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Robust, multifunctional flood defenses in the Dutch rural riverine area

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Abstract. This paper reviews the possible functions as well as strengths, weaknesses, opportunities, and threats for robust flood defenses in the rural riverine areas of the Netherlands on the basis of the recent literature and case studies at five locations in the Netherlands where dike reinforcement is planned. For each of the case studies semi-structured interviews with experts and stakeholders were conducted. At each of the five locations, suitable robust flood defenses could be identified that would contribute to the envisaged functions and ambitions for the respective areas. Primary strengths of a robust, multifunctional dike in comparison to a traditional dike appeared to be the more efficient space use due to the combination of different functions, a longer-term focus and greater safety.

1 Introduction

1.1 History of flood defenses in the Netherlands

The Netherlands, situated in the delta region of the Rhine, Meuse, Scheldt, and Ems rivers, has a long history of adapting to its deltaic environment. The first inhabitants settled on natural heights, but the protection against flooding by building earth constructions started already more than 2000 years ago with the creation of artificial mounds in the Wadden Sea region (Cools, 1948). Starting in the Middle Ages, these mounds were progressively connected by dikes, leading to the formation of dike rings protecting the hinterland. In the Dutch riverine areas, construction of raised areas was also initiated some 2000 years ago (by the Romans), mainly for transportation purposes along the Rhine River (Cools, 1948). Like in the coastal area, the process of raising riverine dikes started in the Middle Ages.

1.2 Flood defense system

Initially, everyone protected their own lands, but in the late Middle Ages a collective system of agreements on the building and management of dikes began to emerge. Nevertheless, flooding disasters still occurred on a regular basis due to deferred maintenance or because the dikes were not designed for extreme discharges. After a flood, the dikes were typically raised to withstand the most recent high water level (Technische Adviescommissie voor de Waterkeringen, 1998).

Today, the Dutch have a well-developed flood protection system based on so-called dike rings. By law, these dike rings should protect the encircled hinterland against river floods and storm surges of a severity that could be statistically expected with a frequency of once in 1250 years up to once in 10 000 years, depending on the region and the related values at risk (see Table 1, "Prescribed extreme water levels"). Design requirements are exactly defined in legislation that prescribes amongst other things regular assessment and management. Furthermore, there is ongoing research aimed at increasing understanding of possible failure mechanisms of flood defenses and gaining insight into developments in physical and hydrodynamic boundary conditions, while also monitoring demographic trends and economic values in the hinterland.

To account for changes in conditions and in the protected values during the expected life-time of a flood defense, current Dutch flood protection policy mandates robust design of dike reinforcements (Rijkswaterstaat, 2007; see Table 1, "Traditional dike").

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Table 1. Explanation of dike concepts and related terminology in the Netherlands; the relation between the various concepts is shown in Fig. 1.

Traditional dike	Can withstand statistically prescribed extreme water levels, wave heights and wave overtopping. However, Rijkswaterstaat applies a design that anticipates unforeseen changes and uncertainties with respect to subsidence and climate change over the planning horizon (50 years and 100 years for a dike in built-up areas), and reserves a zone to allow for dike reinforcements in the future (Rijkswaterstaat, 2007). This is called a "robust design" as the dike is designed to be slightly over-dimensioned according to the actual assessment standards at the time of construction.
Prescribed extreme water levels	The Dutch water law provides a safety level in terms of expected flooding frequency. Varies from once in 1250 years (0.08 % annual probability) in the riverine area to once in 10 000 years (0.01 % annual probability) in the province of North Holland.
Over-dimensioned dike	Can withstand more extreme situations (water level and wave heights as well as wave overtopping) than prescribed.
Delta dike	Has practically zero probability of failure due to sudden or uncontrollable failure (Deltacommissie, 2008). Enhanced safety can be achieved by inner constructions (such as sheets and walls) or heightening of the dike; however, increased strength is realized more effectively by enlarging of the inner berm (e.g., Knoeff and Ellen, 2011; Klijn and Bos, 2010).
Unbreachable dike (synonyms: broad dike, by Vellinga, 2008; climate proof dike, by Hartog et al., 2009)	Has 100 times smaller probability of failure due to erosion by overflowing, piping, or macro-instability on the landward side than traditional dikes, due to its increased width (Silva and van Velzen, 2008). However, the unbreachable dike does not exclude overflow or wave overtopping that may lead to damage.
Robust dike	Remains functioning without failure under a wide range of conditions, does not collapse during overtopping and reduces a flood disaster to a shallow flooding event. The concept of a robust dike includes the unbreachable dike and delta dike as subsets.
Robustness	The ability of a system to remain functioning under disturbances, where the magnitude of the disturbance is variable and uncertain (e.g., De Bruijn et al., 2008; Hall and Solomatine, 2008; Haasnoot, 2011; Mens et al., 2011).
Multifunctional dike	Combines other functions with the primary flood protection function. In practice, incorporation of multiple functions requires over-dimensioning and may thereby help to create a robust dike. The complement of a "multifunctional dike" is a "monofunctional dike", which only considers the flood protection function.
Complementary functions, secondary functions	Functions that a dike can fulfill in addition to its primary flood-defense function, such as transport, housing, agriculture, nature and recreation. A dike with a road on top, for instance, is a multifunctional flood defense. Houses with water-retaining walls or parking garages in dunes are other examples.

