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# Defend or raise? Optimising flood risk reduction strategies

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## Abstract

Flood risk reduction can be provided by interventions such as raising land or constructing flood defences. This paper introduces an approach to optimise the selection of risk reduction strategies. It expands existing economic optimization approaches for flood defences, by introducing (largely) analytical formulations to include the effects of approaches to mitigate flood consequences. The method considers the size of the protected area and associated damages, the costs and dimensioning of interventions and the likelihood of flooding. It is applied in several practical cases. Within the context of this economic model, we conclude that a system of flood defences is more economical than a landfill for larger areas. Fills are preferred for small areas and/or for low costs. A combination of strategies is preferred when the value protected by the flood defence is low compared to the value protected by the fill, or when the high value development is relatively small in size. The sensitivity of outcomes to the choice of the main input parameters is presented, as well as implications of the results and selection of strategies in developing and developed countries. Overall, this approach supports decision makers in developing effective strategies to manage and reduce flood risk.

## KEYWORDS

flood management, flood protection, flood risk, mitigation, risk-based optimization

## 1 | INTRODUCTION

Floods account for a large portion of damages from natural disasters worldwide. With rising sea levels, and studies that claim flood events are increasing both in magnitude and in frequency (EEA, 2012; Kovats & Valentini, 2014), the need for effective flood risk reduction strategies is clear.

Different strategies can be applied to reduce flood risks. One strategy is to surround an area subject to flood risk with flood defences, creating a “polder.” A drainage system is installed to drain excess water from the polder to the adjacent rivers or sea. The technique worked so well that the Dutch decided to invest a large part of the profits of the

golden age during the 17th century in reclaiming polders (e.g., the Beemster and the Heerhugowaard polders). Currently, a large part of the Netherlands consists of polders. Polders were also built in countries such as Germany (along the Weser and Elbe rivers), England (along the Fens near Boston), Surinam, Bangladesh and India, where large polders were built in marshes for agriculture purposes. More recent examples include the airport of Suvarnabhumi in Thailand (Seah, 2005) and the Pulau Tekong development in Singapore.

Another strategy for reducing flood risks is to limit potential flood consequences by raising or flood proofing structures, or raising entire areas well above expected flood levels, creating large elevated landfills (or mounds). Local

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examples of this strategy are found along low-lying coastal areas in the United States (e.g., Bolivar Peninsula, Texas), where houses are raised on piles (Tomiczek, Kennedy, & Rogers, 2013), or in unembanked areas in the Netherlands, where farmers built houses on top of large soil mounds. Larger scale examples are found in Singapore, Hong Kong and Jakarta (IPC port developer, 2012). Massive landfills were also used for large reclamation projects in the Netherlands: examples include the Botlek, Europoort and the 2nd Maasvlakte areas in the port of Rotterdam and the IJburg reclamation project in Amsterdam (de Leeuw et al., 2002). Combinations of interventions can also be found, such as the coast of Japan, where flood defences are combined with landfills and large sea walls to mitigate tsunami risks after the 2011 Tohoku Tsunami (Strusińska-Correia, 2017).

While both strategies have pros and cons, a key question is which strategy is optimal for a given situation. Landfills generally reduce damages but require large volumes of soil (or structural interventions) when applied to large scale areas. The required soil volumes for flood defences are generally smaller, but consequences in case of failure of the defences will be larger. Economic optimization methods are often applied within different fields of civil engineering for strategic decision making purposes: examples include tunnels (Arends et al., 2005), coastal and port infrastructure (Mai, van Gelder, Vrijling, & Stive, 2009; Nagao, Moriya, & Washio, 2003). Specifically for strategic decisions concerning flood risk management, economic optimization has often been used to determine elevation levels (Kind, 2014; Tsimopoulou, Vrijling, Kok, Jonkman, & Stijnen, 2014; Vrijling, 2014). Related optimization models have also been used to assess the impact of flood proofing measures on residential building vulnerability (Custer, 2015), to support decisions about the implementation of flood mitigation measures at different points in time (Woodward, Gouldby, Kapelan, & Hames, 2014) or to assess the trade-off between levee setback or heightening (Zhu & Lund, 2009).

A number of limitations hamper the ability of existing methods to investigate trade-offs between flood defences and mitigation of consequences (with landfills). Most approaches in this field focus on one intervention, mostly flood defences (Eijgenraam, 2006; Kind, 2014; Vrijling, 2001), but also house elevation (Xian, Lin, & Kunreuther, 2017). Approaches that consider both defences *and* landfills (Tsimopoulou et al., 2014) approach this problem numerically and for a limited number of alternatives, without an analytical solution. Existing approaches also mostly assume a specific case or area, which does not lead to more generally applicable insights for different area sizes.

The aim of this work is to develop an analytical model that supports strategic decision making in flood risk management, specifically considering trade-offs between fills and

flood defences. The analytical model provides a (largely) analytical solution for optimising elevation levels and costs of a landfill or flood defence strategy. Solving the optimization model analytically can provide insight in (a) the largest drivers of cost and risk and (b) the influence of different variables (e.g., size and value of the area, costs of interventions and potential damages) on preferred strategies. This information is essential for strategic decision making in flood risk management.

The strategies for flood risk management included in the model are simplified to highlight their respective (economic) differences. Here, landfills represent approaches that reduce the economic consequences of floods, such as flood proofing or raising structures. Non-economic factors that may influence strategic decision making are not explicitly included in the proposed model (e.g., loss of life), but are discussed separately in Section 4. Strategies other than flood defences or landfills (e.g., land use planning, insurance, evacuation and emergency measures for flood prevention) are beyond the direct scope of this paper.

The paper is organised as follows: Section 2 derives the methodology that enables optimization of the costs of raising land and constructing flood defences (or combinations), depending on the area to be developed and its value. Section 3 discusses which strategy is preferred for specific practical examples. Section 4 discusses other aspects associated with both strategies that may influence decision making. Finally, Section 5 concludes with the main findings of this paper and directions for future research.

## 2 | METHODOLOGY

This section derives a mathematical model that enables optimization of the costs associated with raising land or constructing flood defences. The mathematical model includes the dependency of damages on flood depth to accurately model flood risk and particularly the effect of raising of structures by means of landfills or other measures. The approach builds on existing models used to evaluate the economic implications of multi-layered safety (Jonkman, Kok, & Vrijling, 2005; Tsimopoulou et al., 2014; Vrijling, 2014) and to optimise reclamation levels for port terminals (Lendering, Jonkman, van Gelder, & Peters, 2015). Generally, these models compare the total costs of flood protection based on a summation of the investment cost and the present value of flood risk (i.e., the expected damages due to flooding over the lifetime), see Equation (1). Flood risk is defined here as the expected annual damages of flooding. This approach was first used by van Dantzig to optimise elevation levels for flood defences in the Netherlands (van Dantzig, 1956); his method was later improved by Eijgenraam (2006) to account for time dependencies

(e.g., economic growth, degradation of flood defences and sea level rise) (see also (Kind, 2014)).

$$\text{Total cost} = \text{Investment} + \text{Risk}. \quad (1)$$

The total costs are minimised to determine optimal elevation levels (e.g., the flood defence or fill level), or in other words, elevation levels that lead to minimal total cost. Here, for simplicity, the before mentioned time dependencies of optimal safety levels are neglected. The following subsections subsequently derive and compare the investment costs (2.1) and the risk (2.2), after which the total costs are optimised (2.3).

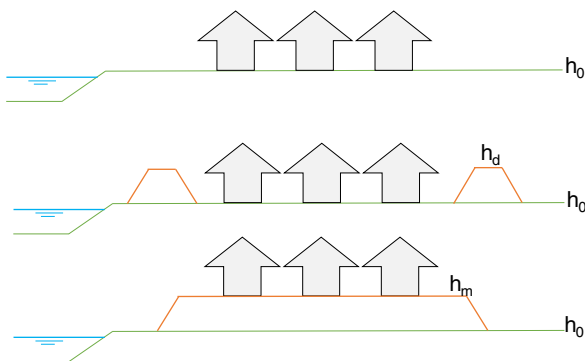
## 2.1 | Investment cost

The investment cost of the considered flood risk reduction strategies depends on the size of the area to be protected, the elevation level and the marginal cost. We consider a housing project on a floodplain, see Figure 1. The base level of the area is modelled by  $h_0$ . The area to be protected from flooding is modelled by variable  $A$  and depends on the land use (e.g., housing, agriculture or industry), the amount of structures and their footprint (e.g., 200 m<sup>2</sup> per structure). Additional space is reserved for infrastructure in and around the houses. The total size of the area to be developed is found by Equation (2):

$$A = N_d A_d C_d \text{ [m}^2\text{]}, \quad (2)$$

with  $N_d$ , the number of structures (–),  $A_d$ , the footprint per structure (m<sup>2</sup>) and  $C_d$ , an addition for infrastructure around each development (–).

