Document Version
Final published version

Citation (APA)
Kok, M. (2022). Assessing economic risk, safety standards, and decision-making. In S. Brody, Y. L., & B. Bee Kothuis (Eds.), *Coastal Flood Risk Reduction: The Netherlands and the U.S. Upper Texas Coast* (pp. 137-148). Elsevier. https://doi.org/10.1016/B978-0-323-85251-7.00011-1

CHAPTER 11

Assessing economic risk, safety standards, and decision-making

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Introduction

Flood risk can be perceived and analyzed in many ways. It can be seen as a natural hazard, but others consider it as a by-product of our technological society. And indeed, without advanced flood defenses, the risk would be much different in many areas. However, because of the benefits of living in flood-prone areas and the protection of flood defenses against natural hazards, the majority of humankind lives in Delta regions. In all these regions, the social benefits of protection have been considered higher than the social costs of protection.

In this chapter, we follow the probabilistic risk analysis approach as advocated in Bedford and Cooke (2001), which aims to quantify the risk caused by an uncertain event in situations where classical statistical analysis is difficult or impossible. In this approach, the risk has to do with the probability of the uncertain event (that may be the extreme weather conditions or the flood) and the consequences of the event (economic damages, loss of life, environmental losses, etc.).

We will discuss flood risk approaches in three countries: the United States of America, the United Kingdom, and the Netherlands. We will see that these approaches have much in common, especially if we look at the way economic risk is defined. However, if we look more specifically at the safety standards in the three countries, we see many differences.

Risk approaches

Risk is often defined as a combination of probability and consequences of unwanted events. The probability has a strong relationship with the hydraulic loads (discharges, water levels, waves) and the strength of the flood defense system (levees, hydraulic structures, storm surge barriers). Consequences depend heavily on the hydrodynamic characteristics (e.g., water depth, duration of the flood), the land use (in urban and industrial areas the damage is much higher compared with rural areas), and the evacuation strategy (preventive evacuation can lower the number of casualties dramatically).

Coastal Flood Risk Reduction
https://doi.org/10.1016/B978-0-323-85251-7.00011-1

There are many common elements in the flood risk approach all over the world. In general, the probability that a flood defense structure will fail is determined by the probability of a particular load and the probability that the structure will not be able to withstand this load (CIRIA, 2013). A flood can occur in an almost endless variety of ways, depending on factors such as the conditions in which it occurs, the location of levee breaches, and the stability of linear elements in the landscape such as raised roads and railway lines. The impact of a flood depends on the vulnerability of the area affected and the decisions taken by members of the public and the authorities as the threat of flooding increases. The success of any preventive evacuation depends to a great extent on the time available and the conditions in which the evacuation must take place. Evacuation can reduce the number of victims, but traffic chaos in a low-lying polder could in fact cause many casualties in a flood. All these factors are uncertain, and we can consider them for example in terms of probabilities of scenarios. Combining all the possible effects (consequences) with their probabilities gives us a complete picture of the flood risk.

In Kok, Jongejan, Nieuwjaar, and Tanczos (2017), five steps have been proposed to assess the risk:

(a) *Load*: assessing probability distributions of hydraulic loads.

(b) *Flooding probability*: for possible loads, assess the strength of flood defenses to assess the flooding (or failure) probability.

(c) *Flood scenario*: for each failure, assess flood scenarios, that is the likely progress of flooding that might occur, and the probability of the flood scenarios.

(d) *Consequences*: for each scenario, assess the economic and social consequences (e.g., loss of life), taking uncertainties in hydraulic characteristics, land use data, and evacuation planning into account.

(e) *Risk*: combine the probabilities of flooding with the consequences to obtain a representation of the risk.

In Fig. 1, an example of a flood scenario in the Netherlands is given. On the left-hand side, an overview of all possible flood scenarios is given. On the right-hand side, one possible scenario is shown, with the *red dot* showing the breach location along the river Lek (which is one of the Rhine branches). There is a 10 m elevation difference between the river and the lake (10 vs 0 m above sea level, which is indicated by NAP).

