ECONOMIC OPTIMISATION AS A BASIS FOR THE CHOICE OF FLOOD PROTECTION STRATEGIES IN THE NETHERLANDS

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Abstract: At the beginning of the new century several strategies are proposed that aim at increasing the level of flood protection in the Netherlands. In this paper an economic method for the analysis of these strategies and their effectiveness is suggested. The method of economic optimisation takes into account the expenditure for a safer system and the expected (value of the) economic damage. In the economically optimal situation the total costs in the system, the sum of investments and expected economic damage, are minimised. The results following from the economic optimisation should be considered as a technical advice to policy makers. Several flood protection strategies applied or considered in the Netherlands, such as dike heightening, "Room for rivers" and flood insurance, have been schematised in the economic optimisation. The paper also shows how future developments, such as climate change and economic growth, can be taken into account in the method. From these schematisations criteria have been derived which can be applied for cost benefit analysis of alternatives.

Keywords: flood risk, flood protection, economic optimisation, cost benefit analysis

Figure 1: The Netherlands without flood protection (the dark area would be flooded due to sea and river floods)

1. INTRODUCTION

Large parts of the Netherlands are located below sea level and/ or are threatened by river floods. Without the protection of dunes, dikes and hydraulic structures more than half of the country would be almost permanently flooded as is shown in figure 1.

The Netherlands has a long history of floods. The last disastrous flood occurred in 1953. A storm surge from the North Sea inundated large parts of the Southwest of the country. Apart from immense economic damage, 1835 persons drowned during this disaster. After the 1953 flood the Delta Committee was installed to investigate the possibilities for a new safety approach. Based on this work flood protection levels have been derived for the flood prone areas in the Netherlands. Since the work of the Delta Committee, performed in the late 1950's, some

developments have resulted in an increased awareness of flood risks. Firstly, the economic value of the country has increased rapidly. It can be questioned if the protection standards as derived by the Delta Committee still provide enough protection when the current economic value is considered. Moreover, in 1993 and 1995 extremely high river discharges occurred, which made large-scale evacuations necessary. In the future climate change, the associated sea level rise and higher river discharges and soil subsidence will lead to an increase of flood hazards for the Netherlands.
This overview of developments illustrates the necessity of re-consideration of the level of flood protection in the Netherlands, in which the necessary investments and the increase of the values to be protected will have to be taken into consideration. At the beginning of the new century new strategies have been proposed in the Netherlands, which mainly aim at increasing the level of flood protection, without raising the dikes in the river system. The discussion on the level of flood protection lacks a general framework for rational evaluation and comparison of alternative solutions. Aim of this paper is to contribute to the debate from a technical point of view by suggesting an economic method for the analysis of flood protection strategies and their effectiveness, based on the concept of flood risk. The approach will limit itself to economic factors, although it is realised that many other aspects are of importance in the final decision on flood protection, such as the ecological and social aspects. The ideas brought forward in this paper can thus be considered as advice to the decision makers from a technical/ economical point of view.
The paper is structured as follows. Section 2 will introduce the concept of flood risk and give a brief overview of some flood protection strategies. Section 3 shows how these strategies can applied in a framework for economic decision making, with the use of the methods of economic optimisation and cost benefit analysis. The conclusions from this study are summarized in section 4.

2. FLOOD RISK APPROACH AND FLOOD PROTECTION STRATEGIES

2.1. FLOOD RISK

The concept of flood risk in the Netherlands was already introduced by the Delta Committee, which was installed after the 1953 disaster to investigate the possibilities for a new approach of flood protection [van Danzig, 1956]. The Delta Committee decided that the level of protection of a flood prone area should be dependent on the probability of occurrence of a flood, the damage that it could cause and the amount of investments required to achieve a certain level of protection. In a risk based approach the probabilities and consequences of flooding have to be considered together and in coherence. (Flood) risk is generally defined as the product of probabilities and consequences.
Due to limitations in knowledge and computing power a simplified approach of flood protection has been adopted by the Delta Committee in the 1960’s, in which dikes are dimensioned based on a design water level with a certain probability of exceedance. In the last decade of the 20th century methods have been developed to determine the probability of flooding and the consequences of a flood, which form the basis for the risk based approach of flood protection. It introduces the possibility to compare different measures for their effectiveness and to include costs and benefits in the analysis. Furthermore a comparison with risk levels in other sectors of society is possible.

