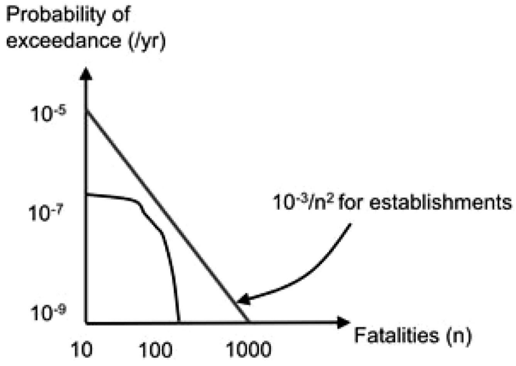

Figure 2. The Dutch societal risk criterion for hazardous establishments and a fictitious FN-curve.

an iso-(individual)risk contour. When individual exposures are low, there could still be a chance that a single accident kills a large number of people. While a vast number of small accidents can go by without hardly being noticed, multi-fatality accidents can shock a nation. Psychometric studies have indeed shown that "dread", or catastrophic potential, is an important factor in explaining risk perceptions (Slovic 1987). To prevent the too frequent occurrence of large-scale accidents, societal risk criteria were implemented in the Netherlands. Societal risk is graphically represented by an FN-curve that shows the exceedance probabilities of the potential numbers of fatalities ($P(N \geq n)$) on double log scale (Fig. 2).

The Dutch societal risk criterion of $10^{-3}/n^2$ per installation per year was initially developed for LPG-fuelling stations. It was later applied to all Seveso establishments. Similar societal risk criteria thus apply to hazardous establishments of different character and size, despite considerable differences between the marginal costs of risk reduction in different cases (see Jongejan (2008) for further discussion).

3 QUANTIFYING MORTALITY RISKS FOR FLOODS

3.1 *Flood risk analysis*

To quantify flood risks, state of the art modeling techniques combine (i) probability density functions of hydraulic conditions (ii) probability density functions of the variables that determine the load bearing capacity of a flood defense, (iii) fault tree models to analyze failure modes, and (iv) flood propagation models, land-use data and loss functions to relate flood characteristics and land-use data to the consequences of flood scenarios (e.g. Van Manen & Brinkhuis 2005). This paper focuses on the quantification of loss of life for a given flood scenario. The quantification of flood probabilities and flood characteristics (such as flow velocities, rise rates, and inundation depths) is outside the scope of the present paper and discussed in e.g. Steenbergen et al. (2004).

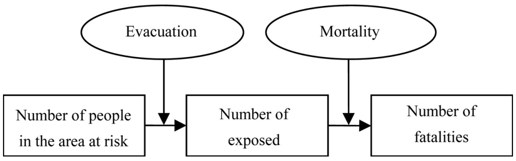

Figure 3. Flood risk analysis: quantifying loss of life (after Jonkman 2007)

The number of fatalities for a particular flood scenario depends on the spatial distribution of (time-variant) flood characteristics, the population densities of affected regions, possibilities for evacuation, and the probabilities of death of the affected individuals. The probability of death of an affected individual is typically assumed to depend only on flood characteristics, i.e. hydraulic conditions. Differences between the vulnerabilities of different individuals are thus ignored. The approach used in the Netherlands is shown schematically in Figure 3.

The approach used for the estimation of loss of life in floods shows considerable resemblance to the approach that is used in the Dutch major hazards policy. In both cases, the probability of a critical event (loss of containment or flood) is estimated using fault tree analysis, after which the physical effects associated with that critical event are considered (using e.g. dispersion or flood propagation models) and related to mortality estimates (using dose-response functions or flood mortality functions). But while the potential for evacuation is often limited when it comes to explosions or toxic releases, it could be significant when it comes to floods.

3.2 *Mortality functions*

Mortality functions relate flood characteristics to mortality estimates. Historical evidence suggests that different mortality functions should be defined for three different zones (Jonkman 2007):

1. *Breach zone*: a zone characterized by high flow velocities near a breach location. Flow velocities cause buildings to collapse and/or be displaced. Mortality in this zone is (almost) one. The threshold for this zone is given by:

   $$h \cdot v \geq 7m^2/s \quad \text{and} \quad v \geq 2m/s \tag{1}$$

   where h = inundation depth [m]; v = flow velocity [m/s].
2. *Zone with rapidly rising water levels*: a zone characterized by high rise rates, making it difficult for people to bring themselves to safety. Threshold:

   $$w \geq 0.5m/hr \tag{2}$$

   where w = rise rate [m/hr].
3. *Other*: a zone in which flow velocities, rise rates and inundation depths are relatively low. Vulnerable individuals could however still drown or die from hypothermia.