An important issue in flood risk is the interpretation of risk. It seems that sometimes the failure probability is seen as a property of the flood defense. And, that seems quite obvious: a strong flood defense has a smaller failure probability compared with a fragile flood defense, assuming that these flood defenses are attacked with the same hydraulic loads. However, in the risk analysis literature, it is also widely known that the failure probability also depends on the knowledge of the flood defense itself. Compare for example two identical levees: one levee where the soil below the levee is known, and another levee where the soil is not known. The uncertainties of the second levee are much larger, and hence it might be expected that the failure probability of the second levee is larger

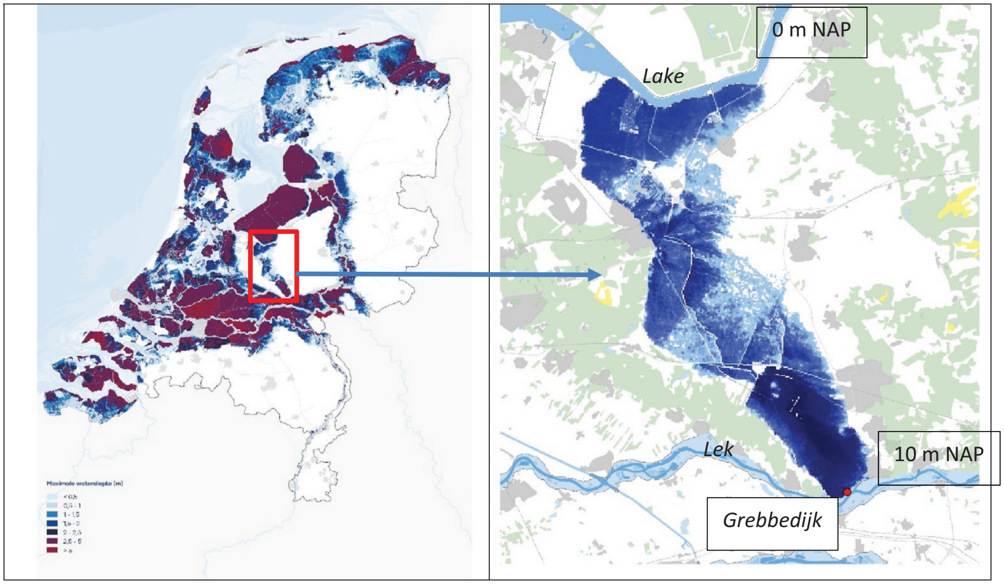

Fig. 1 All possible flood scenarios in the Netherlands *(left)* and example of flood scenario: Gelderse Vallei flooded by a breach of a flood defense along the river Lek *(right)*.

than the levee which properties are perfectly known. This interpretation is called the Bayesian interpretation: the probability of flooding is a measure of the likelihood that a flood will occur, given the knowledge at our disposal. The difference between inherent and knowledge uncertainty is irrelevant in the Bayesian interpretation, according to which the probability that a flood will occur is not uncertain; the probability is a measure of uncertainty. The probability is no longer, therefore, a physical property but a subjective "degree of belief." According to the Bayesian interpretation, a person can give only one answer to the question of whether the probability of flooding is lower than the standard. However, the probability estimates of different people can differ. In practice, such differences can be overcome by exchanging data, second opinions, and the establishment of best practices.

In all risk approaches, much attention is given to the economic and individual risk (Kok et al., 2017). *Economic risk* concerns the cost of risk bearing, expressed in euros (or US dollars), or in euros (US dollars) per year. In cost-benefit analyses, economic risk is often equated with the annual expected value of the damage, the product of probability and damage. The idea behind this is that the government can efficiently spread the cost of any damage among all residents of the Netherlands. If this does not happen and everyone has to bear the cost of the damage they themselves sustain, the cost of risk bearing will often exceed the annual expected value of losses. For example, if the yearly economic risk is privately insured, the insurance costs will often be (much) higher than the expected yearly damage, which can also be seen as a "risk averse" premium (see also van Erp, 2017).