2.2. FLOOD RISK REDUCTION APPROACHES

In this section an overview is given of measures, which reduce the economic flood risk. Flood risk mitigation in the Netherlands traditionally aimed at reduction of flood hazards through improved dike construction by heightening and / or strengthening of the dikes along the rivers. Nowadays the concept of preventing flooding *without* raising the dikes is generally adopted. For example by giving more “Room for rivers” with riverbed widening and deepening and the planning of additional green rivers. Recently the option of creation of so-called emergency storage areas in the river system has been investigated. An emergency storage area situated upstream will be flooded intentionally in case of extreme river discharges. Part of the extreme discharge will be stored in the emergency storage area and thus flooding of the area with large economic value, which is situated downstream, can be prevented. Furthermore strategies that aim at reduction of damage when a flood occurs are distinguished. As part of the spatial planning policy important economic values in flood prone areas can be moved to higher grounds. Secondary water defences, dikes that stop the flood propagation after breach of the main dike, can prevent flooding of valuable areas. Guidelines for the construction of buildings can limit the vulnerability of buildings for flooding conditions and therefore reduce economic damage. As a mitigating measure the occurred economic damage can be compensated, either by government or by an insurance company. These two options mean in fact a financial reallocation of the flood damage. Based on the concept of flood risk as outlined in section 2.1 the measures described above can be classified as is shown in table 1.

Table 1: Overview of measures to economic flood risk

Flood risk reduction	
Reduction of flooding probabilities	**Mitigation of flood damages**
Dike strengthening and heightening	Spatial planning
Room for rivers: riverbed widening and deepening, green rivers	Secondary water defences
Emergency storage areas	Building restrains
	Flood insurance
	Compensation by government

3. ECONOMIC OPTIMISATION AND COST BENEFIT ANALYSIS

The method of economic optimisation is presented as a framework for the derivation of an economically optimal level of risk in section 3.1 for the measures shown in table 1. This method is closely related to the cost benefit analysis, as is shown in section 3.2.

3.1. ECONOMIC OPTIMISATION

The derivation of the (economically) acceptable level of risk can be formulated as an economic decision problem. According to the method of economic optimisation, 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 ($E(D)$). In the optimal economic situation the total costs in the system are minimised:

$$\min(C_{tot}) = \min(I + E(D)) \tag{1}$$

The application of the economic optimisation for the measures mentioned in table 1 will be shown in some simplified examples in section 3.1.2. It will also be shown how future developments can be taken into account in 3.1.3.

3.1.1. Basic case: dike heightening and river widening

The method of economic optimisation was originally applied by van Danzig [1956] to determine the optimal level of flood protection (i.e. dike height) for Central Holland (this area forms the economic centre of the Netherlands). An exponentially distributed flooding probability (P_f) was assumed, which depends on the flood level h and the parameters A and B of the exponential distribution:

$$P_f = e^{-\frac{h-A}{B}} \tag{2}$$

The total investments in raising the dikes (I_{tot}) are determined by the initial costs (I_{h0}) and the variable costs (I_h). The dike is raised X metres, the difference between the new dike height (h) and the current dike height (h_0).

$$I_{tot} = I_{h0} + I_h \cdot X \qquad and \qquad X = h - h_0 \tag{3}$$

In this study a more general formulation has been chosen between investments and flood protection level (denoted by flooding probability). Based on van Danzig a linear relation between the two has been adopted, but for more practical applications another relation can be chosen. The investment function is reformulated by substitution as a linear function of the negative logarithm of the flooding probability with parameters constant I_0 and steepness I' and formula 4 is obtained:

