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ORIGINAL ARTICLE

Framework for assessing the performance of flood adaptation innovations using a risk-based approach

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The application of risk-based approaches for the design of flood infrastructure has become increasingly common in flood management. This approach, based on risk reduction and reliability, is used to assess the performance of conventional interventions (e.g., flood defences and dams) and to support decisions regarding their implementation. However, for more innovative solutions, performance has often not been quantified by means of these metrics and, therefore, end-users are hesitant to implement them in existing flood risk reduction systems. To overcome the gap between innovators and end-users, we present a framework based on four performance indicators, to ensure the required insights in risk and reliability are provided. The four indicators: effectiveness, durability, reliability and costs, allow end-users to evaluate, select, and implement flood adaptation innovations, and provide innovators with insight into the performance of the technology and the criteria and information necessary for successful market uptake of their innovation. The practical application of the framework is demonstrated for a (hypothetical) case of a hospital complex built in an area that has subsided below the surrounding area, which is subject to tropical rain showers. The following innovations are considered: an early flood warning system, a green roof, and a temporary flood barrier.

KEYWORDS

climate change, flood mitigation, integrated flood risk management, risk analysis

1 | INTRODUCTION

Societies have shown increasing vulnerability to flood events (Bouwer, 2011). Between 1980 and 2014, flood-related damages accounted for 36% of all losses from natural disasters globally (Hoeppe, 2016). Recent climate observations suggest that the frequency and intensity of flood events are increasing resulting in larger flood hazards and less lead time prior to an event (e.g., due to increasing precipitation intensities, higher storm surges and sea level rise) (EEA, 2012; Kovats et al., 2014). Coupled with growing urbanisation in flood-prone areas—especially along coastlines and in river deltas—human exposure to floods (i.e., potential for loss of life) and flood damages are also rising (Hallegatte et al., 2013). The trend of increasing flood risk is expected to continue during the 21st century (IPCC, 2014).

To mitigate evolving flood risks, existing flood protection systems will need to be adapted and new systems designed and implemented. In addition to conventional forms of structural interventions for flood protection (e.g., flood defences and dams), innovative solutions offer the potential to reduce annual flood losses by decreasing flood risks. In other cases, innovative solutions may be critical for reducing risk in the short term while existing flood risk reduction systems are adapted or reinforced, or more comprehensive systems are built.

In flood management, the performance of structural interventions is commonly assessed based on risk reduction and reliability, and many methods and tools have already been developed and applied to do so. Examples include guidelines for the design and evaluation of levees (Ciria, 2014), dams (FEMA, 2004) and storm surge barriers (Mooyaart et al., 2014; PIANC, 2006). In countries like the Netherlands, the

United Kingdom and the United States, flood management policy is based on risk reduction, which often rely on set requirements for reliability (Schweckendiek, 2015). Here, probabilistic risk-based approaches are developed and applied to establish safety levels and assess flood risk.

In this paper, flood adaptation innovations are defined as solutions that have not been assessed in terms of risk reduction or solutions that have not yet been applied in practice. Examples include temporary flood barriers, green infrastructure and early flood warning systems. Due to limited experience with their operational performance, end-users are often hesitant to implement these innovations as key components in flood risk reduction systems instead falling back on more conventional interventions like sand bags and soil berms even though they have widely recognised limitations (Leeuw, Vis, & Jonkman, 2012; Lendering, Jonkman, & Kok, 2016; Wibowo & Ward, 2016). In addition, risk-based approaches often require information about the performance of solutions that is not typically provided by innovators. As a result, there is a knowledge gap between the information that end-users require when evaluating whether to implement an innovation and product-testing performed by innovators, hampering the widespread uptake of flood adaptation innovations.

Thus, the question of how to systematically analyse the performance of flood adaptation innovations within the risk-based framework has become increasingly important for their uptake. This paper presents a framework for evaluating the technical performance of flood adaptation innovations based on their ability to reduce flood risk. By doing so, we aim to provide practical guidance to enable end-users to evaluate, select, and implement flood adaptation innovations. The framework also provides innovators with insight into the minimum criteria that should be provided to an end-user to facilitate market uptake. The framework was developed as part of the BRIdging the GAp in Innovations for Disasters (BRIGAID) Project, funded by the European Union through the Horizon 2020 Programme. BRIG AID's aim is to develop a framework for evaluating the socio-technical performance of innovations for climate adaptation because, specifically in Europe, there is no unified strategy for evaluating the performance of these innovations (European Commission, 2015).

The paper is organised as follows: Section 2 describes the basic principles of the risk-based approach and Section 3 describes typical flood adaptation innovations and how they are integrated into flood management. Section 4 presents the framework for assessing the performance of flood adaptation innovations based on four performance indicators: effectiveness, durability, reliability and cost; and Section 5 provides a case study with three examples of innovations for which the framework is applied. Section 6 discusses the effectiveness of this approach and limitations for implementation of the framework, while Section 7 presents the findings and directions for future research.

2 | BASIC PRINCIPLES OF THE RISK-BASED APPROACH

Traditionally, flood risk management is based on a safety-oriented approach in which structural measures (e.g., levees and storm surge barriers) are built to protect to the height of a design flood (Schumann, 2017). The safety-oriented approach relies primarily on the quantification of the hazard for a given return period (i.e., the design flood) and assumes complete flood control. Because the probability of events larger than the design flood is small, the risk behind a structure is (generally) ignored (Figure 1) (Ludy & Kondolf, 2012). In this case, it would imply that events with probabilities of 1/500 (corresponding to the design level of the defence) and smaller are ignored. The safety-oriented approach is currently used as the basis for decisions regarding flood mitigation in the United States, where flood insurance is only mandatory for federally-mortgaged structures in the 100-year floodplain and areas located behind levees are removed from the floodplain maps and considered to be safe. Currently, there are calls to move towards a more risk-based approach in the United States (Jonkman & Kok, 2008; NRC, 2013; NRC, 2014).

Within a risk-based approach, interventions in flood risk reduction systems are often compared based on their potential to reduce annual flood risk. While the definition of risk varies across different disciplines (Klijn et al., 2015), herein annual risk is defined as the product of the annual probability of a hazard and its potential adverse consequences, where consequences are a function of the exposure of, for example, people, buildings, and infrastructure to the hazard and their vulnerability (i.e., engineering, economic, social, environmental vulnerability) (Cardona et al., 2012; Klijn et al., 2015; Traver, 2014). In theory, to assess the flood risks

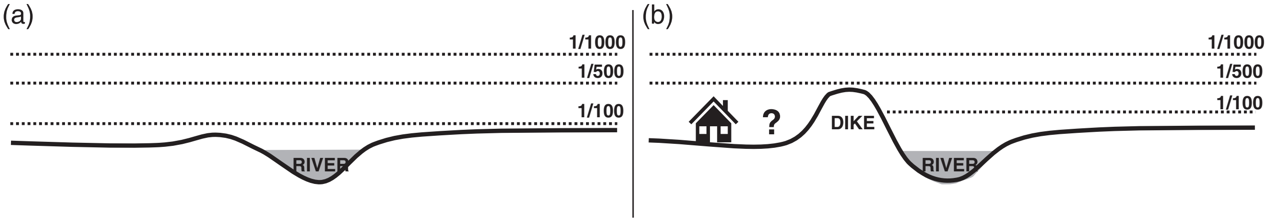

FIGURE 1 Annual probability of flooding in a river system without (a) and with (b) flood defences

associated with a risk reduction system, all scenarios that may lead to flooding (e.g., coastal, pluvial and fluvial) are considered. Following this definition, annual flood risk is found by the summation of the risks associated with each scenario (Equation 1).