Economic risk relates to risk in the flood-prone area. It does not provide any insight into the risks for individual persons. The local individual risk (LIR) is a measure of risk that expresses the probability that a person who is permanently present at a particular location will die as a result of flooding, taking into account the potential for evacuation. Using local individual risk provides everyone in the Netherlands regions protected by levees with a basic level of protection.

Economic optimization

An important point in the flood risk approach is the economic optimization: what would be the best decision if we only look at the economic costs and benefits, where also non-monetary values (such as loss of life) are taken into account? Such a question can only be answered if we make assumptions about the future, and that we have knowledge about failure probabilities and consequences of a flood. This knowledge is always uncertain, but this is not a special property of floods: every risk analysis of technical installation (like missiles) or hazard (like earthquakes) has these issues. What is important is that these assumptions are "most likely," since these assumptions are not demonstrable.

The classic way of economic optimization is well explained in Kok et al. (2017). More investment in the reliability of flood defenses reduces the flood risk. The investments and the risk are the total costs to society. Minimizing the total costs allows the optimum reliability of the flood defenses to be identified. This principle was first put into practice by the original Dutch Delta Committee in 1953 (van Dantzig, 1956), and is schematically represented in Fig. 2.

The optimum investment strategy is also associated with a certain progression in the probability of flooding over time. This takes the form of a sawtooth wave because the probability of flooding reduces immediately when a levee is reinforced, then gradually rises due to subsidence, increasing river discharge rates and sea-level rise. The scale of reinforcement (and thus the reduction in the probability of flooding after reinforcement) and the time until the next round of reinforcements are strongly influenced by the relationship between the *fixed* and *variable* costs of the intervention. The fixed costs of the intervention are not related to the size of the intervention measure, like for example a storm surge barrier. If the fixed costs are relatively high, it is economically advisable to postpone a new intervention for as long as possible. If the fixed costs are relatively low, as they are along the sandy coastline, it makes more economic sense to make small interventions more frequently.

Safety standards

Standards are the result of a political process based on the results of risk calculations and a cost-benefit analysis. In many cases, the results have been adopted, with due consideration of the uncertainty associated with the input.

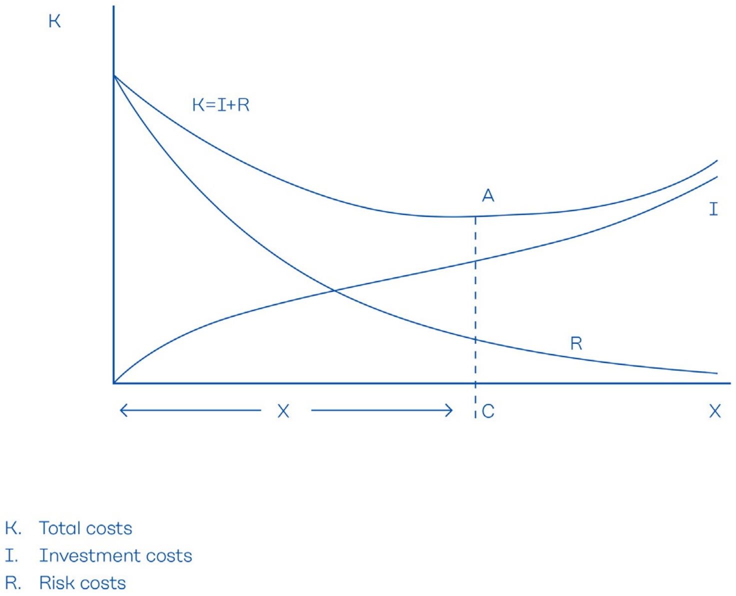

Fig. 2 The basic principle of economic optimization. The total costs (K) are equal to the investment costs (I) associated with improving reliability (here: heightening levees) plus the present value of the risk (R). The optimum lies at the point where the total costs ($I+R$) are lowest. *(Source: Kok, M., R. Jongejan, M. Nieuwjaar and I. Tanczos, 2017. Fundamentals of flood protection. Ministry of Infrastructure and the Environment and Expertise Network for Flood Protection. https://www.enwinfo.nl/publish/pages/183541/grondslagenen-lowresspread3-v_3.pdf.)*

Safety standards are not a goal in itself but have to serve the framework of "acceptable risk." In the concept of acceptable risk, two questions are important:

(a) How safe is it?
(b) Is it safe enough?

