Economically efficient flood protection levels
Effects of system interdepencies

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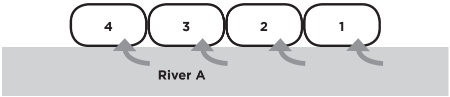
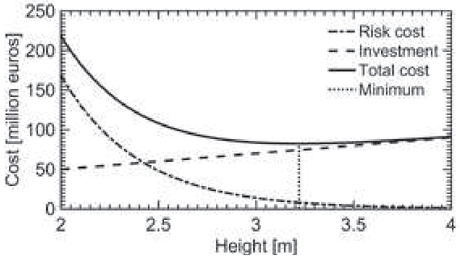
Figure 1 (top left). Top view of a river with four dike rings. The arrows indicate possible breaches.

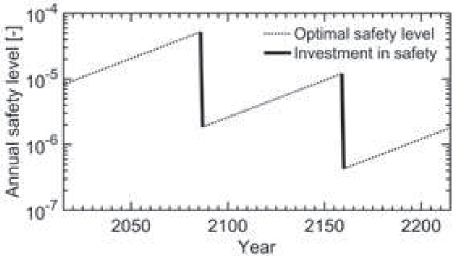
Figure 2 (top right). Example of an economic cost-benefit analysis for a flood defense.

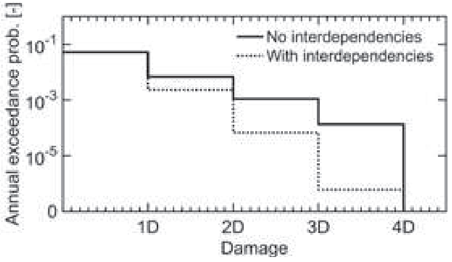
Figure 3 (Bottom left). Example of a changing economically optimal safety level over time due to for example economic growth. The 'investment in safety' lines indicate the optimal moments (and how much) to invest.

Figure 4 (bottom right). Flood damage curve with and without interdependencies for the flood defenses of figure 1. If a flood defense breaches, a constant damage D will occur. Therefore, the horizontal axis shows the damage in terms of D.









Guy Dupuits

ECONOMICALLY EFFICIENT FLOOD PROTECTION LEVELS

EFFECTS OF SYSTEM INTERDEPENCIES

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(Tentative) dissertation title:
'Economic optimization of flood defense systems with multiple lines of defense.'

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In the Netherlands, economic cost-benefit analysis plays an important role when deciding on safety levels for flood defenses. The cost of increasing the safety level is weighed against the reduction in flood risk (the benefit). The optimal level occurs where the sum of the cost and benefits is at its minimum; this is shown graphically in Figure 2. However, when conditions change over time, due to for example economic growth, the optimal safety levels change as well. This is illustrated in Figure 3. An in-depth description of the current use of cost-benefit analyses in the Netherlands can be found in Kind (2014).

Specifically, economic cost-benefit analyses can offer support in decisions regarding to where, when and how much to invest. Where to invest can be identified by selecting locations where benefits outweigh the costs. For these locations, deciding on when and how much to invest can be supported by results such as shown in Figure 3. Additionally, the results of a cost-benefit analysis can be used to clarify the service levels presented by the government to the public.

The benefit part in an economic cost-benefit analysis is the reduction in flood risk. The flood risk associated with a flood defense is often defined as the flood probability times the flood damage. When flood defenses are analyzed separately, each flood defense can have its own, isolated cost-benefit analysis. However, once flood defenses are viewed as dependent on each other, for example if they form a system with multiple lines of flood defenses, the interdependencies between flood defenses also needs to be taken into account in the cost-benefit analysis.

interdependencies for flood defenses
When dealing with flood defenses, the relevant interdependencies are those that have an impact on the hydraulic loads. For example, consider a river with a number of dike rings, as shown in Figure 1. If dike ring 1 has a breach during a flood event, a certain amount of water would be diverted from the main river into the lower-lying land protected by the dike ring. Even though this will probably lead to damage behind dike ring 1, less water will reach dike rings 2 to 4. In other words, a breach upstream at dike ring 1 will reduce the risk for the remaining dike rings. Flood defenses that interact with each other, like the one described in Figure 1, therefore not only protect their own area, but can also influence the safety levels of other adjacent flood defenses.

Flood defenses, interdependencies and risk
In the previous example a positive interdependency effect will occur in the case of a breach. However, a breach can also have a negative effect, for example if extra water enters another river due to the breach. This extra water increases the flood risk for areas alongside that other river. The consequences of interdependencies can therefore be either positive or negative.

In my research, the consequence of interdependencies has been expressed in terms of changes in the hydraulic loads. In order to quantify this, the various hydraulic loads need to be modeled, as well as potential breaches and potential flood damage resulting from such a breach. As the behavior of a river and its hydraulic loads are important when estimating flood probability, as well as possible damages, including interdependencies in the cost-benefit analysis improves the flood risk part of the cost-benefit analysis.

In order to quantify the flood risk associated with a flood defense, the interdependencies need to be incorporated in probability distributions of hydraulic loads. A straightforward method of moving from deterministic hydrodynamic simulations to probability distributions of hydraulic loads is by using a Monte Carlo simulation, for example as implemented by De Bruijn et al. (2014). If we take the example in Figure 1, with a constant damage estimate for each flood defense, a flood damage curve with and without interdependencies looks like the graph in Figure 4. This indicates that the interdependencies in Figure 1 decrease the probability of multiple breaches during the same extreme discharge event.

Impact of including interdependencies on a cost-benefit analysis
As previously described, an economic cost-benefit analysis balances risk costs and investment costs. Therefore, a change in flood risk can lead to different economically optimal investments. With interdependencies, the total number of relevant system configurations can become large. For example, suppose the flood defenses in Figure 1 can have five possible heights per defense. Without interdependencies, a total of $5*4=20$ combinations are possible. With interdependencies, the number of combinations rises to $5^4=625$. This number increases further if the timing of investments is included. For example, in case of a time span of 100 years with yearly increments, the number of combinations rises to 2000 and 62,500, respectively. The challenge, therefore, is not only to find the optimal solution among many different options, but also to calculate these different options efficiently, in order to reduce computation time.

When interdependencies are quantified and incorporated in a cost-benefit analysis, the results can be compared with those of a simpler cost-benefit analysis without interdependencies. Though the results can differ significantly, the differences are heavily dependent on the specific characteristics of each case. Examples of such case-specific characteristics are the distribution of flood damages over the flood prone areas, or the ratio between risk and investment costs. Practically, results of a cost-benefit analysis with interdependencies can lead to different sets of optimal safety levels, as well as to different ('more efficient') investment schemes for the flood defenses. Furthermore, the method is not limited to traditional flood defenses such as earthen levees; for example, emergency storage areas or storm surge barriers can also be included.

Figure 5. Example of multiple lines of defense - Houtribdijk in Lake IJssel, The Netherlands (Photo courtesy Jesse Allen, NASA images)