The investment cost function is derived for both fills and flood defences. The investment cost of a fill is a function of



**FIGURE 1** A proposed development of a number of houses that require flood protection (top). Protection can be provided by surrounding the area with flood defences (middle) or raising the area on a large fill (bottom)

the area ( $A$ ), the crest level ( $h_m$ ) and the marginal cost for raising land ( $C_m$ ), see Equation (3).

$$I_m = A \cdot (h_m - h_0) \cdot C_m \text{ [€]}, \quad (3)$$

with  $A$ , area of the fill,  $h_m$ , crest level of the fill and  $C_m$ , unit cost to build the fill [€/m<sup>2</sup>].

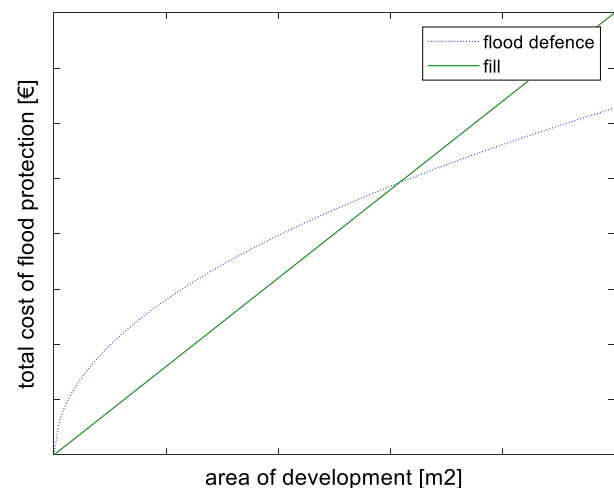
A similar relation is derived to estimate the investment cost of a system of flood defences surrounding the area. We assume that the total area to be protected is circular. The length of the flood defences that surround the area is derived with Equation (4), which calculates the circumference of the area. The investment costs of the flood defence system ( $I_p$ ) are a function of the marginal cost for a flood defence ( $C_d$ ), its length ( $L$ ) and the crest level ( $h_d$ ), see Equation (5).

$$L = 2 \cdot \sqrt{\pi \cdot A} \text{ [m]} \text{ (i.e., the circumference of a circular area)}, \quad (4)$$

$$I_p = L \cdot (h_d - h_0) \cdot C_d = 2 \cdot \sqrt{\pi \cdot A} \cdot (h_d - h_0) \cdot C_d \text{ [€]}, \quad (5)$$

with  $L$ , length [m],  $h_d$ , crest level of the flood defence (or dike) [m] and  $C_d$ , marginal cost for the flood defence [€/m].

The investment cost of a fill increases linearly with the size of the area, while the investment cost of the fill has a quadratic relation with the area, as illustrated in Figure 2. In general, for small areas, the cost for raising land is lower than the cost of flood defences. For larger areas, flood defences result in lower costs.



**FIGURE 2** Investment cost for a fill (blue dotted line) and a system of flood defences (red straight line), depending on the area that requires protection

The area where the investment cost of a system of flood defences becomes lower than those of raising land is modelled with variable  $A_r$ , is found with Equation (6):

$$A_r = 4 \cdot \pi \cdot \left[ \frac{C_d \cdot (h_d - h_0)}{C_m \cdot (h_m - h_0)} \right]^2 [\text{m}^2]. \quad (6)$$

Note that a straightforward prioritisation of flood defences over fills, based on a solely the comparison of their respective investment cost, is not complete, because this ignores the differences in flood risk.

## 2.2 | Risk of flooding

Risk is estimated by the present value of expected damages over the considered lifetime (i.e., the expected value of damages). It is defined by the product of the annual flood probability with its potential consequences (Equation (7)). The annual flood probability depends on the considered flood risk reduction system (if any) and the potential flood hazards (e.g., fluvial, pluvial or coastal flooding). For a fill, the probability of flooding is determined by the probability that water levels exceed the crest level of the fill. For an area surrounded by flood defences, the probability of flooding is determined by the probability that these flood defences fail (i.e., breach). Failure may occur due to overflow or geotechnical failure (e.g., piping or instability). In our model, the flood probability of an area protected by flood defences is estimated by the probability of overflowing. It is then assumed that the probability of other failure mechanisms is negligibly small compared to the overflow probability. Design guidelines such as (Ciria, 2014) provide guidance for the design of flood defences with negligible probabilities of failure mechanisms other than overflow.

The annual risk is quantified with Equation (7), given a probability density function of annual water levels  $f(h)$  and a damage function  $D(h_w)$ . The present value of flood risk is determined with Equation (8) for a finite lifetime ( $T$ ), taking in to account a discount rate  $r$ . In choosing values for the discount rate, developments in cost and economic growth should be considered. For simplicity, the lifetime is assumed to be infinite, which simplifies Equation (8) in to Equation (9). The probability density function of water levels and the damage function are derived in the following subsections.

$$R = \int f(h_w) \cdot D(h_w) dh_w [\text{€}/\text{yr}]. \quad (7)$$

$$R = \sum_{t=1}^T \frac{\int f(h_w) \cdot D(h_w) dh_w}{(1+r)^t}. \quad (8)$$

$$R = \frac{\int f(h_w) \cdot D(h_w) dh_w}{r} \text{ for } T \rightarrow \infty [\text{€}]. \quad (9)$$

### 2.2.1 | Probability density function of water levels

The annual probability of flooding is estimated by the probability of water levels exceeding the crest level of the fill ( $h_m$ ) or flood defence ( $h_d$ ), as illustrated in Figure 3. Annual extreme water levels ( $h_w$ ) are typically described by an exponential distribution (Jonkman et al., 2005; van Dantzig, 1956) with constants  $a$ , the *location* parameter in meters, and  $b$ , the *scale* parameter in meters (see Equation (10)).

$$f(h) = \frac{e^{-\frac{h_w - a}{b}}}{b}. \quad (10)$$

Equation (11) describes the probability of non-exceedance of water levels ( $P[h_w \leq h_d \text{ or } h_m]$ ). The probability of exceedance of water levels ( $P[h_w > h_d \text{ or } h_m]$ ), which represents the probability of overflow, is found with Equation (12):

$$F(h) = 1 - e^{-\frac{h_w - a}{b}} [\text{yr}^{-1}]. \quad (11)$$

$$P_f(h_w > h_d, h_m) = 1 - F(h) = e^{-\frac{h_w - a}{b}} [\text{yr}^{-1}]. \quad (12)$$

### 2.2.2 | Damage function

The damage of flooding is typically divided in direct damages (i.e., material damages) and indirect damages (i.e., business losses). Here, indirect damages are assumed to increase linearly with direct damages, in line with the approach proposed by Hallegatte, Green, Nicholls, and Corfee-Morlot (2013). Therefore, indirect damages are included in the direct damages, and depend on the land use (e.g., housing, agriculture or industry).

The direct damage of flooding ( $D_{\text{pot}}$ ) is determined by the value of the protected area, which, among others, consists of the value of all structures and infrastructure in the

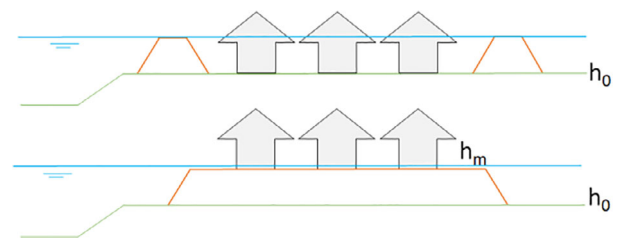


FIGURE 3 Flooding of an area in a polder and on a fill

area. It is quantified with Equation (13), which is a function of the size ( $A$ ) and value ( $V$ ) of the area.

$$D_{\text{pot}} = A \cdot V [\text{€}] \quad (13)$$

A linear relation is used to estimate flood damages for increasing flood depths. In case of dike failure, water levels in the protected area are assumed to become equal to the outside water level. Other flood characteristics and dynamics (flow velocity, rise rate) are not included in the simplified modelling here. Thus, for an area behind a flood defence, the flood depth after failure is equal to the water level ( $h_w$ ) minus the initial level of the floodplain ( $h_w - h_0$ ). For fills, the flood depth is equal to water level minus the level of the fill ( $h_w - h_m$ ). This is illustrated by the following figure:

Damage occurs when the water levels exceed the crest of the flood defence or fill. Flood damages are bounded by a maximum food depth ( $d_{\text{max}}$ ), for which all value is assumed to be lost, which depends on the land use. For example, agricultural land will have a lower value of  $d_{\text{max}}$  than industry or housing, because all crops are assumed to be lost once the surface of the land is flooded. Here, the value of  $d_{\text{max}}$  includes all potential damages of the protected area, including infrastructure and indirect damages. The resulting damage function for fills (Equation (14)) and flood defences (Equation (15)) are included below:

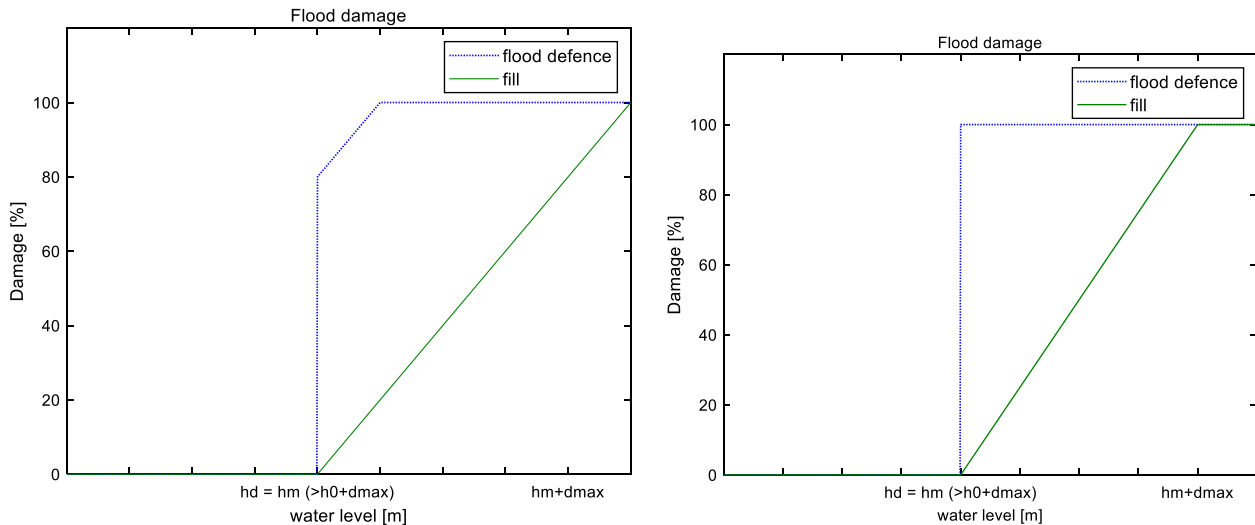
$$\begin{aligned} D_{\text{fill}} &= 0 [\text{€}] \quad h_w < h_m \\ D_{\text{fill}} &= D_{\text{pot}} \cdot \frac{h_w - h_m}{d_{\text{max}}} [\text{€}] \quad h_m < h_w < h_m + d_{\text{max}} \\ D_{\text{fill}} &= D_{\text{pot}} [\text{€}] \quad h_w > h_m + d_{\text{max}} \end{aligned} \quad (14)$$

$$\begin{aligned} D_{\text{dike}} &= 0 [\text{€}] \quad h_w < h_d \\ D_{\text{dike}} &= D_{\text{pot}} \cdot \frac{h_w - h_0}{d_{\text{max}}} [\text{€}] \quad h_d < h_w < h_0 + d_{\text{max}} \\ D_{\text{dike}} &= D_{\text{pot}} [\text{€}] \quad h_w \geq h_0 + d_{\text{max}} \end{aligned} \quad (15)$$

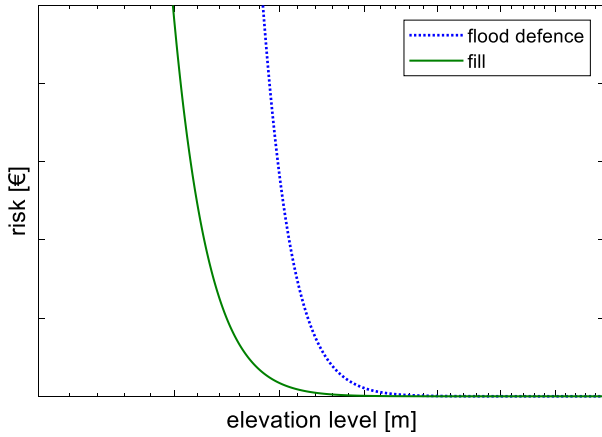
The relations between flood damage and flood level are illustrated in the conceptual damage functions in the left graph of Figure 4, which assumes that the flood defence level is lower than the level at which maximum flood damages occur ( $h_d < h_0 + h_{\text{max}}$ ). When the flood defence level is higher than the level at which maximum damages occur ( $h_d > h_0 + d_{\text{max}}$ ), all value inside the flood defence system will be lost once the flood defence fails. This is illustrated in the right graph of Figure 4 (and depicted in Equation (16)). The graphs also illustrate that, for a given water level, the flood damages of an area protected by flood defences (i.e., a polder) are higher than the damages to the same area on top of a fill.

$$\begin{aligned} D_{\text{dike}} &= 0 [\text{€}] \quad h_w < h_d \\ D_{\text{dike}} &= D_{\text{pot}} [\text{€}] \quad h_w \geq h_d \end{aligned} \quad (16)$$

Risk is found by multiplying the potential food damages with the probability of flooding. The following conceptual graph illustrates the present value of the risk for increased elevation levels of fills and flood defences. The risk decreases with increased elevation levels for both strategies, because the probability of flooding reduces with increased elevation levels. Notice how the risk of flood defences is always higher than of fills, because once an elevation level is exceeded, polders flood completely resulting in higher damages than fills (Figure 5).



**FIGURE 4** Damage function for  $h_d < h_0 + d_{\text{max}}$  (left) and for  $h_d > h_0 + d_{\text{max}}$  (right)



**FIGURE 5** Conceptual graph of flood risk depending on the elevation level of fills or flood defences

## 2.3 | Total costs and optimization

Economical optimization is used to determine optimal elevation levels, based on minimal total costs. The total costs are found by summing the investment costs with the present value of the risk (Equation (17)). The minimal total costs are determined by minimising the respective total cost functions with respect to the fill and flood defence level (Equation (18)).

$$TC(h_{d,m}) = I(h_{d,m}) + R(h_{d,m}), \quad (17)$$

$$\frac{\partial TC}{\partial h_{d,m}} = 0, \quad (18)$$

with  $TC$ , total cost,  $I$ , investment cost and  $R$ , present value of risk.

### 2.3.1 | Optimization of total costs of a fill

The total cost function for a flood risk reduction system consisting of a fill ( $TC_m$ ) is found by combining Equations (1), (3), (9), (10), and (14), providing the following function (see Appendix S1):

$$TC_m = A \cdot (h_m - h_0) \cdot C_m + R_m, \quad (19)$$

$$\text{with } R_m = \frac{A \cdot V \cdot b}{r \cdot d_{\max}} \cdot \left( e^{-\frac{h_m - a}{b}} - e^{-\frac{h_m + d_{\max} - a}{b}} \right). \quad (20)$$

Including the risk function in the total cost function gives the following equation for total costs of a fill:

$$TC_m = A \cdot (h_m - h_0) \cdot C_m + \frac{A \cdot V \cdot b}{r \cdot d_{\max}} \cdot \left( e^{-\frac{h_m - a}{b}} - e^{-\frac{h_m + d_{\max} - a}{b}} \right). \quad (21)$$

Note that the present value of the risk of floodplains without flood risk reduction measures is found when solving Equation (21) for  $h_m = h_0$ . Equation (21) is minimised to obtain the optimal level of the fill ( $h_m$ : optimal),

$$\frac{\partial TC}{\partial h_m} = A \cdot C_m + \frac{A \cdot V}{r \cdot d_{\max}} \cdot \left( e^{-\frac{h_m + d_{\max} - a}{b}} - e^{-\frac{h_m - a}{b}} \right) = 0$$

$$h_{m;\text{optimal}} = a - b \cdot \ln \frac{C_m \cdot d_{\max} \cdot r}{V \cdot \left( 1 - e^{-\frac{d_{\max}}{b}} \right)}. \quad (22)$$

The optimal elevation level of a fill depends on the parameters ( $a$  and  $b$ ) of the exponential distribution of water levels, the marginal cost for raising fills ( $C_m$ ), the depth where flood damages are maximised ( $d_{\max}$ ) and the marginal value of the area ( $V$ ). It is not influenced by the size of the area, since both the cost and damages increase linearly with the area.

### 2.3.2 | Optimization of total costs of a polder

The total cost function for a system of flood defences surrounding a (circular) polder ( $TC_d$ ) is found by combining Equations (1), (5), (9), (10), (13), and (15), providing the following function (see Supplementary Material):

$$TC_d = L \cdot (h_d - h_0) \cdot 2 \cdot \sqrt{\pi \cdot A} \cdot C_d + R_d \quad (23)$$

$$\text{with } R_d = \frac{A \cdot V \cdot b}{r \cdot d_{\max}} \cdot \left( \left[ \frac{h_d}{b} - \frac{h_0}{b} + 1 \right] e^{-\frac{h_d - a}{b}} - e^{-\frac{h_0 + d_{\max} - a}{b}} \right). \quad (24)$$

Including the risk function in the total cost function provides the following equation for total costs of a flood defence system, surrounding a polder:

$$TC_d = (h_d - h_0) \cdot 2 \cdot \sqrt{\pi \cdot A} \cdot C_d + \frac{A \cdot V \cdot b}{r \cdot d_{\max}} \cdot \left( \left[ \frac{h_d}{b} - \frac{h_0}{b} + 1 \right] e^{-\frac{h_d - a}{b}} - e^{-\frac{h_0 + d_{\max} - a}{b}} \right). \quad (25)$$

Equation (25) is minimised to obtain the optimal elevation level of the flood defence ( $h_d$ : optimal):

$$\frac{\partial TC}{\partial h_d} = 2 \cdot \sqrt{\pi \cdot A} \cdot C_d + \frac{A \cdot V}{r \cdot d_{\max}} \cdot \left( \left[ \frac{h_0}{b} - \frac{h_d}{b} \right] \cdot e^{-\frac{h_d - a}{b}} \right) = 0$$

$$(h_d - h_0) \cdot e^{-\frac{h_d - a}{b}} = \frac{2 \cdot \sqrt{\pi \cdot A} \cdot C_d \cdot d_{\max} \cdot r \cdot b}{A \cdot V}. \quad (26)$$

The optimal flood defence level depends on the parameters ( $a$  and  $b$ ) of the exponential distribution of water levels, the marginal cost for raising flood defences ( $C_d$ ), the depth where flood damages are maximised ( $d_{\max}$ ) and the marginal value of the area to be protected ( $V$ ). In addition, the initial level of the area ( $h_0$ ) to be protected and the size of the area to be protected ( $A$ ) also influence optimal flood defence levels. Equation (26) can be rewritten in the form  $W \cdot \exp(W) = Z$ , in which  $Z$  is a given constant and  $W$  the unknown variable. This so-called “Lambert function” is solved numerically in the practical examples in Section 3, because functions of this type cannot be solved analytically. Other examples with similar functions are found in (Kok, Vrijling, van Gelder, & Vogelsang, 2002; Lendering, Jonkman, & Peters, 2014). As will be shown in Section 3, larger areas to be protected result in higher optimal elevation levels for flood defences.