From a theoretical point of view, it can be remarked that the same risk framework should be applied to all kinds of natural hazards (earthquakes, floods, hurricanes, etc.) and technical artifacts (ferries, airports, traffic, plants, dikes, powerplants, missiles, etc.), because risk levels can be compared with each other. However, we see in reality that such an approach seems not achievable. Moreover, safety is not a separate discipline, but part of the design of technical artifacts, so the risk framework is (or should be) part of the technical guidelines.

Having a risk framework is not a goal but needs to serve more underlying objectives. In Vrijling (2008), the following aims are mentioned:

(a) a predictable decision process
(b) a basis for technical design
(c) to avoid changes after each disaster
(d) discharge of the engineering profession

Especially the last mentioned is important from an engineering point of view. Without a framework, it cannot be detected whether the engineer made a mistake for which he is responsible, or whether he or she was acting in a socially responsible way.

There are many ways to relate the risk framework to safety standards. We will discuss three of them, and in the next paragraph, we will discuss the pros and cons of these arrangements. It is important to notice that there is, from a scientific point of view, no best way to set up an arrangement.

(a) Exceedance probability of design water level

In this approach, the flood defenses are designed and maintained to withstand a hydraulic load with a fixed exceedance probability, for example a water level which is on average exceeded in 100 years (so an annual exceedance probability of 1/100). As such the standard seem to focus only on the hydraulic load. Though the strength of the flood defenses played a major role, it was not explicitly reflected in the numerical standard.

(b) Flooding probability

In this approach, the probability of flooding is the key parameter of the safety standard (VNK, 2015). The main reason for defining the safety standard to the probability of flooding is that it properly reflects the degree of protection from flooding. The probability of flooding depends both on the hydraulic load (water levels and wave action) and on the strength of the defenses (height, width, type of material etc.). In a safety standard, the food probability norm can be based on the risk of flooding. Risk refers to both the probability and the consequences of flooding (see above). The possible consequences focus often on fatalities and victims. For example, the loss-of-life risk can play an explicit role in the updating of standards for flood defenses. An example is the risk limit in the protected areas in the Netherlands where the government has decided that the probability of loss of life due to flooding may not exceed 1/100,00 per year.

(c) Costs < benefits

In this arrangement, the safety standard is not a number, but a decision rule: if costs of measures are lower than the risk reduction by these measures, these measures should be applied.

It can be seen directly that the second and third alternatives are directly related, because in order to assess the costs and benefits, the flooding probability has to be assessed. There are many methods to assess this probability. The concept of probabilities is directly related to uncertainties. These uncertainties can arise from, for example, data constraints and lack of knowledge. This means that data collection and further investigation can lead to a change in the probability of flooding. If the probability of flooding were regarded as a property of a flood defense system, this would of course be impossible. The probability of flooding is not an easily definable property of a flood defense structure, like its height, but a judgment based on knowledge of the structure. The probability of flooding is therefore also a measure of our uncertainty, as the probability depends on the knowledge and information available to us. For instance, our uncertainty about the flood defense capacity of a new dam, for example, declines dramatically once the reservoir has been filled. After it has been filled, we judge the probability of a breach to be considerably smaller as it is now successfully retaining a large body of water, though the properties of the dam have not changed at all. This also means that a flood probability is not the same as the probability that a particular water level will be exceeded, leading to flooding. This would only be the case if we were able to know exactly what water level the flood defense will breach. This is however uncertain in practice, because of our lack of knowledge about the subsurface, for example. As a result of this uncertainty, there is a chance that the flood defenses will breach even at a relatively low water level, but it is also possible that this will not happen until the water level is relatively high (see Kok et al., 2017).