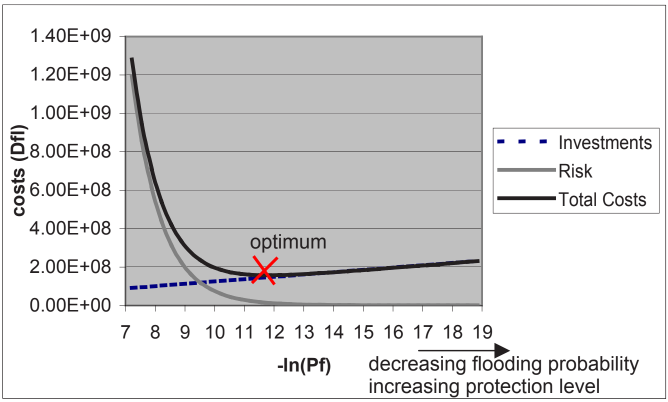
$$I_{tot} = I_0 + I' \cdot (-\ln(P_f)) \tag{4}$$

The total costs are the sum of investments and the expected value of the economic damage. This expected damage has to be discounted to present value with reduced interest rate (r'), which is the difference between real interest rate (r) and economic growth rate (g): $r' = r-g$. The economic optimum is found by minimising the total costs. The derivative of the total costs and the flooding probability results in the economically optimal flooding probability ($P_{f,opt}$), from which the optimal dike height can be derived:

$$C_{tot} = I_0 + I' \cdot (-\ln(P_f)) + P_f \cdot D / r' \tag{5}$$

$$dC_{tot} / dP_f = 0 \quad \Rightarrow \quad P_{f,opt} = I' \cdot r' / D \tag{6}$$

The relation between (decreasing) flooding probability and investments, risk and total costs is shown in figure 2.



Parameters (based on [van Danzig, 1956]:
$I_0 = 3.56.10^6$ (Dfl)
$I' = 1.2.10^7$ (Dfl)
$D = 24.10^9$ (Dfl)
$r' = 0.015$ (/yr)

Results:
$P_{f,opt} = 7.5 \,.\, 10^{-6}$ (/yr)
$- \ln (P_{f,opt}) = 11.8$

Figure 2: Relation between total costs and decreasing failure probability, for the example and corresponding variables analysed in [van Danzig, 1956]

This case shows the application of the economic optimisation for the measure of dike heightening. If a linear relation between (the negative logarithm of) flooding probability and investments is assumed for river widening measures, then this case will also be applicable for that situation.

3.1.2. Economic optimisation of other measures

Emergency Storage areas

In order to prevent flooding of an area with large economic value it can be considered to create an emergency storage area upstream which will be flooded intentionally in case of extreme river discharges. The area will be designed to prevent a large flood with probability of exceedance (P_f). This requires a certain investment (for example the construction of hydraulic structures to allow for a controlled flood) and the acceptance of a certain damage in the emergency storage area (which is also considered as an investment). These investments will have a steepness of I_{NOG}. The probability of a flood in the economically valuable area will be reduced with a certain fraction α. This fraction can be considered as the residual risk, for the cases that the use of the storage area fails or when it does not prevent flooding of the large area. The total costs and the optimum can now be written as is shown in formula 7:

$$C_{tot,NOG} = I_0 + I_{NOG} \cdot (-\ln(P_f)) + \frac{(1+\alpha\cdot)\cdot P_f \cdot D}{r'} \quad \Rightarrow \quad P_{f,opt,NOG} = \frac{I_{NOG} \cdot r'}{(1+\alpha)\cdot D} \tag{7}$$