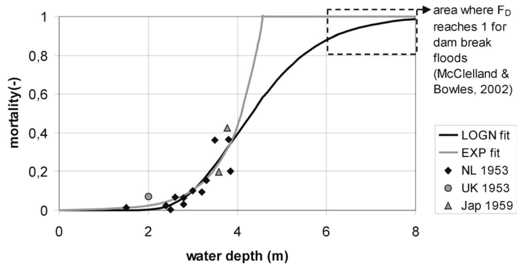

Figure 4. Mortality function for the second zone: rapidly rising water levels.

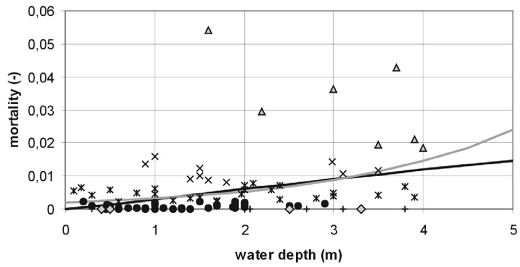

Figure 5. Mortality function for the third zone: other.

Mortality functions have been derived for zones two and three, using data about historical floods in Japan (1934: Typhoon Muroto; 1950: Typhoon Jane; 1959: Ise Bay Typhoon), the Netherlands (1953: storm surge), the UK (1953: storm surge), and the US (1965: Hurricane Betsy) (data from: Tsuchiya and Kawata, 1981; Grieve 1959; Summers 1978). These mortality functions have been validated using data about historical floods in the UK (1912: Norwich; 1952: Lynmouth; 2002: Gowdall), South Africa (1981: Laingsburg), Japan (Typhoon No. 19) (data from: Rasbottom et al. 2003; EMDAT 2004; Takikawa 2001). For further details about the derivation of the mortality functions for zones two and three, the reader is referred to Jonkman (2007). The mortality function for the second zone with rapidly rising water levels ($w \geq 0, 5$m/hr) is given by:

$$F_D(h) = \Phi\left(\frac{\ln(h) - \mu}{\sigma}\right) \quad \text{with} \quad \mu = 1.46; \sigma = 0.28 \tag{3}$$

where $F_D(h)$ = flood mortality [-]; h = inundation depth [m].

The mortality function for the third zone ("other") is given by:

$$F_D(h) = \Phi\left(\frac{\ln(h) - \mu}{\sigma}\right) \quad \text{with} \quad \mu = 7.6; \sigma = 2.75 \tag{4}$$

where $F_D(h)$ = flood mortality [-]; h = inundation depth [m].

The mortality functions can be used to estimate the probability of death at a given location for any given flood scenario, as well as the number of deaths for that scenario. The spatial distribution of the overall probability of death can be calculated according to:

$$P_d(x,y) = \sum_{i=1}^{n} p_d(c_i(x,y)) \cdot p_i \tag{5}$$

where $P_d(x,y)$ = probability of death at location (x,y) [yr^{-1}]; $p_d(c_i(x,y))$ = probability of death in case of flood characteristic c at (x,y) in scenario i [-]; p_i = probability of scenario i [yr^{-1}]; n = number of flood scenarios [-].

Using equation (5), the overall probability density function of the number of flood fatalities can be found by integration over the population density of the affected region.

3.3 *Modeling the effectiveness of evacuation*

Extreme river discharges can be forecasted days ahead. An extreme weather or water level forecast can lead to the decision to evacuate people from a flood prone region to reduce potential loss of life. Even if such forecasts were 100% reliable, it would still be difficult to forecast the occurrence of *floods* in regions protected by flood defenses, such as the Netherlands. This is because flood probabilities depend not only on the uncertainty related to hydraulic conditions, but also on the uncertainty related to the load bearing capacity of flood defenses:

$$P_f = P(S > R) = \int_R^{\infty} \int_{-\infty}^{\infty} f_{R,S}(R,S)\,dR\,dS \tag{6}$$

where P_f = probability of failure of a flood defense; R = resistance; S = load; $f_{R,S}$ = joint probability density function of resistance and load.