The flooding probability as a safety standard has been recently introduced in the Netherlands. This probability standard relates to flood defense sections of about 20–30 km is between 1/100 and 1/1,000,000, and this depends on the consequences (economic losses and loss of life) of a breach in the flood defense. An overview of the standards is given in Fig. 3.

The *flooding probability* as a safety standard has been adapted in the Netherlands in 2017. Until now, the new approach has still some challenges in practice. For example, the assessment carried out by the water authorities shows some remarkable results (ENW, 2019). Some dike sections have been judged with a failure probability of 1/10, which is quite remarkable since these dike sections have not seen failures in the past 100 years. Recommendations are given in ENW (2019) on how to improve the method and the application of the method (assessments of the flood defenses), for example, to have independent reviews of the assessments.

The *exceedance probability of designing water level* as a safety standard can be seen in the United States. Often, a standard of 100 years or 500 years is used as the exceedance probability (which is the inverse of the average return period). The exceedance probability has a relation with the flooding probability, but this is not a one-one relation. This can be easily explained, because the flooding probability also depends on the strength of the flood defenses. For the design of the flood defenses, guidelines and manuals are available (for example, the International Levee handbook). Also, the design and the deterioration of these flood defenses have a large influence on the flooding probabilities.

The *Cost < Benefits* approach is being applied in the United Kingdom. There are many small rivers in the United Kingdom with relatively small damages if there is a flood, so it seems that this approach is more suited for these small-scale damages and relatively high costs to prevent these damages. Also, appropriate spatial planning seems important to reduce flood risk in the future, where more extreme rainfall events might be expected.