$$\text{Flood Risk} = \sum_{i=1}^{n} \text{Annual probability}\,(i) \cdot \text{Consequences}\,(i). \tag{1}$$

Thus, the risk-based approach allows for cost benefit analyses of interventions, where benefits are expressed as a reduction of annual risk. As an example, the cost of building or raising flood defences can be compared and optimised against the damages avoided (i.e., annual benefits). This method was used by van Dantzig for the derivation of safety standards of flood defences in the Netherlands (van Dantzig, 1956). In this way, van Dantzig showed how the risk-based approach and the safety oriented come together: the risk based approach was used to derive safety standards, where the probability of overtopping was used as a proxy for the probability of flooding.

In the Netherlands, advanced probabilistic methods have been developed that not only take the probability of overtopping into account, but also other failure mechanisms of the flood defence (e.g., piping and instability) (Rijkswaterstaat, 2016). Using these methods, updated safety standards for flood defences have been derived based on economic damages and loss of life (Jonkman, 2007; Jonkman, Kok, & Vrijling, 2005; Kolen, 2013; Rijkswaterstaat, 2015; Slijkhuis, van Gelder, & Vrijling, 2001; Vrijling, Van Hengel, & Houben, 1998). The new methods constitute a significant advance in the field of flood risk management (Vrijling, 2001) and provide opportunities to include the effectiveness of previously neglected solutions in the reliability and risk assessment of flood defences as shown by Lendering et al. (2016).

Outside of the Netherlands, other countries have also made progress in developing methods and tools for assessing risks and reliability of flood defence systems, for example, in the UK (Hall et al., 2003), United States (USACE, 2009) and in the Shanghai region in China (Jiabi et al., 2013). Overall, it can be observed that the insights from risk and reliability analyses are now at a stage that they can be more directly applied in policy making (e.g., safety standards) and the design and management of flood defences (Schweckendiek, 2015).

3 | FLOOD ADAPTATION INNOVATIONS

Risk is constantly evolving (dependent on increasing hazard loads, urban development patterns and economic changes) requiring fast adaptation to prevent risks increasing beyond acceptable levels. Intense use of protected floodplain areas previously perceived to be completely safe can cause risk levels to grow beyond what was previously calculated, while the rising costs of floods globally have drawn attention to the potential for damages even in protected areas (Costa, 1978; Tarlock, 2012).

A flood risk reduction system aims to reduce flood risks by decreasing the probability of flooding and its consequences. A wide range of solutions are available to reduce flood risks. In practice, solutions are often categorised as part of one of three layers of risk reduction: (a) protection, (b) prevention, and (c) preparedness (Figure 2) (Kolen, Hommes, & Huijskes, 2012; Kolen & Kok, 2011). In the context of risk as defined in Equation 1, protective measures reduce the probability of flooding through structural measures (e.g., flood defences), whereas preventive and preparedness measures address the consequences of flooding through, for example, spatial planning and evacuation, emergency response, and recovery, respectively (see Table 1).

The proportional investment in each of these layers varies between countries. For example, presently, the U.S. invests primarily in preparedness (e.g., flood insurance and evacuations), whereas the Netherlands is focused on protection (Bubeck et al., 2013). In the Netherlands, the up-front investment required for protection is much higher than prevention or preparedness, but the structural measures for protection are often calculated to be more cost-effective over the long term (Lendering et al., 2016).

Because flood risk management considers the risk reduction potential of all interventions in the system, interventions aimed at reducing flood risk behind protective structures

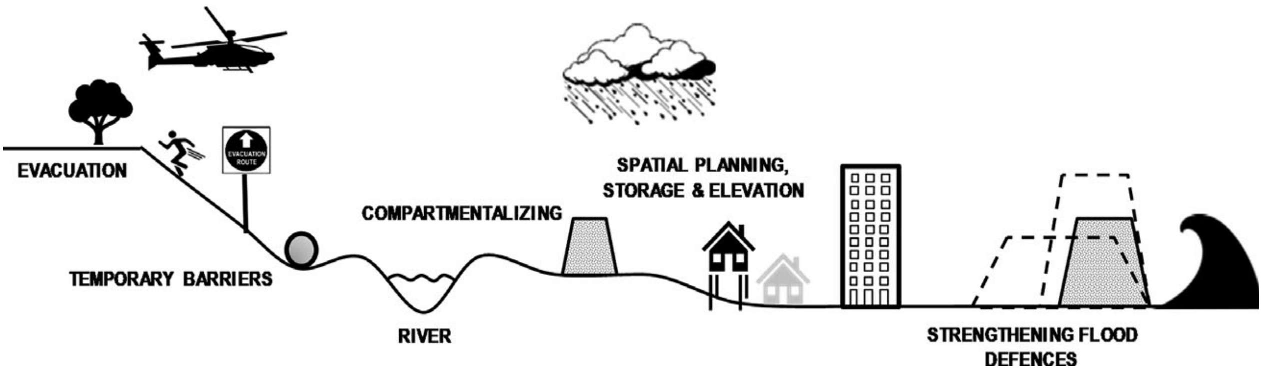

FIGURE 2 Integrated flood risk management and multi-layer safety: (1) prevention, (2) protection, and (3) preparedness

TABLE 1 Examples of solutions for reducing flood risk by layer

Layer	Examples of measures
Protection	Dams; levees; floodwalls; dikes; seawalls; flood gates; floodways and spillways; channel modifications; storm water management; on-site retention; detention; breakwaters; bulkheads; groins; revetments; nourishments;
Prevention	Spatial planning; safe land-use practices (e.g., setbacks); construction standards and building codes (e.g., vertical elevation); flood proofing; acquisition and relocation; coastal zone management; green roofs
Preparedness	Forecasting; early warning; evacuation; emergency measures; temporary flood barriers; floodplain mapping; flood insurance; disaster relief; subsidies; public awareness and education

have a marked potential for reducing flood risk at a system level. However, the implementation of innovative solutions within these layers is limited, due to the absence of and tools to evaluate the risk and reliability associated with these innovations. While advanced probabilistic methods to assess flood risk were developed and have been applied to interventions within the protective layer (and are thus straightforward for these applications), they have not been widely applied (or tested) for interventions within the preventive and/or preparedness layers (e.g., for temporary defences [Lendering et al., 2016; Wibowo & Ward, 2016]). Moreover, while end-users generally acknowledge the advantages of the advanced probabilistic methods, they remain computationally expensive (Dupuits, Schweckendiek, & Kok, 2016) and specific applications require new extensions or adjustments of the current methods (Lendering et al., 2016).