Flood damage mitigation by spatial planning or secondary water defences

Investments can be done to prevent damage in case of a flood. Economically valuable areas can be moved to higher grounds due to spatial planning and the construction of secondary water defences can prevent flooding of valuable areas. It is assumed that the investment will depend on the level of flood protection with steepness I_{DAM}. The investments will lead to a reduction of flood damage with a fraction δ. For spatial planning measures it could be assumed that these will limit economic growth (g), and that thus the value for reduced interest rate (r') has to be adjusted. Total cost for ($C_{tot,DAM}$) can now be written as:

$$C_{tot,DAM} = I_0 + I_{dam} \cdot (-\ln(P_f)) + \frac{P_f \cdot \delta \cdot D}{r'} \quad \Rightarrow \quad P_{f,opt,DAM} = \frac{I_{dam} \cdot r'}{\delta \cdot D} \tag{8}$$

Flood insurance and compensation by government

Another possible measure is the insurance of flood damage by a private insurer, see for example [Kok, 2002]. Flood damage will (partly) be compensated, but this requires an additional investment in the form of insurance premiums to be paid in advance. The premium will amount the expected value of the damage multiplied by a factor β to account for profit and income of the insurer (assume $\beta \approx 2$). It can be considered to combine insurance and dike strengthening. All damage will be compensated and the total costs equal the sum of investments and insurance premium, see formula 9:

$$C_{tot,INS} = I_0 + I' \cdot (-\ln(P_f)) + \frac{\beta \cdot P_f \cdot D}{r'} \quad \Rightarrow \quad P_{f,opt,INS} = \frac{I' \cdot r'}{\beta \cdot D} \tag{9}$$

Insurance ($\beta > 1$) will lead to a lower optimal probability and thus to higher protection levels. Note that for $\beta = 1$ (if government compensates all damage) this equation equals the basis case.

3.1.3. Future developments in economic optimisation

Based on previous work [Vrijling, 1980] and [van Danzig, 1956] it will be shown how sea level rise and economic growth can be modelled in the economic optimisation. The examples above assume a constant failure probability. Developments, such as sea level rise and increasing river discharges (or the degradation of the water defences over time), can lead to an increase of flooding probability. This can be modelled by assuming an exponentially distributed flooding probability (with parameters A and B) that will increase over time (t – in years) due to sea level rise, as is shown in formula 10:

$$P_f(t) = e^{-\frac{h-\eta t-A}{B}} = P_{f,0} \cdot e^{\frac{\eta \cdot t}{B}} \tag{10}$$

Where: $P_{f,0}$ flooding probability chosen at t=0

η sea level rise (m/year)

Furthermore (potential) economic damage in the area will increase over time due to economic growth (g). Economic damage at time $D(t)$ can now be written as a function of the economic damage at t=0 (D_0):

$$D(t) = D_0 \cdot e^{g \cdot t} \tag{11}$$

The expected economic value can now be found over planning period T_p, by discounting to the present value with the real interest rate r.[1] and formula 12 is obtained:

$$E(D) = \int_0^{T_p} P_f(t) \cdot D(t) \cdot e^{-r' \cdot t} dt = \int_0^{T_p} P_{f,0} \cdot D_0 \cdot e^{-\gamma \cdot t} dt = \frac{D_0 \cdot P_{f,0}}{\gamma}(1 - e^{-\gamma \cdot T_p}) \tag{12}$$

Where: $\gamma \quad = r - g - \eta / B$

When a linear relation is assumed between investments and the (negative logarithm of the) initial flooding probability the total costs can be formulated as follows. It can be shown by a similar substitution as given for the case of dike heightening that a time dependent variable investment is introduced, which has a steepness of I_t[2]

$$C_{tot} = I_0 + I' \cdot (-\ln(P_{f,0})) + I_t \cdot t + \frac{D_0 \cdot P_{f,0}}{\gamma}(1 - e^{-\gamma \cdot T_p}) \tag{13}$$