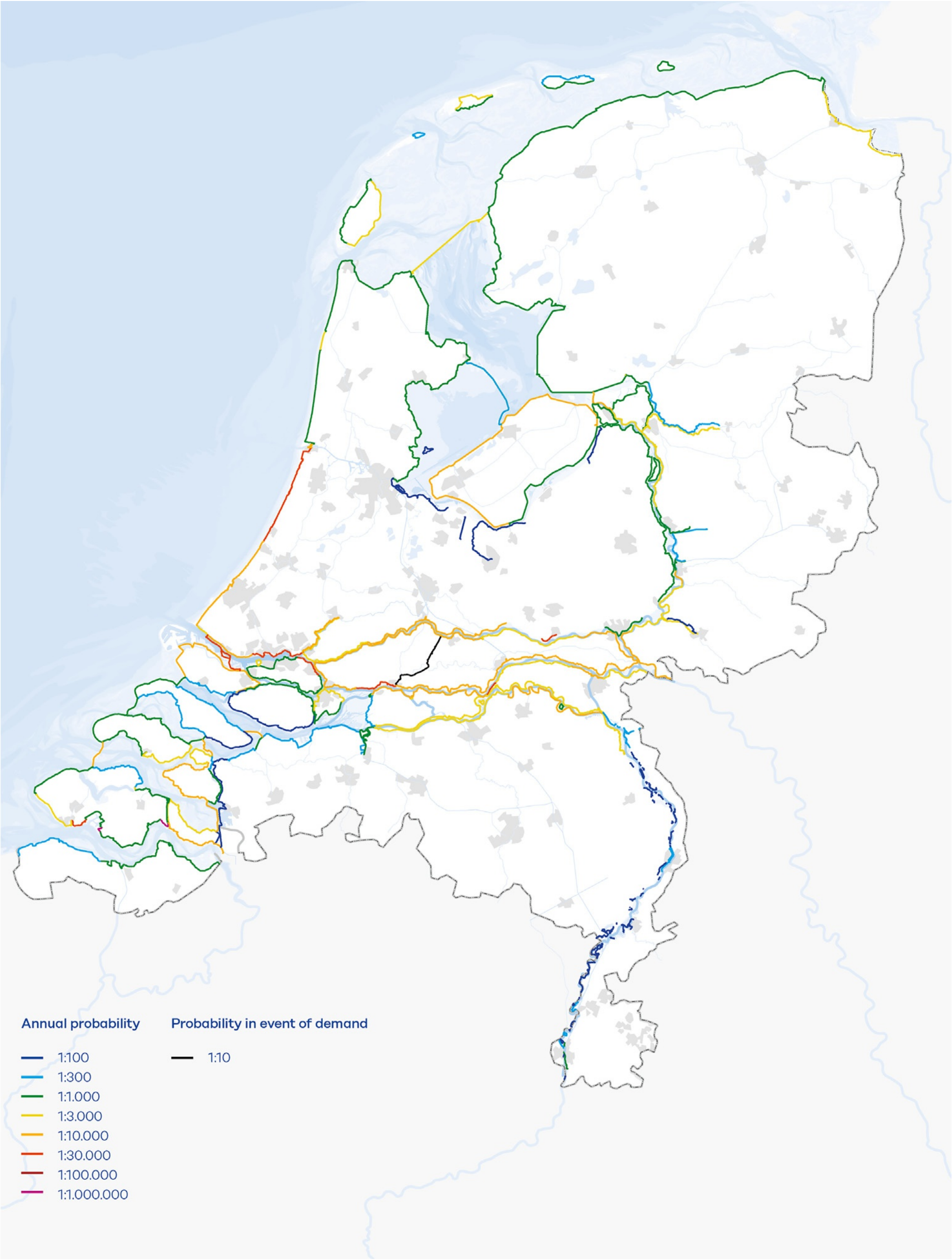

Fig. 3 Maximum permissible flood probabilities in the Dutch Water Act.

Examples

When illustrating the different risk frameworks, it must always be kept in mind that the outcomes of the three frameworks depend heavily on the location and the available information. We use the example of a river stretch of 10 km long and catastrophic damage of 10 billion euro to illustrate two of the frameworks. This example was inspired by the Grebbedijk in the Netherlands, which is located along the river Lek, and shown in Fig. 2.

Exceedance probability framework

The exceedance probability framework is a way to define the design load, for example, the design water level (or for rivers the design discharge, which needs to be transferred to local water levels). See Fig. 4 for an example for the river Rhine in the Netherlands, in this figure the exceedance frequency line discharge of the river at the border with Germany is shown.

An example of this approach: for the Grebbedijk a safety standard of 1/1250 was chosen in the recent past, this means that before January 1, 2017 the flood defenses had to be designed in such a way that these flood defenses can withstand the design water level with an exceedance frequency of 1/1250 (1/year).