As other countries also begin to move towards utilising risk-based approaches to mitigate the economic impacts of natural hazards, there is a need for insight and research into the application of the risk-based approach to assess the performance of flood adaptation innovations. Thus, to demonstrate the application of the risk-based approach, we focus primarily on innovative solutions which are designed to be integrated in the preventive and/or preparedness layer of a flood risk reduction system. Some examples include small-scale green infrastructure (e.g., pocket parks, green roofs, and smart streets), temporary or mobile flood defences, and local flood warning or flood forecasting systems.

4 | FRAMEWORK FOR ASSESSING PERFORMANCE OF FLOOD ADAPTATION INNOVATIONS

The move towards utilising risk-based approaches to design integrated flood risk management systems requires performance-based planning of flood mitigation measures. Innovators aiming to market flood adaptation innovations are therefore required to provide the information necessary for end-users to evaluate their performance in terms of the risk reduction potential relative to existing risk reduction systems. End-users require such information before deciding whether to implement an intervention in the risk reduction system.

The framework demands "risk-informed decision-making," which must be based on aspects such as costs and benefits over the lifetime of the innovation, where benefits are expressed as damages avoided (i.e., annual risk reduction). In the cost benefit analysis, costs are balanced by obtained risk reduction from an economic point of view. Costs are determined by an innovation's investment costs (I) and its annual operation and maintenance cost. Cost effectiveness is evaluated based on a comparison of an innovation's ability to reduce flood risk (i.e., ΔR = flood risk reduction) against its cost (C) discounted over the innovations lifetime. Here, risk reduction is expressed as the present value of avoided damages (ΔEAD) discounted over the lifetime (T) of the innovation, while costs are determined by an innovations investment cost ($I_{t=0}$) and the present value of the operation and maintenance cost (O&M) discounted over the lifetime (T), taking a discount factor (r) into account.

$$\text{Cost} < \text{Risk reduction} = C < \Delta R, \tag{2}$$

where $C = I_{t=0} + \sum_{t=1}^{T} \frac{O\&M}{(1+r)^t}$ and $\Delta R = \Delta\ \text{EAD} = \sum_{t=1}^{T} \frac{\Delta\left(P_f \cdot D\right)}{(1+r)^t}$.

Several challenges have to be addressed in order to allow for risk-informed decision making. First, insight is required into the risks associated within the existing system. Second, a framework is required that allows innovators to systematically analyse the performance of the innovation within the risk-based framework. Finally, the performance of the entire risk reduction system is analysed with the flood adaptation innovation in place. To do so, testing within laboratory or operational environments is often performed to obtain data and information about the performance of the innovation, as experience with the practical performance of the innovation during a real hazard is often lacking. A framework for addressing these challenges is proposed in the following sections.

4.1 | General approach to assessing flood risk

The following section describes how flood risks are estimated based on the *probability* and *consequences* of flooding of an exposed area, more detailed guidelines can be found in Ciria (2014), Rijkswaterstaat (2016), and Schanze (2006). While there are many different mathematical tools that can be applied during the process, the general framework shown in Figure 3 applies to all types of flooding (i.e., coastal, pluvial and fluvial).

An assessment of flood risk starts with a description of the risk reduction system (if any) and its boundaries. The considered system can have different scales ranging from large river deltas and coastal areas to smaller catchments and

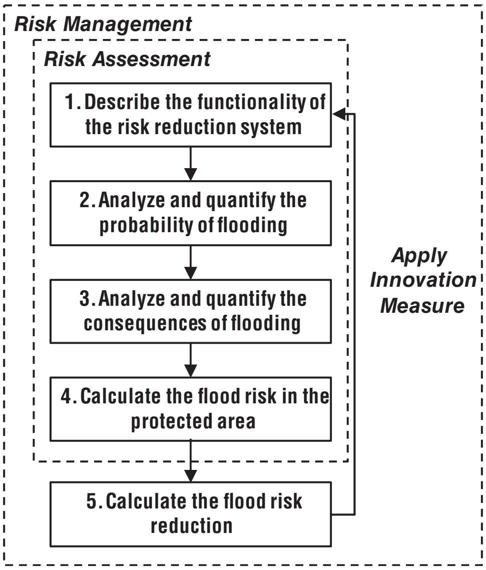

FIGURE 3 Assessment of flood risk in an existing system (Steps 1–4) and risk reduction of an innovative measure (Step 5)

watersheds, or local sites. For the entire system, all scenarios that may lead to flooding are analysed and described: extreme rainfall, rising water levels, failure of physical components of the system and/or organisational or process failures (Jonkman et al., 2015).

The system description is followed by a study of the probability of flooding, considering all scenarios that can lead to flooding and any interventions that have been applied to reduce the probability. For example, for fluvial and coastal flooding, the probability of flooding is determined by the probability of exceedance of a given water level in the river or sea. If flood defences were built, the probability of flood defence failure needs to be taken into account (e.g., due to overflowing or structural failure) (Jonkman et al., 2017). For pluvial flooding, the probability of flooding is calculated based on the probability of a given water level occurring driven by a rainfall event of a certain intensity, duration, and frequency. Similarly, any interventions (e.g., increasing drainage capacity) that increase the capacity of the system to handle pluvial flooding or reduce flood impacts need to be considered when calculating the probability of flooding.

The consequences of flooding are assessed by simulating inundation levels and quantifying the potential consequences in monetary terms, considering both direct (material) damages and indirect (economic) losses. The risk is then quantified by multiplying the probability of flooding of all scenarios with their potential consequences and summing the risk associated with every scenario. An evaluation of acceptable levels of risk often considers three criteria: risk to individuals, society and the economy (Vrijling et al., 1998; Vrijling, Van Hengel, & Houben, 1995). According to Vrijling et al., decisions regarding acceptable levels of risk should be based on the most stringent of the three criteria (Vrijling et al., 1998).

Flood adaptation innovations are applied if risks are deemed too high. After application, the risk and reliability associated with the specific scenario are reassessed with the innovation in place. This cyclic process is followed until end-users find the risk to be reduced sufficiently. Part of this process may be to make changes to the considered innovation to increase its effectiveness. Such changes could consider the implementation or operation process, the technical design or operation and maintenance protocols. Ultimately, innovators will continue this cyclic process until the end-user conditions are met.

4.2 | Performance indicators

To provide the necessary information to support risk-informed decision making, four performance indicators (PI) are used: effectiveness, durability, reliability, and cost (Table 2). In developing these PIs, different frameworks for evaluating the performance of different types of innovations were reviewed, including temporary flood barriers (Lendering et al., 2016; Margreth & Romang, 2010; Wibowo & Ward, 2016) and early flood warning systems (Sättele, Bründl, & Straub, 2015; Sättele, Bründl, & Straub, 2016). While recognising that tests and results for individual innovations may vary, the PIs are generally applicable and relevant for all flood adaptation innovations. Note that the here proposed methods serve as an example; other methods can be used (and could be more effective) when analysing the performance of different types of innovations, so long as the required insights of each indicator are provided.