The (un)reliability of long-term forecasts of extreme hydraulic conditions and the uncertainty related to the resistance of flood defenses mean that floods cannot be perfectly predicted: floods might occur unexpectedly. But even when timely warned, people might be reluctant to leave, and evacuation might fail due to congestion. The evacuation rate, expressed as the percentage reduction of the number of exposed individuals, is thereby a stochastic variable. A simplified, discrete function is used in the Netherlands to account for the effect(iveness) of evacuation in flood risk assessments. The evacuation rate will strongly depend on the quality of forecasts, and level of preparedness. The evacuation rate is therefore estimated using an event tree that distinguishes between four possible outcomes, based on these two variables (Fig. 6).

The probabilities of timely warning and preparedness vary the region and have been estimated by means of expert judgment. The probability of timely warning is lower for sea floods than river floods.

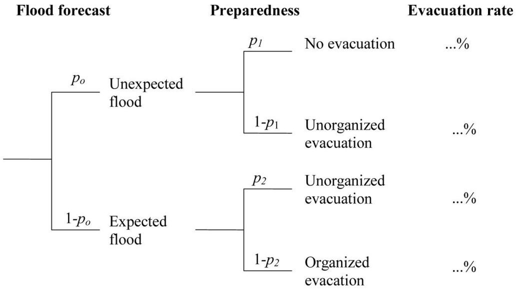

Figure 6. Event tree analysis: estimating the evacuation rate.

3.4 *Individual and societal risk estimates*

Flood probabilities and consequences have been estimated for a number of dike rings in the Floris project (Ministry of Transport Public Works and Water Management 2005). Figure 7 shows a map of levels of individual risk throughout dike ring 14, Central Holland. The individual risk estimates exclude the effect of evacuation, just as in the Dutch major hazards policy. Even without taking the effect of evacuation into account, levels of individual are generally below 10^{-6} per year for this particular dike ring because (i) the probability of flood is relatively low, (ii) flood mortality is typically substantially less than one, and (iii) not all flood scenarios affect similar parts of Central Holland.

Although levels of individual risk are relatively low throughout Central Holland, floods could still cause

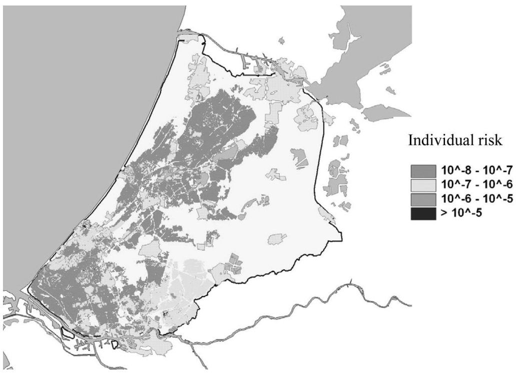

Figure 7. Individual risk map for Central Holland.

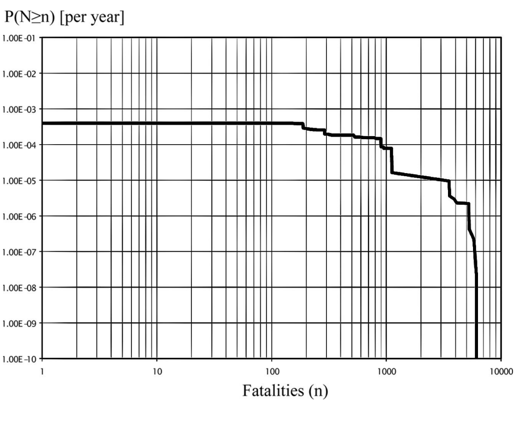

Figure 8. FN-curve for Central Holland.

severe loss of life. The FN-curve shows that the number of fatalities could exceed 1000, albeit with a probability of less than 10^{-4} per year (Fig. 8).

4 POTENTIAL USES OF INDIVIDUAL AND SOCIETAL RISK IN THE DUTCH FLOOD SAFETY POLICY

4.1 *Evaluating individual and societal risks*

The present-day flood safety policy in the Netherlands focuses strongly on economic damages. Informed by cost-benefit analyses, safety standards were defined for the Dutch primary flood defenses in the 1960s and 70s. The most valuable regions are thus best protected. To inform decision-making about new flood safety standards, a new cost-benefit analysis has been commissioned. This analysis will take the increase in potential damages into account (past economic growth has exceeded expectation). Apart from purely welfare economic considerations, loss of life will also play a role in the design of new safety standards. As discussed in the previous sections, loss of life can be evaluated from two distinct perspectives:

1. The individual perspective: the safety of a particular individual.
2. The societal perspective: the probabilities of large numbers of fatalities.