Note that the previous derivations (Equations (23) to (26)) represent situations where the flood defence level is lower than the water level where maximum damages occur ( $h_d < h_0 + d_{\max}$ ). If the flood defence level exceeds the level where maximum damages occur ( $h_d > h_0 + d_{\max}$ ), all value behind the flood defence is lost once it fails. This assumption is often used in previous work (van Dantzig & Kriens, 1960; Vrijling, 2001). Equation (25) then simplifies to Equation (27) and the optimal flood defence level is found with Equation (28).

$$TC_d = (h_d - h_0) \cdot 2 \cdot \sqrt{\pi \cdot A} \cdot C_d + \frac{A \cdot V}{r} \cdot e^{-\frac{h_d - a}{b}} \text{ for } h_d > h_0 + d_{\max}. \quad (27)$$

$$h_{d;\text{optimal}} = a - b \ln \left[ \frac{2 \cdot \sqrt{\pi \cdot A} \cdot C_d \cdot b \cdot r}{A \cdot V} \right] \text{ for } h_d > h_0 + d_{\max}. \quad (28)$$

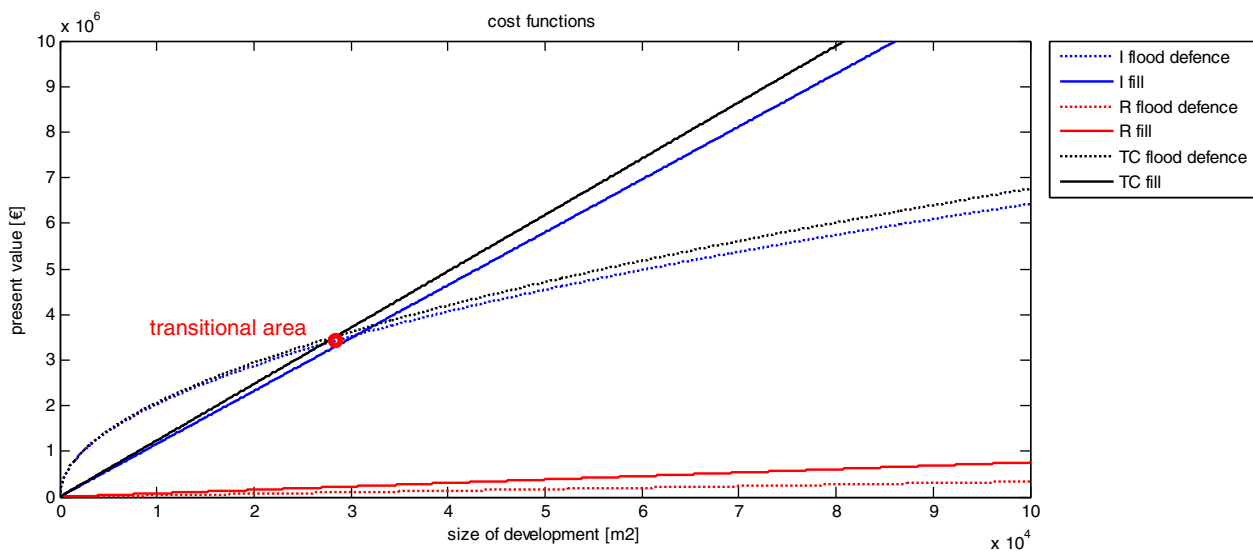
The following conceptual graph illustrates the investment, risk and total costs of fills and flood defences, given optimal elevation levels and increasing size of the protected area (Figure 6). The example is based on the values included in Table 1.

For small areas, the total costs of fills are lower than the total cost of flood defences. The transitional area is defined as the area size for which the total cost of fills and flood defences are equal, see Figure 6. The following graphs illustrate the investment cost, risk and total costs of both flood defences and fills for areas smaller (Figure 7) and larger (Figure 8) than the transitional area (given the data in Table 1). For areas smaller than the transitional area, fills are always preferred over flood defences since this strategy will lead to lower total costs. For areas larger than the transitional area, flood defences are preferred over fills from a certain elevation level: the transitional elevation level. This level is found by finding the elevation level for which the total cost of both strategies is equal. A similar analysis was performed in (Lendering et al., 2015), where elevation levels for land reclamation where optimised for fills and polders.

### 3 | CASES

#### 3.1 | Introduction

Several practical examples are discussed to analyse situations where a strategy containing one or multiple layers of protection (i.e., a landfill and/or a flood defence) is preferred from an economical point of view. While the following examples have been highly simplified, they represent



**FIGURE 6** Investment, risk and total costs for increasing size of the protected area



**TABLE 1** Generic case study variables

Description	Variable	Value
The base level of the floodplain.	$h_0$	0 m
Location (a) and scale (b) parameters of the exponential water level distribution. This level represents a case similar to the North Sea along the Netherlands, with a relatively mild sloping exponential distribution.	$a$	3 m
	$b$	0.3 m
Discount factor for discounting risk over the lifetime, taking in to account changes in economic growth, costs and damage (Deltares, 2011).	$r$	0.05
Marginal cost for raising land with a fill (including cost of outer slope protection against erosion), based on (Jonkman, Hillen, Nicholls, Kanning, & van Ledden, 2013; Lendering et al., 2015).	$C_m$	25 €/m <sup>2</sup>
Marginal cost for constructing flood defences (5 million euro per kilometre for levees with a retaining height of 5 m (Jonkman et al., 2013)).	$C_d$	1,000 €/m/m
Value of residential/ industrial land and depth for maximum damages, based on estimates used in the National Flood Risk Analysis in the Netherlands (Rijkswaterstaat, 2016).	$V$	1,500 €/m <sup>2</sup>
	$d_{\max}$	5 m
Value of agricultural land and depth for maximum damages, based on estimates used in the National Flood Risk Analysis in the Netherlands (Rijkswaterstaat, 2016).	$V$	100 €/m <sup>2</sup>
	$d_{\max}$	1 m

realistic, practical cases in which decision makers are faced with deciding between a protection or consequence mitigation strategy. Table 1 contains the generic input variables

used, which are based on values commonly used in flood risk analyses in the Netherlands.

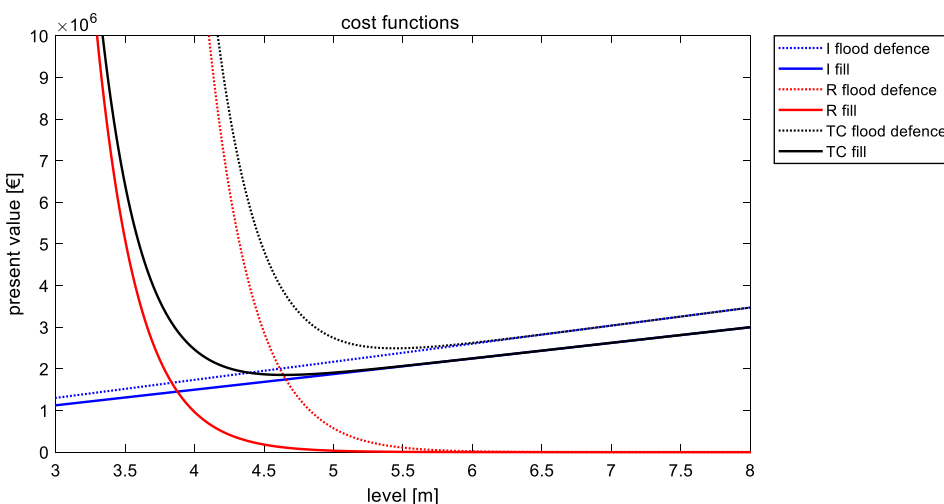
The sensitivity of the examples to the chosen values is investigated with sensitivity analyses. This section includes four case studies: an example with a single land use (3.1), an example with multiple land uses (3.2), an example for reducing risk given an existing flood defence (3.3) and an example where a minimum safety level is required (3.4).