4.2.1 | Effectiveness

Effectiveness is a metric used to evaluate the intended capacity of the innovation to reduce flood risk either by reducing the probability of flooding of the exposed area or by reducing the potential consequences of flooding (Equation 1). For example, a temporary flood barrier provides protection for water levels up to its height, thereby increasing the design

TABLE 2 Description of performance indicators used to analyse the effectiveness of flood adaptation innovations within the risk based framework and their corresponding parameters in equation 2

Indicators	Definition	Parameter
Effectiveness	A metric that describes the intended capacity of the innovation to reduce flood risk, either by reducing the probability (P_f) or consequences (D) of flooding in the exposed area.	ΔP_f or ΔD
Durability	A metric that encompasses the temporary- or permanent-nature of the innovation and its operational lifetime (T) and provides insight in its flexibility of use.	T
Reliability	A metric that describes the likelihood that an innovation fulfils its intended functionality during its intended lifetime ($P_{f;\mathrm{innovation}}$).	$P_{f;\mathrm{innovation}}$
Cost	A metric that describes the costs (C) associated with the purchase, installation and operation (and maintenance) of the innovation over its lifetime.	C

water level and reducing the flood probability. A green roof prevents large run-off flows by providing temporary storage capacity during heavy rainfall, which also reduces the flood probability. In comparison, an early flood warning system provides more lead time in anticipation of a flood to allow for more effective preparation (e.g., evacuation or flood fighting), which reduces the flood consequences.

The approach described here to quantify the effectiveness requires innovators and end-users to describe/ analyse how the innovation interacts with the existing flood risk reduction system and assess the resulting risk reduction in terms of a reduction of the probability (ΔP_f) or consequences of flooding (ΔD). For example, considering a temporary flood barrier used to temporarily heighten levees during a river flood. The obtained reduction of the probability of failure can be assessed using fragility curves for failure of the considered levee, which illustrate the conditional failure probability on the loads exhibited on the innovation, as shown in Figure 4.

The here described approach to determine effectiveness assumes successful implementation of the innovation, but foregoes the probability of failure of implementation of the innovation itself. Innovations may fail due to failure of installation, operation or technical failure. These aspects, as well as the innovation's durability, are taken into account within the durability and reliability indicators.

4.2.2 | Durability

Durability is a metric that encompasses the lifetime of an innovation and describes the temporary- or permanent-nature of the operation of the innovation. It takes into consideration how durable the structural components of the innovation are and whether the innovation is designed for single or repetitive use. Innovations designed for repetitive use may be operated permanently (i.e., continuously) or temporarily (i.e., only during the flood hazard). Assessing the durability of the innovation requires estimating the (percentage of) components that require repair or replacement after each operation of the innovation (if designed for repetitive use).

Together, these aspects provide insight in the lifetime of the innovation—determined by either the lifetime of its structural components or the innovation's climate lifetime—and the long-term operation and maintenance requirements to meet that lifetime. Here, an innovation's climate lifetime is the time at which its performance (i.e., its intended capacity to reduce flood risk) is exceeded by climate change impacts. For example, the climate lifetime of a temporary flood barrier is exceeded when the barrier's height has been exceeded by increased water levels (e.g., due to sea level rise Figure 5).

The ability for repetitive use of an innovation provides a certain flexibility in the application of innovations. For example, innovations that are temporary (and deployable) in nature and can be removed after an event or used at multiple locations are much more flexible than conventional permanent measures. An additional benefit of this flexibility is that such innovations can be adaptable to different loading conditions (e.g., increased loads due to climate change) over their lifetime.

4.2.3 | Reliability

Reliability is a metric that estimates the likelihood that an innovation fulfils its intended effectiveness during its intended lifetime. By definition, reliability is the probability of successful operation, which can also be expressed as the complement of the probability of failure during operation (i.e., *reliability = 1—probability of failure during operation*). Here, failure is described as the inability of the innovation to fulfil its intended function. For example, the reliability of a temporary flood barrier is evaluated by determining the probability that the barrier fails due to failure of mobilisation, placement, or failure to retain water levels up to its design height. Similarly, the reliability of an early flood warning system is evaluated by determining the probability that the system (or its components) is unavailable or that the system fails to predict flooding (Sättele et al., 2015).

To analyse failure modes, all (known) undesired events that may cause failure of the innovation should be identified.

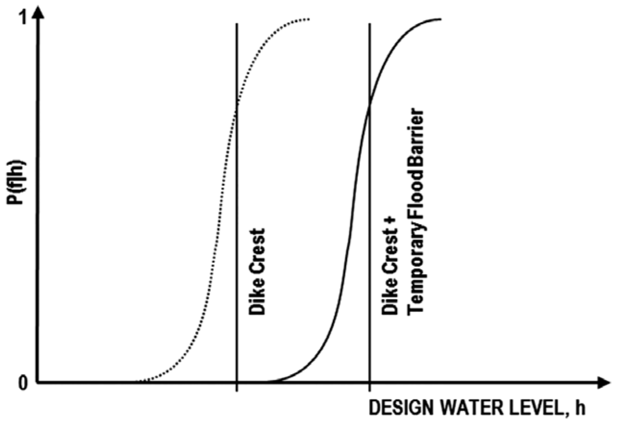

FIGURE 4 Using fragility curves to demonstrate the potential effectiveness of temporary flood barriers used to increase a dike crest

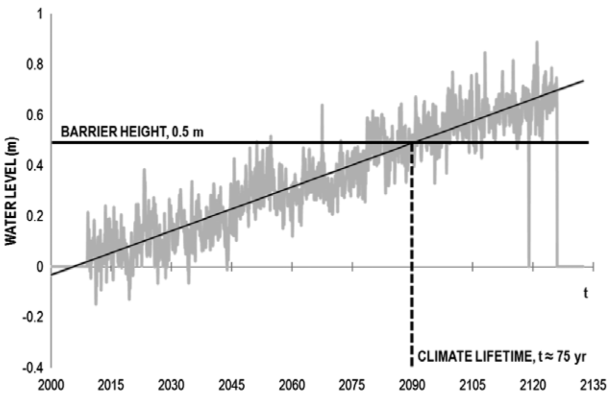

FIGURE 5 Climate lifetime (t_0 = 2015) of a 0.5 m barrier determined by water levels rising at an average rate of 6 mm/year

Distinction is made between two main failure modes: implementation failure and technical failure (Figure 6). Implementation failure only applies to innovations that are operated temporarily and is defined as failure to implement the innovation before operation (e.g., due to logistical failure (Leeuw et al., 2012) or operator error (De Corn & Inkabi, 2013)), whereas technical failure is defined as failure of the innovation to fulfil its intended function during operation (e.g., due to structural component failures). Typical methods used to analyse and understand how implementation and technical failure of innovations may interact include failure mode and effect analyses or failure mode effect and criticality analyses (Ciria, 2014).