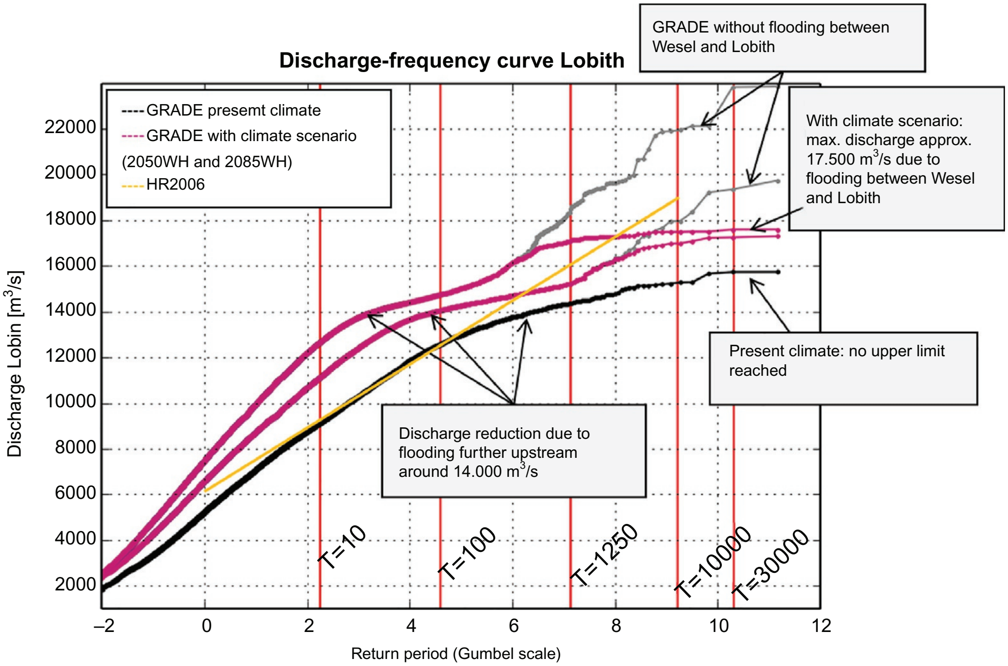

Fig. 4 Exceedance frequency of river discharge of the river Rhine at Lobith for current situation, upstream flooding, and climate change scenarios (Hegnauer, Beersma, van den Boogaard, Buishand, & Passchier, 2014).

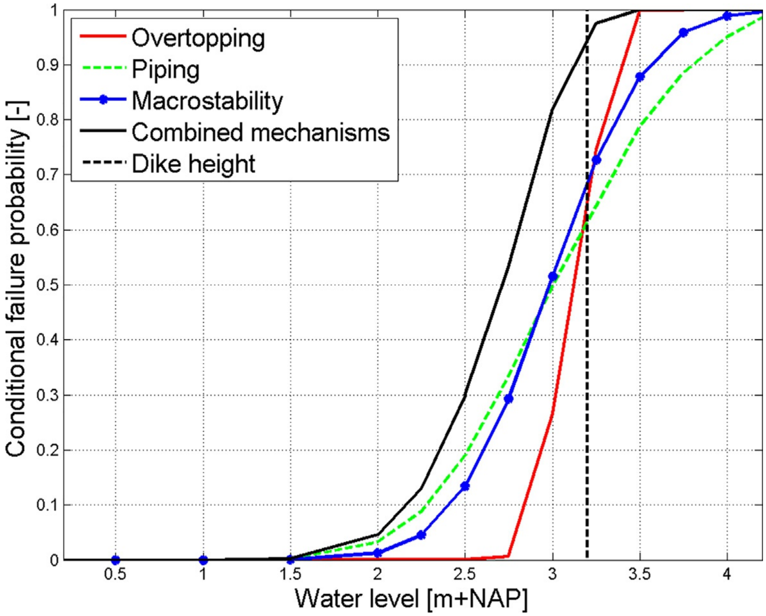

Fig. 5 Example of a fragility curve in the Netherlands. *(Source: Wojciechowski, K., G. Pleijter, M. Zethof, F. J. Havinga, D.H. van Haaren, W.L.A. ter Horst, 2017. Application of fragility curves in operational flood risk assessment, Geotechnical safety and risk, T. Schweckendiek et al. (Eds.) https://doi.org/10.3233/978-1-61499-580-7-528.)*

In the United States, the National Flood Insurance Program uses the (minimum) standard of flood protection of a 100-year return period, often extended with a safety margin of 0.3 m. Although this standard was derived as a criterion for entering the insurance program, it has become a safety standard in practice. Often, improving levees up to stricter standards than a 100-year return period was not considered until recently. Nowadays, new federal flood protection standards are investigated, making the nation more resilient.

Flooding probability framework

In order to assess the flooding probability, not only the hydraulic load (such as water levels) is taken into account, but also the strength of a levee. One way to do so is by using fragility, which shows the conditional probability of failure, given the hydraulic load. An example of a fragility curve is given in Fig. 5, where the conditional probability of failure is given as a function of the water level, and different failure mechanisms of the flood defense are shown.

The flooding probability is then obtained by combining the fragility curve with the probability density function of the hydraulic load (often the water level).