### 3.2 | Single land use

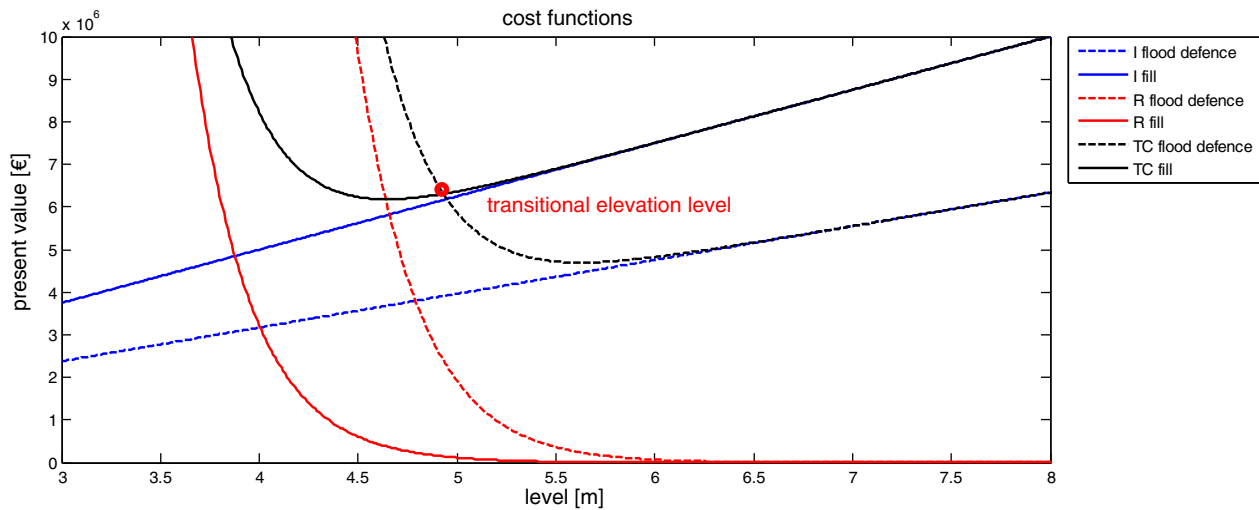
We consider a residential area to be built on a floodplain along a river or coast. Flood risk reduction can be provided by raising the entire residential area to a level well above flood levels or by surrounding the area with a (circular) system of flood defences. The optimal levels for fills and flood defences with increasing size of the protected area are determined, based on the values included in Table 1. The results are shown in the following graphs (Figure 9):

We find that the optimal level for fills is a constant, irrespective of the area that is protected (see Equation (22)). The optimal level for flood defences increases with increasing size of the area, as the optimal level is a function of the area (Equation (28)). Note that in this example the optimal elevation level of the fill is lower than that of a system of flood defences, because the optimal flood probabilities for fills are larger than for flood defences.

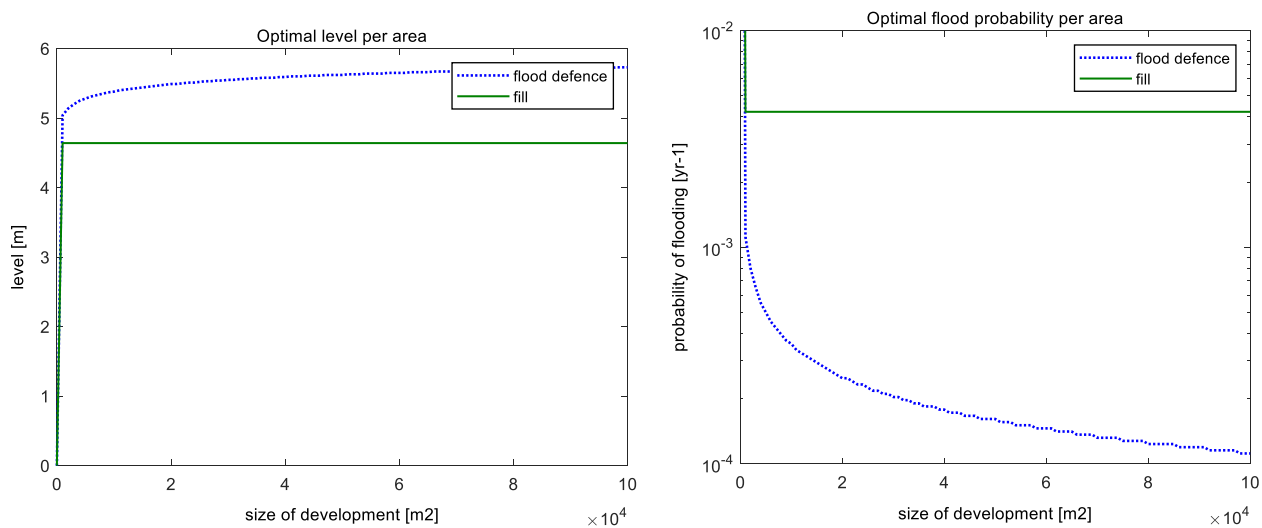
Figure 10 illustrates the resulting total costs for optimal elevation levels of both a fill and a system of flood defences. Raising fills is only beneficial (economically) if the total area is smaller than the transitional area size (in the example about 30,000 square meters). A system of flood defences is more economical over raising the area on top of a fill, provided that the area is larger than the transitional area and optimal elevation levels are chosen.



**FIGURE 7** Investment, risk and total cost for optimal elevation levels, given an area smaller than the transitional area. Here, the fill is preferred over flood defences



**FIGURE 8** Investment, risk and total cost for optimal elevation levels, given an area larger than the transitional area. Here, flood defences are preferred over fills



**FIGURE 9** Optimal level (left) and flood probabilities (right) of raising the residential area on a fill or surrounding the area with flood defences, for increasing size of the protected area

### 3.2.1 | Sensitivity to the marginal costs

The previous example assumed a constant ratio between the marginal cost for fills and flood defences. The following subsection discusses the sensitivity of the results to this ratio. In this analysis, the optimal levels, probabilities and total costs for significantly higher and lower marginal costs of both fills and flood defences is estimated (Figure 11).

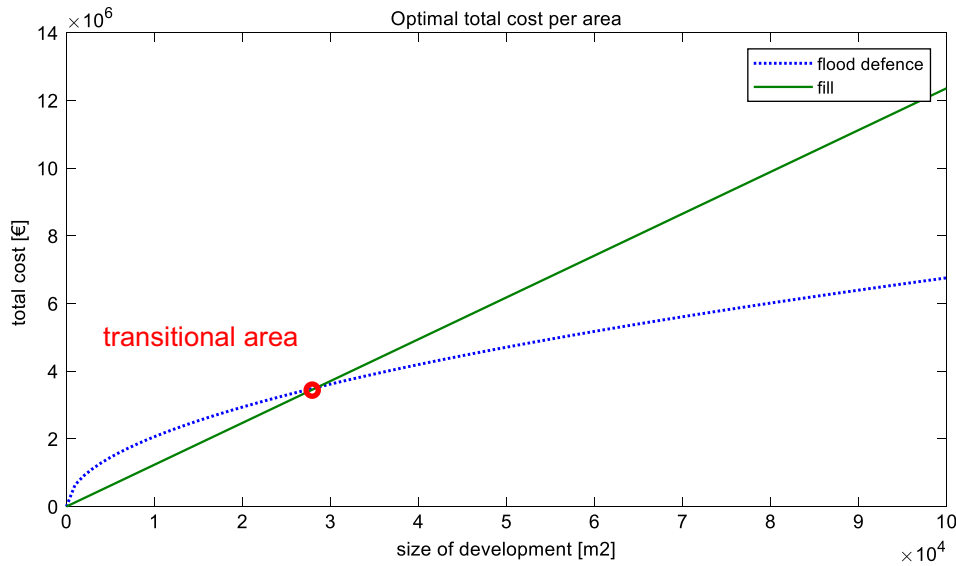
The solid blue lines represent the base case of flood defences (1,000 €/m/m), while the dotted blue lines are the optimal levels for higher (2,500 €/m/m) and lower (500 €/m/m) marginal costs. The solid black lines represent the base case of fills (25 €/m/m<sup>2</sup>), while the dotted black lines are the optimal levels for higher (50 €/m/m<sup>2</sup>) and lower (5 €/m/m<sup>2</sup>) marginal costs. The optimal level of both fills and flood defences reduce with increasing marginal cost, and vice versa for decreasing marginal cost. In summary, higher costs

for raising fills or flood defences result in lower optimal elevation levels.