Probabilistic methods are used to quantify an innovation's reliability. The failure probability of systems that rely on human actions (i.e., operators) is often dominated by the probability of operator errors, which is estimated using Human Reliability Analyses (Bea, 1998; Rasmussen, 1983). These analyses typically seek only order of magnitudes of probabilities of failure. Lendering et al. (2016) developed a method for assessing the probability of human errors during implementation of emergency measures for flood prevention, which can also be used for flood adaptation innovations. In addition, methods were developed to assess the probability of logistical failure, taking into account the available time for implementation. Finally, the probability of technical failure modes, such as component, hardware, software or structural failure, can be estimated for every technical failure mode using probabilistic methods such as Monte Carlo Simulations or First Order Reliability Methods (Jonkman et al., 2015). For warning and operation systems, software and organisational reliability become a part of the overall assessment (Bea, 1998). For these analyses, innovators are required to describe and analyse their innovation and provide data that can be used to estimate probabilities of failure.

4.2.4 | Cost

Costs are determined by the investment cost ($I_{t=0}$) and the operation and maintenance costs ($O\&M$) over the innovation's lifetime (T). The investment costs depend on the costs of the material components and the initial installation costs of the innovation, while the operation and maintenance costs depend on the innovation's durability: whether the innovation is operated continuously or temporarily (and how often); whether the innovation require repairs after each use (and how much); and its intended technical or climate lifetime. Note that for an innovation designed for temporary use, the annual operation and maintenance cost are determined by the number of times the innovation is used per year multiplied by the associated cost. The following equation determines the present value of the cost of the innovation over its lifetime, considering a discount factor (r):

$$C = I_{t=0} + \sum_{t=1}^{T} \frac{O\&M}{1+r^t}. \tag{3}$$

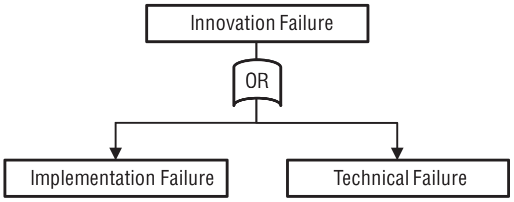

FIGURE 6 Example fault tree including implementation and technical failure

4.3 | Performance assessment

The obtained risk reduction (ΔR) with the innovations in place is measured relative to the existing flood risk reduction system (including any measures that are already in place). It is measured as a function of the overall risk of the considered scenario without the innovation in place. Depending on how the innovation reduces risk (i.e., by reducing the probability or consequences of flooding), its effect is included in the assessment of probability or in the consequences of flooding of that specific scenario. For innovations that focus on reducing flood probabilities (i.e., prevention), the obtained risk reduction is calculated as follows:

$$\Delta R = \sum_{t=1}^{T} \frac{(Pf;old - Pf;new) \cdot D}{1+r^t}, \tag{4}$$

where $P_{\mathrm{f;new}}$ represents the new probability of flooding with the innovation in place and $P_{\mathrm{f;old}}$ represents the probability of flooding without the innovation in place.

The probability of flooding with the innovation in place is calculated using the total law of probability, taking into account both the effectiveness and reliability of the innovation. The probability of flooding with the innovation in place considers two scenarios: successful operation of the innovation and failure of the innovation:

$$P_{\mathrm{f;new}} = P_{\mathrm{f;innovation}} \cdot P_{\mathrm{f;old}} + \left(1 - P_{\mathrm{f;innovation}}\right) \cdot \left(P_{\mathrm{f;old}} - \Delta P_f\right). \tag{5}$$

For innovations that are designed to reduce the consequences of flooding, risk reduction is calculated as follows:

$$\Delta R = \sum_{t=1}^{T} \frac{Pf \cdot (Dold - Dnew)}{1+r^t}, \tag{6}$$

where D_{new} represents the potential damages of flooding with the innovation in place and D_{old} represents the potential damages of flooding without the innovation in place.

The potential damage of flooding with the innovation in place is estimated considering both successful operation of the innovation as well as the likelihood of innovation failure:

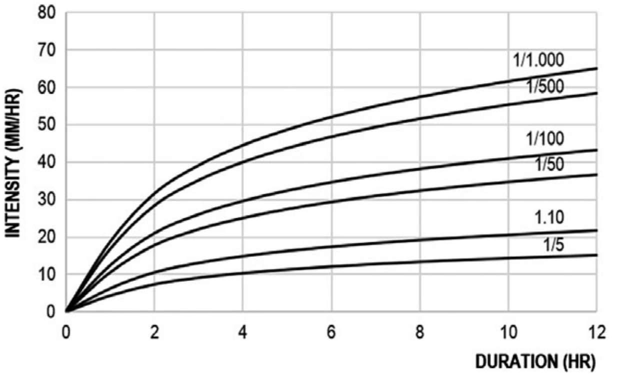

FIGURE 7 Intensity-duration-frequency curves for fictional case study of a large hospital complex

$$D_{\text{new}} = P_{\text{f};\text{innovation}}\, D_{old} + \left(1 - P_{\text{f};\text{innovation}}\right) \cdot \left(D_{old} - \Delta D\right). \quad (7)$$

By comparing the resulting risk reduction to the costs associated with the innovation, end-users are able to evaluate the costs and benefits of the innovation over the intended lifetime (T). Innovations are cost effective when their cost is lower than the present value of the expected damages over the considered lifetime (Equation 2).

5 | APPLICATION IN PRACTICAL SITUATIONS

To demonstrate the application of the proposed framework in practical situations, the framework was applied within a given, fictional, and case study. We consider a large hospital complex built in an area of about 0.24 km^2 which has subsided approximately 2 m below the surrounding area. The hospital facilities cover about 75% of the total area and the total value of the hospital complex is estimated to be €1 billion. The area is subject to tropical rain showers which can result in flash flooding due to insufficient drainage capacity in the surrounding area. Statistical analysis of rainfall intensities resulted in the intensity-duration-frequency curves shown in Figure 7.

Using the intensity-duration-frequency curves for rainfall, return period water levels were estimated for the area, as shown in Figure 8a. We assume that the system is closed, and that negligible infiltration is occurring. Figure 8b shows estimated material damages dependent on the depth of flooding and expressed as a fraction of the total value. The annual risk of flooding is found by integrating the damages associated with different return periods and summing (Equation 1), resulting in a value of €22 million.

To reduce flood risk to the hospital complex, several flood adaptation innovations are considered consecutively: a flood warning and operation system to increase lead time and management of flood risks, green roofs to delay runoff and reduce pluvial flooding, and temporary flood barriers to protect hospital entrances.

5.1 | Flood warning and operation system

Currently, no flood warning systems are implemented in the area. Pluvial flooding may occur unexpectedly, leaving little time for any mitigative measures to be put in place. The hospital is considering implementing an early flood warning system (FWS) that provides a lead time of 4 hours for pluvial floods. An example of such a solution was implemented at the Texas Medical Center (Fang et al., 2014). The lead time provided by the FWS allows the hospital to close existing submarine doors to the parking garage under the hospital and prevent critical facilities from flooding. During previous flood events, little to no warning and lack of protocol resulted in the submarine doors being left open, rendering them ineffective for reducing flood losses. A description of obtained results for each performance indicator is included in Table 3.