A limit to individual risk can be used to guarantee a minimal safety level to every individual living behind a primary flood defense. The introduction of such a basic safety level has also been proposed by the Second Delta Committee (2008) that advised Parliament and the Executive about the long-term prospects for protecting the Netherlands against floods. The proposed individual risk limit equaled 10^{-6} per year (including the effectiveness of evacuation), similar to the individual risk limit used in the Dutch major hazards policy. Further research is needed to see whether such a stringent safety standard would be feasible, given the measures that would have to be taken.

FN-curves show the probability distribution of the number of fatalities and can be used for the evaluation of fatality risks from a societal perspective. To facilitate the evaluation of FN-curves, criterion lines could be defined: an FN-curve should, in principle, not exceed the criterion line. An FN-criterion is defined by three variables: (i) its base point (the exceedance probability of 1 fatality), (ii) its slope, and (iii) its probability and/or consequence cut-off. Figure 9 shows the different constraints that together make up an FN-criterion.

While a theoretical link between expected utility theory and FN-criteria might be hard, if not impossible, to establish (Bedford 2005; Jongejan 2008), FN-criteria have proven themselves in the Dutch major hazards policy as practical tools for the evaluation of the probabilities of large-scale accidents. The FN-criteria used in the Dutch major hazards policy have a quadratic steepness, meaning that the exceedance

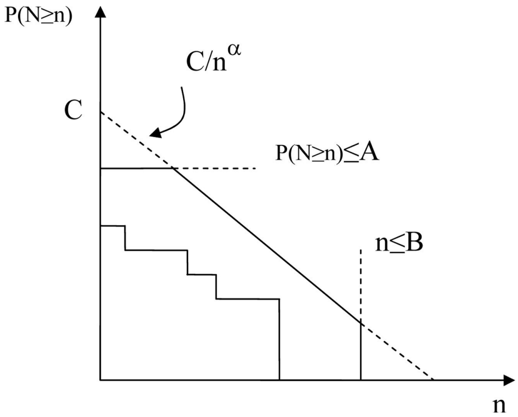

Figure 9. A fictitious FN-curve and an FN-criterion.

probability of 10 times as many fatalities should be 100 times lower. This has been motivated by public aversion to large numbers of fatalities. It should however be noted that different slopes are used in different counties (Ball and Floyd, 1998).

The stringency of societal risk criteria could, amongst other, be based on cost-benefit considerations or revealed preference models that link hazard characteristics to accident statistics and risk estimates (e.g. Vrijling 1998).

4.2 *Visualizing the effectiveness of alternative risk management strategies*

FN-curves and individual risk maps are useful tools for demonstrating the effects of a wide variety of risk reduction measures on fatality risks. They can thereby be used to facilitate the choice between alternative flood risk management strategies. Broadly speaking, there are three types of strategies to mitigate flood risks:

1. *Reducing flood probabilities*. Measures include dike strengthening, beach nourishment, and widening rivers to increase their runoff capacity. Reducing flood probabilities will cause the FN-curve to shift downwards.
2. *Reducing the consequences of floods*. Measures include flood proof construction, improving the opportunities for evacuation (early warning, constructing shelters, etc.), safety zoning, and splitting dike rings into smaller compartments. Note that the latter measure could also worsen fatality risks because rise rates are higher in smaller compartments. Reducing the consequences of floods will cause the FN-curve to shift to the left.
3. *A mixture of the above*. Unless one of the aforementioned strategies is dominant, i.e. always preferable over the other in terms of effectiveness, feasibility, and social cost, a mixture of probability and consequence reduction would be preferable (the same holds for alternative strategies within each category).

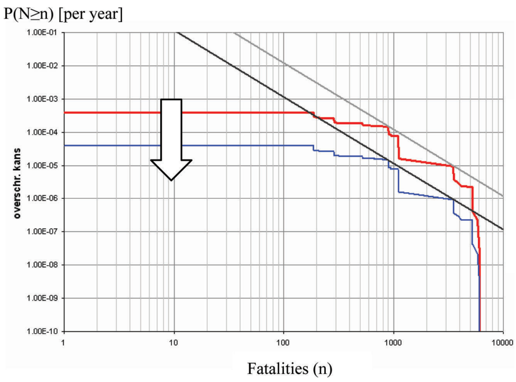

Figure 10. The impact of reducing flood probabilities by a factor 10 on the FN-curve for dike ring 14.