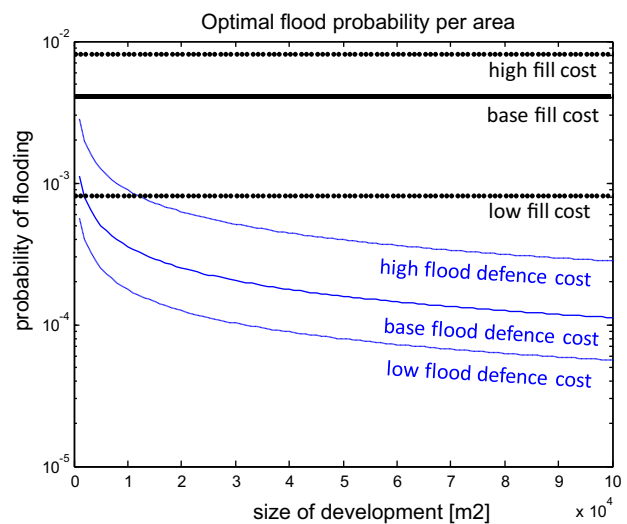
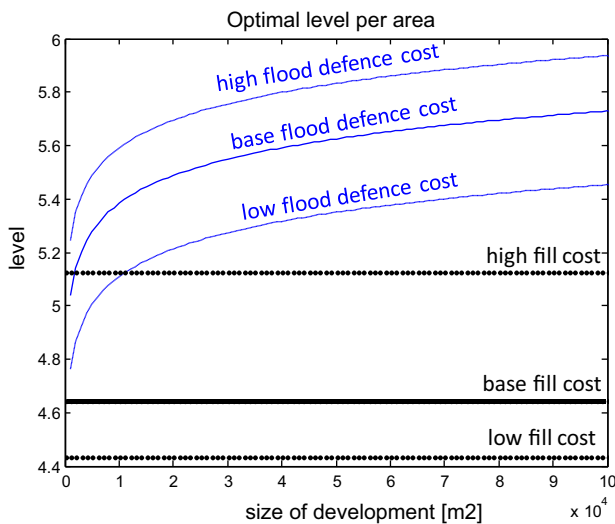
The increased marginal cost of fills (50 €/m/m<sup>2</sup>) benefit flood defences over fills (left graph of Figure 12). For this specific example, flood defences are more economical for areas larger than about 7,000 square meters. Such high costs for fills may represent projects where existing residential areas are to be raised or redeveloped to reduce flood risk. In contrast, reduced marginal cost for fills (5 €/m/m<sup>2</sup>) result in a larger fill development size where fills are preferred over flood defences (Figure 12).

### 3.2.2 | Sensitivity to the land use value

The sensitivity of the model to different land use values is analysed by reducing its value significantly, which may



**FIGURE 10** Total costs for optimal elevation levels of a fill and a system of flood defences, given increasing size of the protected area



**FIGURE 11** Sensitivity of the optimal elevation level (left) and probability of flooding (right) to the marginal costs. The solid blue and black lines represent the base case of a flood defence and fill respectively. The dotted lines represent the scenario with low and high costs

represent agricultural land use (Table 1 assumed a residential or industrial area; Figure 13).

Smaller optimal elevation levels for both fills and flood defences are found due to a reduction of the land use value. The transitional area (30,500 square meters) does not change significantly compared to the base case (Figure 10), suggesting that the sensitivity of the transitional area to the land use value is small.

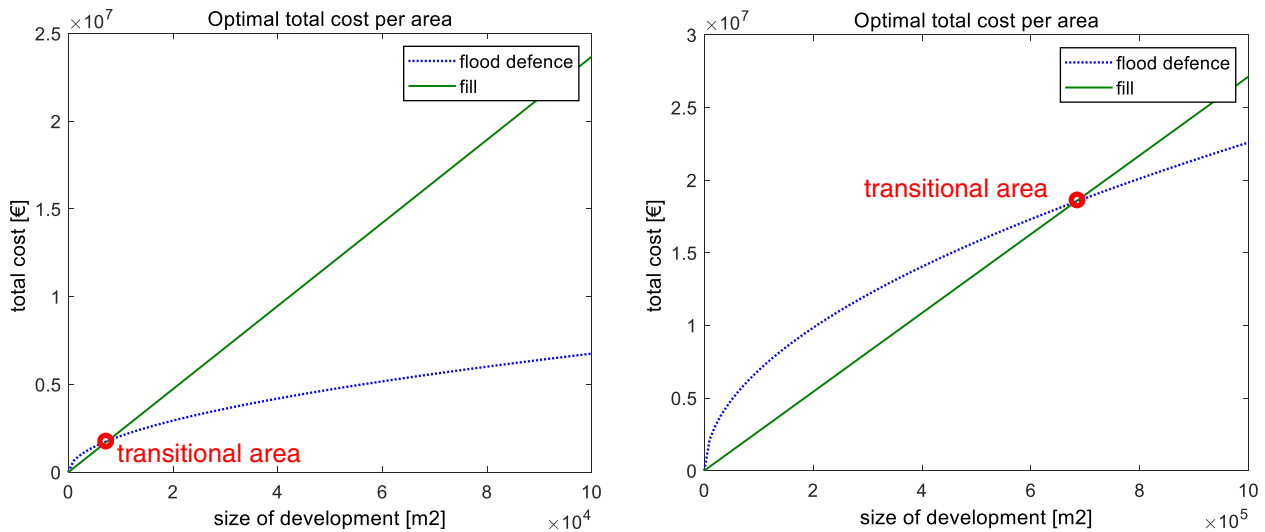
### 3.2.3 | Results

The results for the base case use typical values for western countries such as the Netherlands, with relatively high investment costs and damages. While the potential damages do not have a large influence on the preferred strategy (only

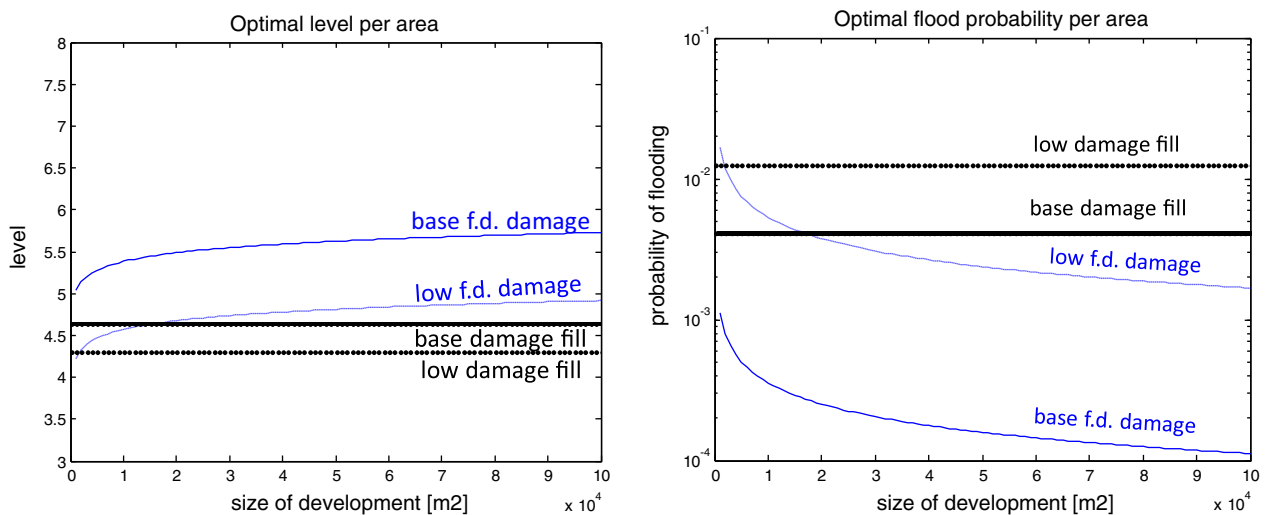
on optimal elevation levels), high marginal costs result in a strong preference for flood defences over fills. In contrast, low costs and damages (e.g., for developing countries) would typically lead to a stronger preference for fills, because the area where flood defences become more economical over fills increases significantly.

### 3.3 | Combining multiple land uses

This subsection discusses examples in which multiple types of land use are combined in an area, each possibly requiring a different strategy for risk reduction. For example, combining agricultural land with a residential area (Figure 14). Note that the flood defence and fill are dependent and correlated through the water level. A flood defence in front of a fill will



**FIGURE 12** Total costs for optimal elevation levels of a fill and a system of flood defences, given increasing size of the residential area



**FIGURE 13** Optimal level (left) and flood probabilities (right) of raising a fill or surrounding the area with flood defences (f.d.), for increasing size of the agricultural area. The solid lines represent the base case residential area, with damages of 1,500 €/m<sup>2</sup>