The level of protection that should be chosen at t = 0 can be derived as a function of planning period T_p (in years) with formula 14:

$$C_{tot} / dP_{f,0} = 0 \quad \Rightarrow \quad P_{f,opt,o}(T_p) = \frac{I'}{D_0} \frac{\gamma}{(1 - e^{-\gamma \cdot T_p})} \tag{14}$$

Note that for the situation of a very long planning period ($T_p = \infty$) and no sea level rise (η = 0, thus $\gamma = r - g = r'$), the optimum following from formula 14 is equal to the optimum derived for the basic case of dike heightening of formula 6. With this equation it can be shown that a lower optimal flooding probability and thus a higher protection level will be found when future developments are taken into account. For the original example of van Danzig (see figure 2 for parameters) the optimal flooding probability is shown as a function of the planning period for different number of sea level rise in figure 3.

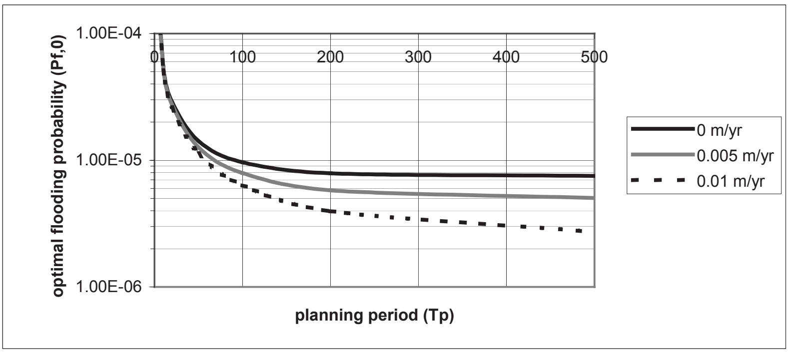


Figure 3: Optimal flooding probability as a function of planning period and sea level rise

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1 This can be modelled as a negative exponential function, since: $1/(1+r')^t \approx e^{-r' \cdot t}$

2 Following the substitution for the basic case of dike heightening it can be shown that $I_t = I_h \cdot \eta$

Economic optimisation and the value of human life

It is possible to take the value of human life into the economic optimisation [Vrijling, 2000]. Assume that a certain scenario will result in N fatalities and that every person has an economic value l. The economic optimum can again be found by minimising the total costs, which has been shown here for the basic case of dike heightening:

$$C_{tot} = I_0 + I' \cdot (-\ln(P_f)) + P_f \cdot (D + N \cdot l) / r' \quad \Rightarrow \quad P_{f,opt} = I' \cdot r' / (D + N \cdot l) \tag{15}$$

The valuation of human life may raise numerous ethical and moral questions, because some people consider life invaluable. From the equation it can be seen that not taking into account the economic value of human life in the economic optimisation will lead to lower expected damages and thus to lower optimal safety levels. Experience shows that the influence of loss of life is relatively limited in an economic analysis. In this section the possible application of the method of economic optimisation for different cases has been shown. Of course, this offers the possibility to combine some of the formulations shown: for example economic optimisation for dike heightening, including the value of human life and future developments.

3.2. COST BENEFIT ANALYSIS

The basic principle of cost benefit analysis requires that a project results in an increase of economic welfare, i.e. the benefits generated by the project should exceed the costs of it. The economic optimisation merely takes into account the cost side of the flood protection problem, and does not consider the potential economic benefits of an improved flood protection of the area. It has been shown by Voortman [2002] how economic benefits can be taken into account in the framework presented above. This shows that the economic optimisation as presented above is a special (limited) case of this full cost benefit analysis. In a simplified cost benefit analysis, as for example applied in [Parker, 1987], the cost benefit criterion is formulated as follows. The risk reduction (i.e. the benefits) for a certain project should exceed the costs of (or investments in) this alternative. This corresponds with the condition that should be checked in addition to the economic optimisation: total costs in the initial situation should exceed the total costs after completion of the project. In the table 2 the investments for the measures described above and the risk reductions achieved are summarized, using the given formulation. Also the derived economic optima are shown.