The annual obtained risk reduction is calculated using Equations 4 and 7 and amounts to € 220,000. The present value of avoided damages due to implementation of the early flood warning system amounts to €1 million considering a discount factor of 2.5% and a lifetime of 5 years. The innovation's cost, determined by the investment cost (€500,000) and annual operation and maintenance cost (€50,000), are €732,000. These are lower than the benefit (€1 million); thus, the innovation is cost effective, with a benefit/cost ratio of approximately 1.4.

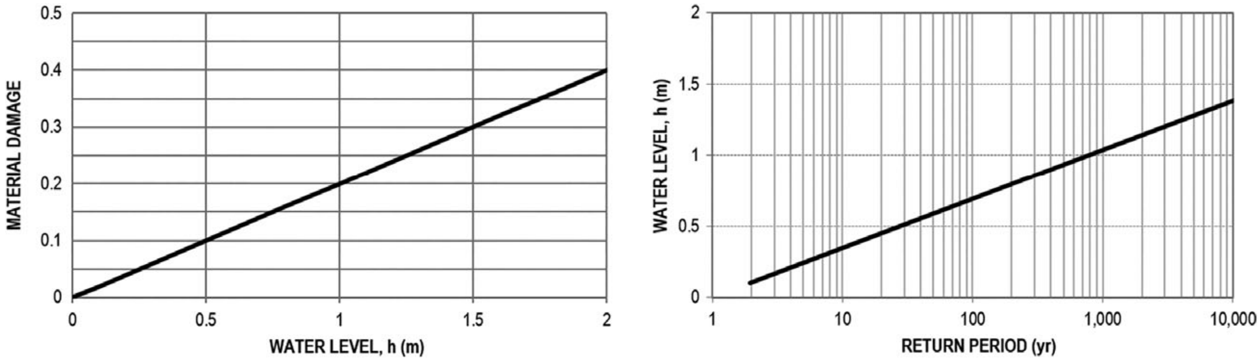

FIGURE 8 Return period of water levels (left) and flood damage estimates (right) expressed as a fraction of the total value of the hospital complex

TABLE 3 Assessment of the flood warning system (FWS) in terms of each performance indicator

Indicator	Description	Variable	Value
Effectiveness	The effectiveness of the FWS is defined by its ability to allow for mitigative action in anticipation of a pluvial flood: In this case closing the submarine doors to protect critical facilities. Total potential damage avoided (ΔD) to the hospital complex is €10 million.	ΔD	€10 million
Durability	The FWS is operated continuously and has a technical lifetime of 5 years, after which it should be replaced or upgraded using state-of-the-art data and models. Operation of the early flood warning system does not require significant maintenance during its estimated lifetime.	t	5 years
Reliability	The system is operated continuously and has a predictive capacity of 99%. This means that it fails to predict flooding during 1% of the time.	$P_{\text{f;innovation}}$	0.01
Costs	The investment cost of the system amount to € 500,000. The operation and maintenance cost during its lifetime are estimated at 10% of investment cost, which amounts to €50,000 per year. The present value of the total cost is €732,000.	C	€ 732,000

5.2 | Green roof

In the baseline scenario, the construction of the hospital has resulted in a reduction of pervious surfaces by upwards of 50%. Response to precipitation is nearly instantaneous, resulting in pluvial flooding. To reduce flood risk, the emergency manager is considering installing innovative green roofs on many of the hospital facilities to retain water temporarily during rainfall events, thereby reducing the total volume of runoff into the area. We assume that the green roof is constructed using peat soils and calculate the rate of infiltration based on Horton and the associated parameters provided in Maidment (1993). Considering that the hospital facilities cover almost 50% of the area, and green roofs can be placed on 67% of the hospital complex (Figure 9), the green roof is able to capture the 5- and 10-year precipitation events and portions of the larger events (Figure 10a). This results in a substantial reduction in flood levels water levels at the hospital facility (Figure 10b). A description of obtained results for each performance indicator is included in Table 4.

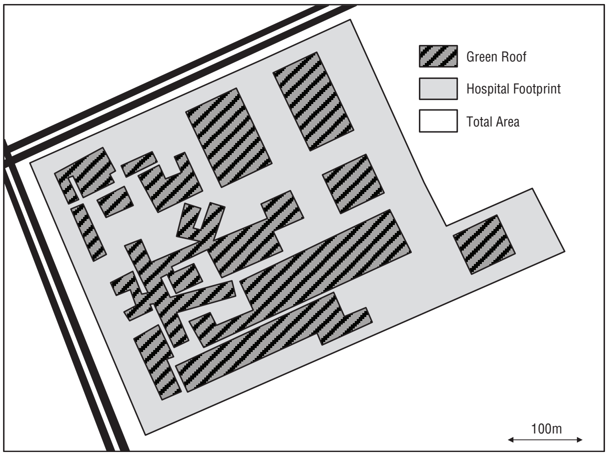

FIGURE 9 Area inside covered by the hospital, illustrating the area covered by green roofs

The annual obtained risk reduction is calculated using Equations 4 and 7 and amounts to € 10 million. The present value of avoided damages due to installation of the green roofs amounts to €89 million, considering a discount factor of 2.5% and a lifetime of 10 years. The innovations cost (€23.5 million) are lower than its benefits (€89 million), thus, the innovation is cost effective with a benefit/cost ratio of 3.8. Its effectiveness can be further increased by increasing its storage capacity or reducing its investment and/or operational cost.

5.3 | Temporary flood barrier

Temporary flood barriers can be applied to close the hospital entrance and prevent it from flooding. The conventional method for preventing flooding through the entrance is to use sand bags. However, the installation of sand bags is labour intensive, time consuming and sand bags are difficult to remove. In contrast, temporary flood barriers can be installed quickly prior to—and removed entirely after—an event. We consider water-filled tubes. The tubes provide protection up to their design height, typically 0.5 m (see Figure 12), and obtain stability through the weight of water that flows inside the tube. An analysis of every indicator is included in Table 5.

To assess the probability of failure of the barrier, both implementation and technical failure are considered. Implementation failure may occur due to operator error or logistical failure (i.e., failure to transport the innovation to the required location), with operator error being the dominant failure mode. Technical failure can occur due to instability of the tube (e.g., due to sliding or turning over), ruptures of the canvas material, or seepage/leakage under the tube. Figure 13 illustrates a fault tree for the barrier. It is noted that this is a series system with OR gates, so all elements need to be sufficiently reliable to ensure adequate overall performance of the system.

The annual obtained risk reduction is calculated using Equations 4 and 7 and amounts to €18 million. The present value of avoided damages due to operation of the temporary flood barriers amounts to €310 million, considering a discount factor of 2.5% and a lifetime of 20 years. The innovation's cost (€25.6 million) is lower than its benefits (€310 million), with a benefit/cost ratio of 12.