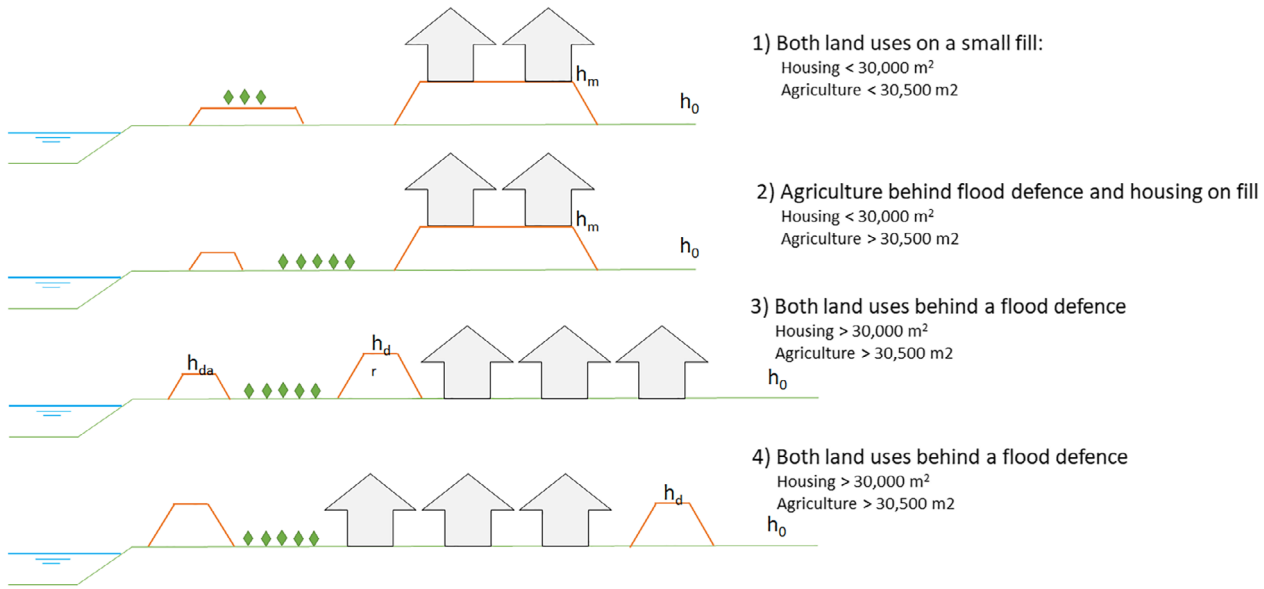
lower the flooding probability of that fill if it has a higher level than the fill (and vice versa), thus also reducing the risk associated with the protected area on the fill.

Based on the findings of the preceding section, we find that a flood defence is economically more beneficial than a fill for areas larger than the transitional area. Different combinations of land uses and preferred flood risk reduction strategies are shown in Figure 14 and in Table 2 (given the data of Table 1).

A combination of a flood defence and a fill is only preferred if one land use is smaller than the corresponding transitional area and the other larger. For example, a residential area smaller than its transitional area can be placed on a fill, while the surrounding agricultural land (smaller than its transitional area) is protected by flood defences. This is

illustrated in the second sketch in Figure 14. From an economic point of view, a combination is also preferred if the agriculture area is smaller than its transitional size, while the residential area is larger than its transitional size. In this case it might be more practical to have both land uses be protected by a flood defence, if there is sufficient room for the agricultural land to be placed behind the flood defence (see fourth sketch of Figure 14). A single layer of protection is preferred for all other combinations.

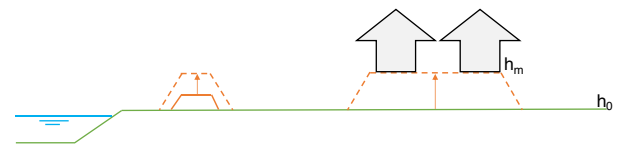
We also find that optimal elevation levels for flood defences are lower for smaller land use values. For this case, it may be more economical to construct one flood defence to protect both land uses. As further discussed in Section 4, additional planning considerations (e.g., water management and infrastructure) may also greatly affect the choice for a



**FIGURE 14** Combination of multiple land uses and risk reduction strategies in a floodplain

**TABLE 2** Combination of multiple land uses and risk reduction strategies in a floodplain

	Agriculture area smaller than transitional area	Agriculture area larger than transitional area
Residential area smaller than transitional area	Both agriculture and residential area on fills	Combination preferred: agriculture behind (small) flood defence and residential area on fill
Residential area larger than transitional area	Combination preferred: agriculture on fill and residential area behind flood defence, although possibly more practical to have both land uses be protected by a flood defence.	Both agriculture and residential area behind flood defence



**FIGURE 15** Developing behind an existing flood defence: reinforcing the flood defence or raising the floodplain on a fill?

The marginal cost for raising the entire residential area are estimated at 25 €/m<sup>2</sup>. The marginal cost for reinforcing flood defences are 50% of the costs of constructing new flood defences (Table 1): 500 €/m/m. We consider an existing flood defence with an elevation level below the optimal elevation level (see Figure 16). For this case, higher optimal elevation levels are found compared to the base case scenario (Figure 9), as a result of the reduction of the marginal costs.

In addition, we find that raising a fill behind the existing flood defence is only economical for rather small areas (in the example we find a transitional area of about 1,500 m<sup>2</sup>). Reinforcing the existing flood defences is preferred for larger areas. This example illustrates that the presence of flood defences results in a stronger preference for flood defences over fills.

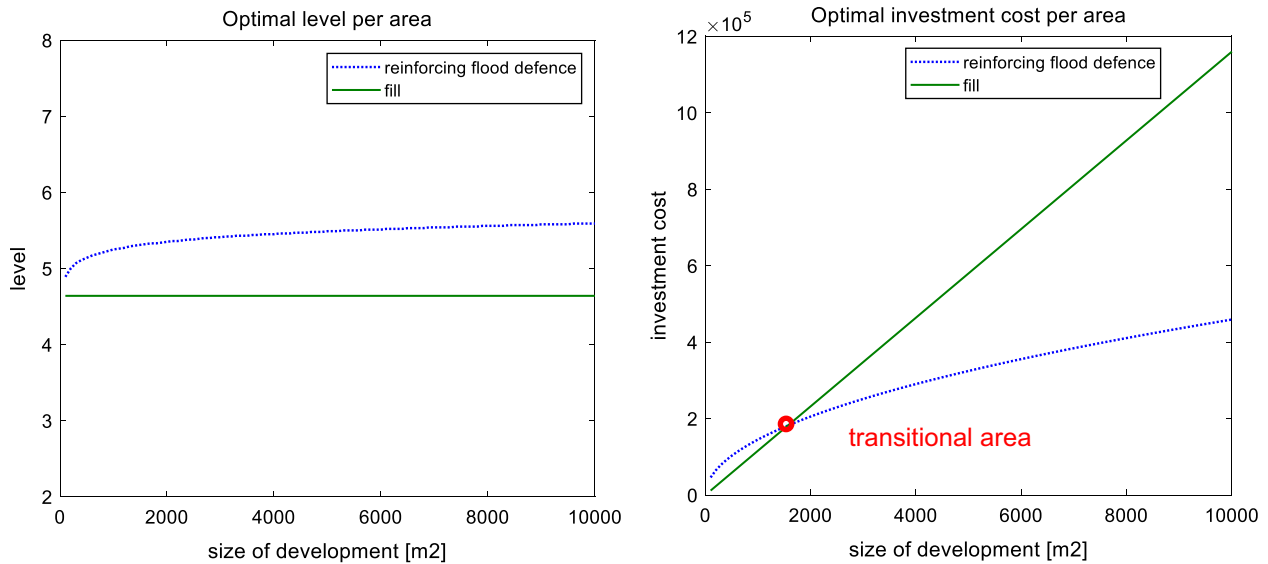
flood risk reduction strategy and its layout and implementation.

### 3.4 | Developing behind an existing levee

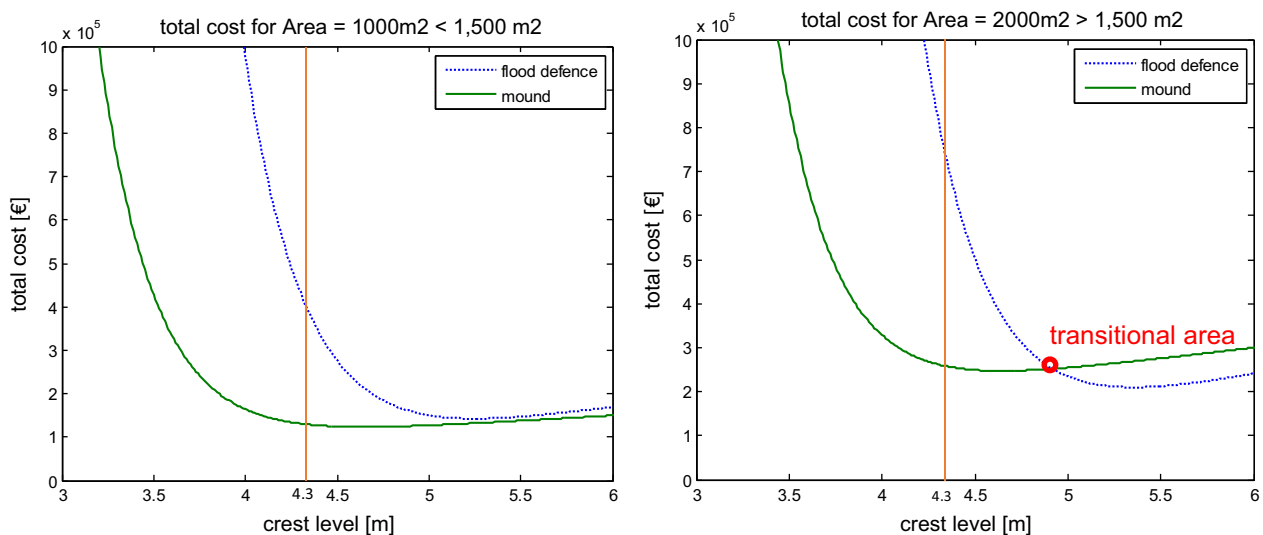
An example case study is considered where an area requiring flood risk reduction is situated behind an existing flood defence. The question here is whether it is wise to raise the existing defence or invest in landfills (Figure 15):

### 3.5 | Design for a minimum safety level

The preceding examples assumed that there is no minimum safety level and the optimization process continues until optimal levels are found. However, there are practical situations in which fixed safety levels are required, which may lay below optimal levels. An example is shown based on



**FIGURE 16** Optimal level (left) and total costs (right) for raising a fill or reinforcing the existing flood defences, given increasing size of the residential area. The existing flood defence level (3 m) is below the optimal level (5 m)



**FIGURE 17** Total costs for a given area smaller than the optimal area (left) and larger than the optimal area (right), for increasing level of protection. Specifically shown is the crest level associated with an annual probability of flooding of 1/100

flood management in the United States, where minimum safety levels are based on an annual flood probability of 1/100.