Figures 10 to 12 show the impact of different measures on the FN-curve for a dike ring area. The case study concerns dike ring 14, Central Holland. All analyses are based on the outcomes of the first Floris project.

Figure 10 shows the effect of dike strengthening or river widening on the FN-curve for dike ring 14. If flood probabilities were proportionally lowered along the entire dike ring, the FN-curve would shift downwards (without changing shape). It should be noted that targeting weak links can be a more cost-effective way to lower the probabilities of n or more fatalities.

Constructing flood defenses within a dike ring can reduce the area affected by a single flood and thereby reduce damages. Figure 11 shows the effect of compartmentalization on the FN-curve for dike ring 14. It should be noted that compartmentalization becomes less cost-effective when the probability of failure of the outer ring (the primary flood defense) becomes smaller. This is because the "functioning" of compartmentalizing flood defenses is conditional on the failure of the outer ring. Hence, the probability that a compartmentalizing flood defense reduces damages depends on the failure probability of the outer ring. In Figure 11, it is assumed that compartmentalizing is highly effective, and that it can reduce consequences by 50% or 75%. In reality, compartmentalizing dike rings can also raise fatality risks, as rise rates in smaller compartments exceed those in larger compartments.

Figure 12 shows the effect of improving the probability of successful evacuation on the FN-curve for dike ring 14. The figure shows four curves: (i) the original FN-curve, (ii) the FN-curve after raising the probability of early warning from 0.5 to 0.9, or 0.9 to 0.99, (iii) the FN-curve after improved early warning and a doubling of evacuation rates, and (iv) the FN-curve after raising the probability of organized evacuation from 0.9 to 0.99 and a doubling of the evacuation rates. As shown by figure 12, the extreme tail of the FN-curve cannot be avoided by efforts to improve early warning or to improve disaster preparedness. This is because the probability of a failed evacuation stays non-zero.

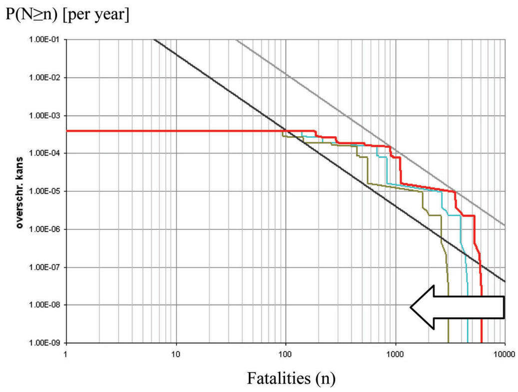

Figure 11. The potential impact of compartmentalization on the FN-curve for dike ring 14.

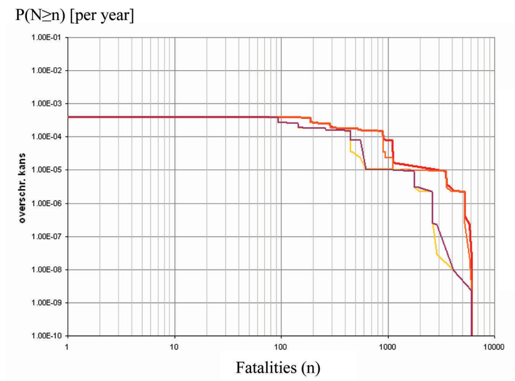

Figure 12. The impact of raising the probability of successful evacuation on the FN-curve for dike ring 14.

As shown by figures 10 to 12, the FN-curve provides a useful basis for comparing the effectiveness of alternative flood risk management strategies. Figure 11 for instance shows that popular claims that floods can never be prevented *so that* we should shift from a focus on prevention to a focus on flood (crisis) management rest on a fallacy: the probability of failure of crisis management is also non-zero.

Similar exercises can illustrate the effect of alternative risk management strategies on individual risks. Accounting for the probability of successful evacuation might for instance lead to a reduction in the individual probability of death of up to about 0.01 per year (indicating that the probability of timely and successful evacuation is 99%, a figure that seems rather optimistic).

4.3 *The status of individual and societal risk*

Individual and societal risk could play a number of different roles in a flood safety policy, depending partly on the status that is given to the yardsticks for judging the acceptability (or tolerability) of individual and societal risks. Under the least binding alternative, individual and societal risk are merely used for agenda-setting and/or policy evaluation purposes: there is no formal decision rule stipulating a need for action when some predefined level of individual or societal risk is exceeded. Policymakers consider (past or potential changes in) levels of individual and societal risk when making policy choices.