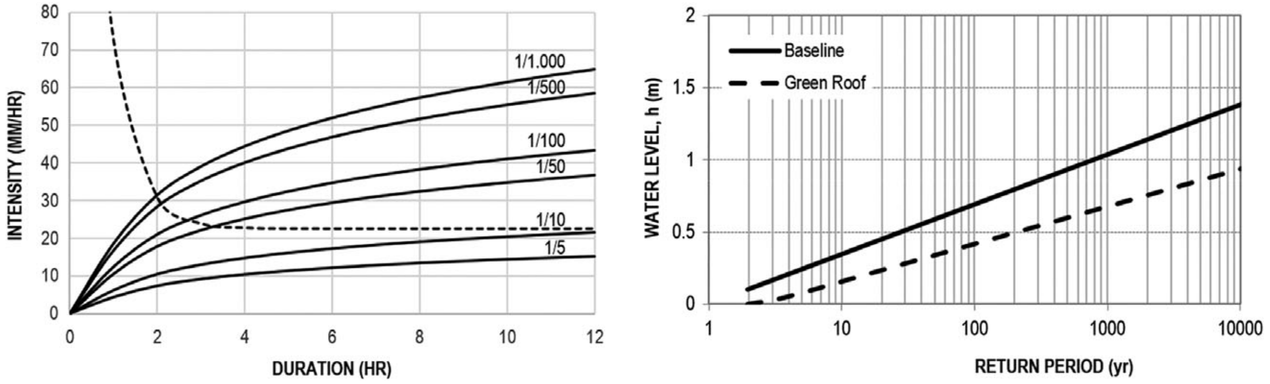

FIGURE 10 Intensity-duration-frequency curves for fictional case study illustrating the rate of infiltration achieved by the green roof (dotted line, left figure) and the resulting return period water level curves after installation of the green roof (right)

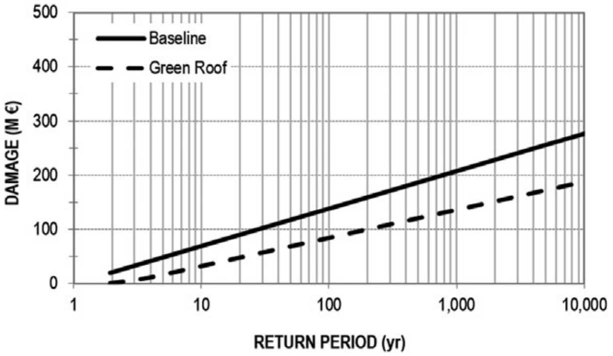

FIGURE 11 Resulting damage return period curves after installation of the green roof

TABLE 4 Assessment of the early warning system in terms of each performance indicator

Indicator	Description	Variable	Value
Effectiveness	The effectiveness of the green roof system is defined by its ability to reduce flood water levels by 0.2–0.5 m for return periods ranging from 1/10 to 1/10.000, respectively. This translates to reduced damages (€ 25 to 50 million) for these return periods as shown in Figure 11.	ΔD	€ 25 to 50 million
Durability	The green roof system is operated continuously and has a technical lifetime of 10 years, after which it should be replaced or upgraded. Operation of the system requires annual maintenance of the release system.	t	10 years
Reliability	The system is operated continuously. Its probability of failure is determined by the likelihood of the green roof being fully saturated (i.e., not releasing stored water in time before succeeding rainfall events). Based on an analysis of the frequency of extreme rainfall events, the annual probability of failure is estimated to be 10%.	$P_{\mathrm{f;innovation}}$	0.10
Costs	The investment cost of the system amount to €22.5 million, based on a unit cost of €250/m^2 and a total area of 90,000 m^2. The annual costs of operation and maintenance are estimated at 0.5% of the investment cost: €112,500 per year. Together, the present value of the cost amounts	C	€23.5 million

6 | DISCUSSION

Of the three considered innovations in the fictional case study, temporary flood barriers are found to be the most cost effective suggesting that when trying to immediately reduce risks, these should be implemented first. These results should be considered in light of the considered case study and its characteristics. Areas subject to different flood hazards, such as, coastal or fluvial flooding, may give different results.

The case study examples demonstrate the necessity of clusters or combinations of innovations because a single innovation is not always able to reduce flood risk. For example, a flood warning system on its own cannot reduce structural damage to the hospital, but, when used in combination with submarine doors or temporary flood barriers, a flood warning system has the potential to achieve a higher cost–benefit ratio than the other alternatives applied alone. Ultimately, the performance of flood adaptation innovations should not be evaluated in isolation, but always considering the existing risk reduction system.

In the case study we applied the innovations successively. For example, in considering the performance of the temporary flood barrier, we assumed that a flood warning system is in place and that its reliability is captured within the failure mode "insufficient time" (Figure 12). In reality, the successful operation of temporary flood barriers relies on the accuracy and lead-time provided by a flood warning system and if no system were installed, the probability of insufficient time will likely be one and the temporary flood barrier rendered ineffective. In many cases, combinations of measures reduce the probability of failures in the system by increasing redundancy. For example, mobile or temporary measures, while

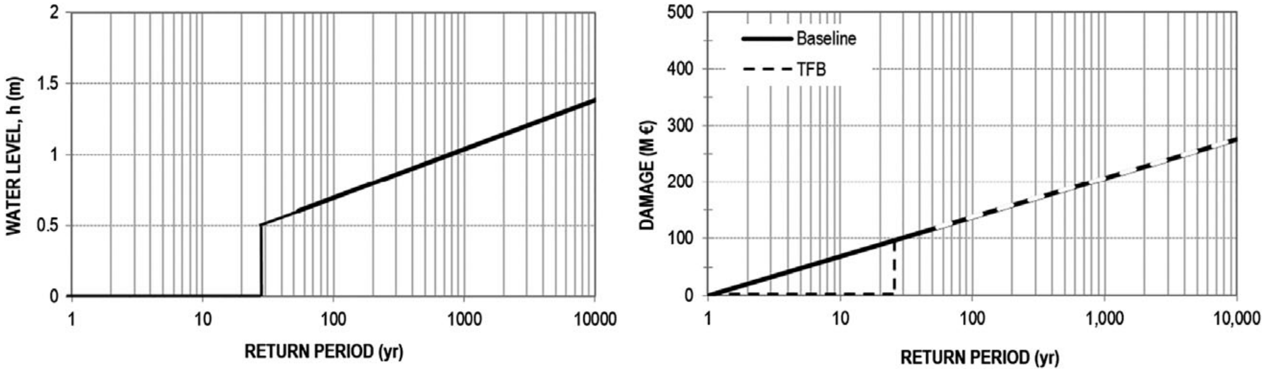

FIGURE 12 Return periods of flood levels with temporary flood barrier in place (left) and damage estimates for a situation with temporary flood barriers (dotted line) compared to the baseline situation. The return periods correspond with flood water levels

inexpensive, often have a high probability of failure unless they are applied tandem with a warning system. In contrast, other innovative alternatives, like the green roof, have a low-failure probability, but high-initial investment cost.