In those cases, optimization of the elevation level can become less relevant. However, it can still be interesting to consider whether consequence mitigation is an attractive alternative to reach the same amount of risk reduction. The following graphs compare the total cost of raising fills and constructing flood defences, specifically for a flood probability of 1/100 per year (corresponding with an elevation level of 4.3 m in the base case). While a system of flood defences is more economical when the total costs are

optimised, the figure shows that the costs of raising fills are lower than the costs of flood defences (irrespective of the size of the area to be developed; Figure 17).

## 4 | DISCUSSION

### 4.1 | Results and practical implications

The model concept serves as a basis for strategic decision making. More realistic inputs for elevation levels, damage density and investment costs could be incorporated in more detailed analyses—often necessitating numerical elaboration.

Country—specific values for sea-level rise, costs (e.g., Jonkman et al., 2013), damage values and discount factors (considering economic growth), can be used to come to realistic local applications and the local “demand for safety” and need for coastal adaptation (Hinkel & Nicholls, 2010). Further localised studies may also consider a broader set of interventions, including protective measures such as storm surge barriers, nourishments, reefs and different forms of damage reduction.

The results for the base case use typical values for western countries (e.g., the Netherlands), with relatively high investment costs and damages, resulting in a strong preference for flood defences. The model framework can also be applied to cases and applications in developing countries, typically characterised by relatively low investment costs and damage densities. Such characteristics lead to a stronger preference for fills, because the transitional area where flood defences are preferred over fills is much larger.

While this study focused on an economic-engineering consideration of risk, other drivers may determine which strategy is preferred. For example, flood defences are better adaptable to changing boundary conditions due to sea level rise or subsidence: it is easier to raise existing flood defences than to raise an entire fill. Another important aim could be to prevent or minimise future settlements, which are larger when fills are constructed compared to flood defences (fills have a larger footprint and therefore higher pressures on the subsoil). Raising fills on weak subsoils can become very costly and time consuming, if soil replacement is needed to prevent large settlements.

A flood defence solution generally requires more space than a landfill solution. First, due to the footprint of the flood defences, and second, because polders require a water storage and drainage system, to drain excess water (due to rainfall or seepage). Therefore, the effective area for development inside a polder is smaller than a fill. This can be included in more detailed analyses, as well as the operation and maintenance cost of the water storage and drainage system. Another driver that may influence decision making are the higher potential flood damages behind flood defences once flood levels exceed elevation levels. Decision makers may want to prevent such hazards partly or entirely. Such risk aversion can be included in optimization models, as was shown by Slijkhuis, van Gelder, and Vrijling (2001).

Time constraints may drive decision makers to choose for costlier strategies, in order to finish a project earlier, achieve protection and/or start generating revenue. To avoid long construction times due to large settlements, a deck on piles was built in the Tanjung Priok port terminal in Jakarta, (IPC port developer, 2012). A large fill or polder may have been more economical (Lendering et al., 2015), but would have resulted in significantly longer construction times. In

addition, landfill solutions can be built in parts, up to the needs of the urban development, which is not the case for the flood defence solution. Such examples influence the revenue stream of a project and may result in different benefit/cost ratios.

One of the most significant drivers of decision making remains the budget available. In the Netherlands, almost the entire county lives in so-called dike rings, and everyone pays a “water tax,” which is used to construct and reinforce existing flood defences. In other countries, such as the UK and US, only projects with high benefit cost ratios are funded. The practical examples all assumed that there is sufficient budget to raise entire areas to optimal elevation levels, irrespective of their cost. However, budgets are often constrained, which may drive decision makers to choose other than optimal strategies that are within the boundaries of the budget.

A final driver of the choice of a strategy for flood risk reduction concerns the governmental context. Flood protection of larger areas often relies on collective efforts, necessitating the formation of water authorities and taxation. Consequence reduction by landfills or raising of structures is more easily achieved at the local level, up to the individual household.

## 4.2 | Methodological considerations

Follow-up work can focus on the proportions of dimensionless quantities, to understand how preferred solutions depend on (and vary) depending on the chosen parameter values. The sensitivity of the results to the *location* and *scale* parameters of the exponential water level distribution was not analysed. Instead, all examples were based on the distribution parameters included in Table 1, which are representative for a relatively mild exponential distribution as found in the North Sea. Steeper exponential distributions, with larger *scale* parameters (e.g., areas subject to hurricane storm surges), can be found in other areas around the world (see Xian, Yin, Lin, & Oppenheimer, 2018 for a comparison between New York and Shanghai). Larger scale parameters result in higher optimal flood probabilities and higher risk. Due to the assumed values of other parameters (e.g., marginal costs and land use values), significant changes in the exponential distribution do not affect the general conclusions drawn. Nevertheless, for local applications, more research in the statistical parameters is recommended to validate the results, possibly requiring a numerical analysis.

The mathematical model derived in this paper assumes that the marginal cost of flood defences depends on the length and height of the flood defence. More detailed analysis can also take other cost drivers in to account, such as the

total volume of soil, the outer slope protection and the type of flood defence. Furthermore, we assumed a circular polder, while in practice different shapes are found and built. While different shapes may change the analytical derivations found, we expect the impact on the principal results to be small. Another simplification was to assume that the value of  $d_{\max}$  includes all damages associated flooding: both direct and indirect damages, according to Hallegatte et al. (2013). More detailed methods break down direct damages in damages associated with land use and infrastructure and determine indirect damages based on the potential income of the area for a specific period of downtime (Steenge & Bockarjova, 2007).

Finally, loss of life was not considered. Generally, a landfill solution results in significantly smaller risk to life than a flood defence solution. Flood defence solutions may require a minimum safety level to satisfy maximum individual risk standards. Depending on the maximum individual risk standards, such analyses may require higher elevation levels than those found with economic optimization (see Jonkman, Jongejan, & Maaskant, 2011). Another, more direct method to consider loss of life, is to include the value of human lives in cost benefit analyses. For example, in comparable cost benefit analyses, the value of human lives has been estimated by the nett national product (NNP) per inhabitant (Jonkman, Van Gelder, & Vrijling, 2003; Vrijling, Van Hengel, & Houben, 1998).

## 5 | CONCLUDING REMARKS

This paper expands existing methods for optimising the total cost of flood defences and fills, by deriving largely analytical solutions for optimal elevation levels. Variations in the size of the area to be developed, its land use and corresponding value are included to model the total costs more accurately. The derived equations allow for optimization of a single strategy (i.e., a flood defence or a fill), and combination of interventions (i.e., a fill behind an existing flood defence). Using these equations, several practical examples of decision problems in flood risk management have been elaborated and implications for developing and developed countries have been discussed.

Within the context of this economic model, we conclude that a system of flood defences is generally more economical than a landfill for larger areas (above the identified transition level). Fills are preferred for specific combinations of areas and land uses, or when low flood safety levels are required. The ratio between the marginal cost of fills and flood defences largely determines the area size for which flood defences become more economical. An increase of the marginal cost of fills leads to a reduction of its application range from an economic point of view (and vice versa). Besides

economic optimization of strategies, local requirements (limited rainfall flooding or settlements) or other drivers (e.g., time or budget constraints) may influence decision makers in deciding between different strategies.

The practical examples in this paper also demonstrate that investing in a single protective layer (fills *or* flood defences) is generally more economical than combining multiple protective layers (fills *behind* flood defences). Nevertheless, combinations of interventions can be attractive for specific cases. An example of such an optimal multi-layered strategy is found when the value protected by the flood defence is low (agriculture) and the value protected by the fill is high (human lives/housing/ industry) and if the high value development is relatively small in size. The approach also provides insight in tipping points between optimal strategies and the sensitivity for the main problem characteristics.

The model concept can serve as a basis for local applications in decision support models to highlight the essential differences in cost and risk of several risk reduction strategies. The derived methods have focused on landfills but can also be applied to similar strategies such as floodproofing of structures or raising houses. As such, it is relevant for different areas subject to flood risks around the world (e.g., the Vietnam deltas or Japan coasts). Final implementation requires more detailed modelling of cost and risk, while also considering social and ecological impacts of interventions and governance. Ultimately, this work serves as a basis for strategic decision making in flood risk management.

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## CONFLICT OF INTEREST

The authors declare no potential conflict of interest.

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## SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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