Costs-benefits framework

In the appraisal guide in the United Kingdom (Environment Agency, 2010), no indication of safety standards is provided, leaving the appropriate standards to be determined on a risk basis. This means that the benefit-cost ratio becomes relatively more important. In the 2008–2009 to 2010–2011 investment program, every £1 of capital investment in flood and coastal erosion risk management in the United Kingdom provided an average long-term benefit in reduced damage of approximately £8, a ratio of 8. And in more recent years, this ratio went up even further to 9.5 (Jonkman, Jorissen, Schweckendieck, & van den Bos, 2017).

Comparison and discussion

What are the advantages and disadvantages of the three different arrangements?

Exceedance probability of design water level

Advantage	Disadvantage
It looks rather simple: there is a hydraulic load (for example the peak water level) and all decisions about the strength of the flood defense are based on this load	The hydraulic load can have more than one uncertain variable. For example, waves can come is, and of course, water levels and waves are not independent. Also, the duration of load can come into play for some failure mechanisms of the flood defense. Last, but not least, if you want to perform a cost-benefit analysis within this approach

Flooding probability

Advantage	Disadvantage
It indicates a level of protection against floods	The methods to assess the flooding probability is rather complex, since it involves the assessment of failure mechanisms of flood defenses (like for example piping, overflow, etc.) with its associated length effects (that is that the failure probability of a longer dike section is higher than a shorter dike section, with the assumption that all dike sections are all identical)

Costs < benefits

Advantage	Disadvantage
Investments are efficient because these investments are only done if these are cost-efficient	There is no standard, so the need for investments cannot be justified because "it does not fulfill the safety standard" Assessment of flooding probabilities needs to be done, and also the consequences

It can be seen that the three arrangements also have a lot in common because they all are based on the risk approach.

Concluding remarks

In this chapter, we have presented the steps in the risk approach and the way safety standards can be defined. Three different arrangements have been shown, which are used in three different countries. From the overview of advantages and disadvantages, it can be concluded that there is no one way to define safety standards that are superior to other ways.

References

Bedford, T., & Cooke, R. (2001). *Probabilistic risk analysis. Foundations and methods*. Cambridge University Press.

CIRIA. (2013). *The International Levee Handbook (C731)*. CIRIA, Ministry of Ecology, USACE, ISBN: 978-0-86017-734-0. Number of pages: 1348.

Environment Agency. (2010). *Flood and coastal erosion risk management appraisal guidance*.

ENW. (2019). *Naar geloofwaardige overstromingskansen (Towards credible flooding probabilities)*. https://www.enwinfo.nl/adviezen/advies-overstromingskansen/.

Hegnauer, M., Beersma, J. J., van den Boogaard, H. F. P., Buishand, T. A., & Passchier, R. H. (2014). *Generator of rainfall and discharge extremes (GRADE) for the Rhine and Meuse basins*. Final report of GRADE 2.0. © Deltares.

Jonkman, S. N., Jorissen, R. E., Schweckendieck, T., & van den Bos, J. P. (2017). *Flood defences, Lecture notes CIE5314* (2nd ed.). Delft University of Technology.

Kok, M., Jongejan, R., Nieuwjaar, M., & Tanczos, I. (2017). *Fundamentals of flood protection*. Ministry of Infrastructure and the Environment and Expertise Network for Flood Protection. https://www.enwinfo.nl/publish/pages/183541/grondslagenen-lowresspread3-v_3.pdf.

van Dantzig, D. (1956). Economic decision problems for flood prevention. *Econometrica*, *24*, 276–287.

van Erp, N. (2017). *A Bayesian framework for risk perception*. https://doi.org/10.4233/uuid:1ff6ae46-c2bd-4375-aeb1-a4a9313ec560.

VNK. (2015). *The national flood risk analysis for the Netherlands*. Final report Rijkswaterstaat VNK Project Office. https://www.helpdeskwater.nl/onderwerpen/waterveiligheid/programma-projecten/veiligheid-nederland/english/flood-risk-the/.

Vrijling, J. K. (2008). *Flood prevention in the Netherlands and the Safety chain*. Presentation at the English Embassy.