TABLE 5 Assessment of the water-filled tube barrier in terms of each performance indicator

Indicator	Description	Variable	Value
Effectiveness	The effectiveness of the temporary flood barrier is defined by its ability to provide protection up to 0.5 m, which corresponds to protection until the ~1/20 year event (Figure 11).	ΔPf	1/20
Durability	The temporary flood barrier consists of plastic canvas material which has an expected technical lifetime of 20 years. It is estimated that after each use minor repairs (<10%) to the tubes are required; such repairs could include patching a rip in the canvas material or replacing anchors.	t	20 years
Reliability	The operator error is estimated to be 1/50 per task according to the approach developed by Lendering et al. (2016) to assess the reliability of emergency measures for flood prevention, assuming the operator operates at a rule-based level (details are provided in the Appendix S1, Supporting Information). Sliding failure (1/50 per use) will be governing considering the smooth surface of the entrance tiled floor. Assuming that the implementation and technical failures are independent, the probability of failure of both failure modes can be summed. The resulting probability of failure is 1/25 per use. Assuming the barriers are applied for every 1-year event, this results in an annual failure probability of 0.04 (or 1/25).	$P_{f;\text{innovation}}$	0.04
Costs	The investment cost of the system amounts to €10 million. The annual operation and maintenance cost amount to 10% of the investment cost. Over its lifetime, the total cost of the barrier amounts to €25.6 million.	C	€25.6 million

It is important to note that the application and evaluation of combinations of measures within the risk-based framework becomes increasingly complex dependent on number of interventions and the interdependence between the probability of success for any one intervention. An analysis of the entire risk reduction system would be required to accurately assess the performance of combinations of measures. These assessments require detailed information about the hazards and the performance every innovation. Decision support tools that allow end-users to quickly evaluate different options can aid in these assessments (Zanuttigh et al., 2014), and a common set of performance indicators greatly reduces the complexity of the analysis.

Each performance indicator provides a necessary piece of information required to perform the described economic evaluation, as proposed in this paper. A practical guideline is given for this economic evaluation, depending on whether an innovation aims to reduce the probability (Equation 5) or consequences (Equation 6) of flooding of a specific area. The practical examples have shown how each indicator is quantified and serve as an example of the use of the framework. However, the examples do not cover all types of analyses or tools that are available to quantify each indicator. It remains the innovators responsibility to determine which methods and tools should be used for this purpose.

The performance assessment used in this example assumes a discrete situation where the probability of failure, which is included as part of the Reliability indicator, does not depend on the load level (or flow velocity) and the level of damage is constant. In more detailed assessments, this dependency should be considered. In addition, due to the low frequency of extreme events, experience with the actual behaviour of flood adaptation innovations is often lacking, resulting in uncertainties about their effectiveness and reliability. To address this issue, we encourage performing tests in laboratory and operational environments. Practical tests will help to reduce uncertainties, optimise the design, increase the reliability, while also providing insight in to ways an innovation interacts with an existing risk reduction

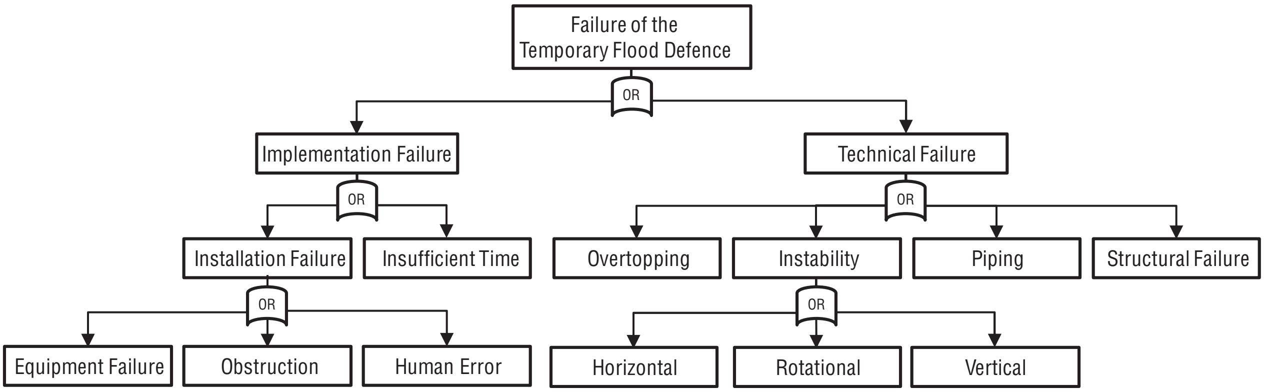

FIGURE 13 Example fault tree for a temporary flood barrier (TFB)

system. Examples are tests of temporary flood defences in a test basin, or pilots with green roofs in cities.

Besides an economic analysis, the evaluation of flood risk reduction strategies, may also need to consider other impacts that cannot be easily translated into monetary terms, for example, an innovation's impact on ecology, nature or its societal impact. These impacts may be positive (e.g., building with nature interventions) or negative (e.g., loss of spatial views due to raising of flood defences) depending on the reference situation. End-users might also set additional conditions to innovative measures, such as limitations to the probability of operator error, logistical failure or an intended lifetime. Often, these criteria are difficult to assess in a laboratory environment, making it difficult to break into a new market or convince end-users that a technology is proven. Therefore, assessing the technical performance of innovations should be part of a broader assessment that also considers other impacts and end-user conditions.

Finally, the framework presented herein assumes that innovations are only evaluated based on their costs and benefits (i.e., risk reduction) from an economic point of view. While these economic analyses generally show that preventative structures (e.g., levees and barriers) are more cost-effective over the long term, flood adaptation innovations can provide an interim solution over the short term. Moreover, flood adaptation innovations can also be applied as secondary and tertiary measures aimed to further reduce risk for specific infrastructure (e.g., hospitals, railways or highways) and/or loss of life.

7 | CONCLUDING REMARKS

In this paper, we developed a framework that enables end-users to evaluate and compare the performance of flood adaptation innovations through a common set of performance indicators. This framework aims to overcome the existing knowledge gap between the information that end-users require when evaluating whether to implement an innovative solution in a given system and the product-testing performed by innovators. To overcome this gap, we proposed a framework that can be used to evaluate any innovations' performance through a common set of indicators: effectiveness, durability, reliability and costs. These indicators allow for a calculation of cost and benefit over an innovations' lifetime, with the benefits expressed as the avoided flood damages. Ultimately, this allows end-users to compare innovations based on their benefit/cost ratio within a given implementation context.

Three examples were used to demonstrate how the framework can be used to obtain initial estimates the performance of every indicator, providing insight into an innovation's risk reduction and reliability, and allowing end-users to compare and choose between different innovations. This illustrates how different categories of flood adaptation innovations can be assessed using a standardised framework. While limited to flood adaptations in this paper, the framework can be easily adjusted to be used to assess innovations intended to reduce risks associated with other climate related hazards such as extreme weather, droughts and wildfires.

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AUTHOR CONTRIBUTIONS

K.L. and A.S. conceived and designed the study, prepared and analysed the results, and drafted a first version of the manuscript. S.N.J. and M.K. helped to design the study and write the paper. All authors revised the manuscript and gave final approval for publication.

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SUPPORTING INFORMATION

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

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