Table 2: Overview of measures, derived economic optima, and cost benefit criteria, (P_f - flooding probability after completion of the project, $P_{f,0}$ – probability in the initial state)

Measure	**Investments**	**Benefits (i.e. Risk reduction)**	**Economic optimum**
dike heightening / river widening	$I_0 + I' \cdot (-\ln(P_f))$	$(P_{f,0} - P_f) \cdot D / r'$	$P_{f,opt} = I' \cdot r' / D$
emergency storage area	$I_0 + I_{NOG} \cdot (-\ln(P_f))$	$P_{f,0} \cdot D / r' - (1+\alpha) \cdot P_f \cdot D / r'$	$P_{f,opt,NOG} = \dfrac{I_{NOG} \cdot r'}{(1+\alpha) \cdot D}$
damage reduction	$I_0 + I_{DAM} \cdot (-\ln(P_f))$	$P_{f,0} \cdot D / r' - P_f \cdot \delta \cdot D / r'$	$P_{f,opt,DAM} = \dfrac{I_{dam} \cdot r'}{\delta \cdot D}$
flood insurance and dike heightening	$I_0 + I' \cdot (-\ln(P_f)) + \beta \cdot P_f \cdot D / r'$	$P_{f,0} \cdot D / r'$	$P_{f,opt,INS} = \dfrac{I' \cdot r'}{\beta \cdot D}$
Special cases, which include			
sea level rise and economic growth	$I_0 + I' \cdot (-\ln(P_f)) + I_t \cdot t$	$P_{f,0} \cdot D_0 (\frac{1}{r'} - \frac{1 - e^{-\gamma \cdot T_p}}{\gamma})$	$P_{f,opt,o}(T_p) = \dfrac{I'}{D_0} \dfrac{\gamma}{(1 - e^{-\gamma \cdot T_p})}$
valuation of human life	$I_0 + I' \cdot (-\ln(P_f))$	$P_{f,0} \cdot (D + N \cdot l) / r' - P_f \cdot (D + N \cdot l) / r'$	$P_{f,opt} = I' \cdot r' / (D + N \cdot l)$

From the table it can be seen that the profitability of a measure will depend on the ratio between investments and risk or damage reduction. Based on the table an analysis of cost effectiveness can be carried out. Decision makers may choose the most cost effective strategy, i.e. the project that achieves the largest risk reduction with the smallest investments. This is the project for which the highest protection level is found (i.e. the smallest optimal failure probability) at lowest cost. However, it should be noted that based on other values, such as ecological, social and political considerations, an alternative could be chosen that would not be the most favourable when merely economic aspects are considered.

4. CONCLUSIONS

In this paper an economic framework for analysis of flood protection strategies and their effectiveness has been suggested in the form of the method of economic optimisation. According to the method of economic optimisation, the total costs in a system are determined by the sum of the expenditure for a safer system and the expected value of the economic damage. In the optimal economic situation the total costs in the system are minimised. The results following from the economic optimisation should be considered as a technical advice to policy makers.

Several flood protection strategies applied or studied in the Netherlands have been schematised in the economic optimisation. It should be noted that this paper considers individual measures, the economic optimisation of a combination of measures should be further investigated. The method of economic optimisation is closely related to the cost benefit analysis. For these schematisations criteria have been derived which can be applied for cost benefit analysis of alternatives. Generally the profitability of a measure will depend on the ratio between investments and risk or damage reduction. Summarizing: when carrying out an economic analysis for projects that aim at improving safety levels it should first be investigated whether the project is beneficial to society, whether the benefits exceed the costs. In addition the optimal level of protection can be found with the economic optimisation.

From an economic point of view decision makers may choose the flood protection strategy that achieves the largest risk reduction at lowest costs. The final decision on a desired flood protection level should not only consider economic aspects, but it should involve a comparison of all relevant alternatives. The economic optimisation and the cost benefit analysis can provide important rational information in this decision-making process.

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