A second option would be to define criteria or reference values for evaluating individual and/or societal risks, but to allow exceedances when there are strong reasons for doing so. Decision rules that seem reasonable in some cases, might lead to grossly disproportionate outcomes in other. Allowing for flexibility can reduce the unintended social cost of rules and regulations, but it can dramatically increase transaction cost (the cost of decision making). In the Dutch external safety policy, there is no legal limit to societal risk, only a reference value. Exceedances of this reference value (as well as increases in societal risk below the reference value) have to be properly motivated by competent authorities. The External Safety Decree lays down the basic elements that have to be considered by competent authorities, and jurisprudence has led to further refinement of the definition of a "properly motivated" decision.

Under the third and most stringent regime, the government lays down legal limits to individual and societal risks. These limits would then have a similar status as the exceedance probabilities that are currently laid down in the Flood Defense Act. Note that the government could also define maximum flood probabilities, based on considerations related to individual and societal risks. In that case, limits to individual and/or societal risk effectively find their way into legal limits to flood probabilities. The Dutch major hazards policy features a legal limit to individual risk of 10^{-6} per year. As discussed in section two, this limit provides a basic safety level to every individual living in the vicinity of a major industrial hazard in the Netherlands. A similar limit has been proposed by the second Delta Committee for the provision of flood safety to those living behind primary flood defenses. It should be noted that the Dutch central government is responsible for living up to the Flood Defense Act. Unlike the External Safety Decree that lays down the rules *that private enterprises and local and provincial governments* have to play by, the Flood Defense Act lays down the rules, defined and enforced *by central government*, that *central government* has to play by. Experience has however shown that legally defined flood safety standards can be highly effective, as they provide a clear basis for the evaluation of the safety of flood defenses.

4.4 *Summary and discussion: alternative uses of individual and societal risk in the Dutch flood safety policy*

As outlined in the previous sections, individual and societal risk can play different roles in shaping and implementing a new flood safety policy in the Netherlands. Key policy choices concern:

1. *The status of individual and/or societal risk:* agenda-setting/policy design, reference values, legal limits (§4.3).
2. *The stringency of individual and/or societal risk criteria*: when risk criteria are implemented (as either reference values or legal limits), how stringent should they be (§4.2)?
3. *The strategy for mitigating flood risks*: reducing flood probabilities, reducing the consequences of floods, a mixture of both (§4.2).

Designing a flood safety policy cannot be based on technical analysis alone. If, for instance, the decision were made to mitigate risks through a combination of flood prevention and safety zoning, rules would have to be laid down to ensure that local governments do not allow or develop spatial plans that lead to increases in potential damages (note that the interests of an individual local government and the central government need not be perfectly aligned).

Designing rules and regulations that steer the behavior of local governments and property developers into a direction deemed desirable by central government would not just require answers to questions of a purely technical nature (e.g. how to ensure that the joint behavior of individual entities does not lead to excessive societal risks?), but also to questions of a political and institutional nature (e.g. how to deal with conflicts of interest between local governments that wish to minimize restrictions on spatial plans and a central government that wishes to minimize investments in flood prevention?).

5 CONCLUSIONS

The Dutch government is currently in the process of updating its flood risk management policy. One of the novelties being considered, concerns a role for fatality risks in evaluating flood risks. Fatality risks already play an important role in the Dutch major hazards policy. Individual risk limits are used there to provide a minimal safety level to those living in the vicinity of major industrial hazards; societal risk criteria are used to prevent the too frequent occurrence of large-scale accidents. This paper reviewed the potential for using individual and societal risk for flood risk management. It has been shown that the techniques are available for quantifying these metrics when it comes to floods, and that individual and societal risk can be used for comparing the effectiveness of alternative risk mitigation strategies and for appraising flood risks.

From a purely technical standpoint, little stands in the way of using individual and societal risk for the evaluation of flood risks. But evaluating risks and designing a flood safety policy are not purely technical exercises. Key policy choices concern the status of individual and/or societal risk criteria (or the decision not to formulate criteria), the stringency of such criteria, and the chosen strategy for mitigating flood risks.

Obviously, loss of life is only one of the vast number of consequences that together make up the personal and social impact of a large-scale flood. The consequences of floods are highly diverse: they can displace large numbers of people, disrupt communities and social networks, and cause severe environmental and economic damage. While insight into the severity of fatality risks might therefore seem to add little detail, it constitutes a significant improvement over an approach that focuses on economics alone.

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