1.3 New challenges

There is currently widespread interest in the development of new dike reinforcement technologies and new dike designs. This is due to the increase in both economic values and in the number of people at risk in low-lying areas, as well as new insights into failure mechanisms, the effects of soil subsidence, and projected impacts of climate change on seawater levels and the frequency of extreme river discharges and storm surges (see, e.g., Vellinga et al., 2009). Climate change implies increased uncertainty regarding the statistical properties of extreme weather events. Significant reinforcement of flood defense works has therefore been deemed necessary to maintain safety levels. In the 1990s, a program on future flood safety (*Waterveiligheid 21e Eeuw*) was initiated to thoroughly reconsider Dutch flood protection policy. A comprehensive set of flood protection studies and projects was conducted within the framework of this program, including studies on possible flood-risk management strategies for an uncertain future (e.g., Klijn et al., 2004). In 2008, the Second Delta Committee advised the Dutch cabinet on an overall strategy for spatial planning and flood safety taking climate change into consideration (Deltacommissie, 2008). In view of the growing economic assets and number of people at risk, the Delta Committee recommended reducing the existing annual probability of flooding by a factor of 10.

1.4 Robust, multifunctional flood defenses

Triggered by the work of the Second Delta Committee (Deltacommissie, 2008), a number of over-dimensioned dike concepts were introduced. Deltacommissie (2008) introduced the delta dike. This was followed by the unbreachable dike (Silva and van Velzen, 2008) and the broad dike (Vellinga, 2008). Table 1 and Fig. 1 specify the meaning of and relationships between these concepts.

The most important paradigm shift in the new robust dike concepts was that overflow would lead to gradually increasing damage in the hinterland, while overflow of the traditional dike (see Table 1) would more likely lead to a

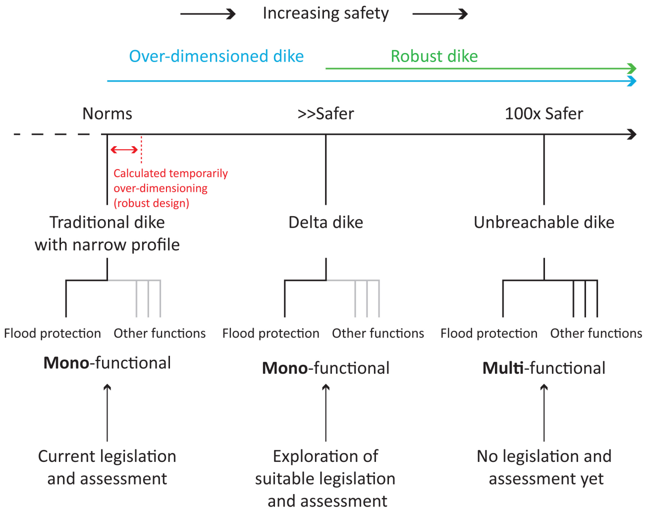


Fig. 1. Visualization of the relation between the various dike concepts in the Netherlands; these concepts are described in Table 1.

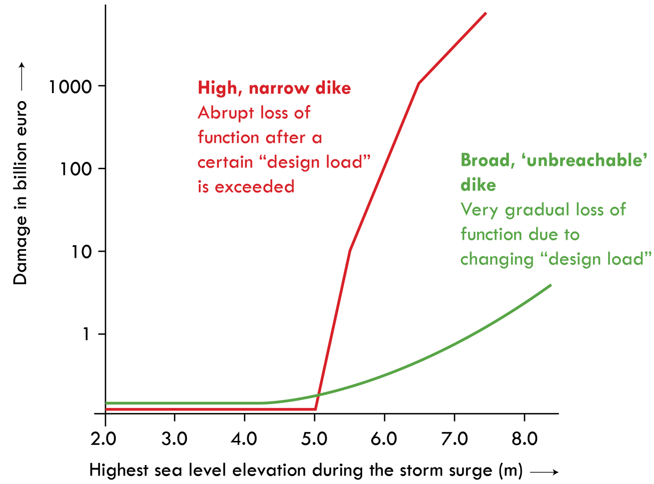


Fig. 2. Damage functions of narrow and broad dikes (Vellinga, 2008).

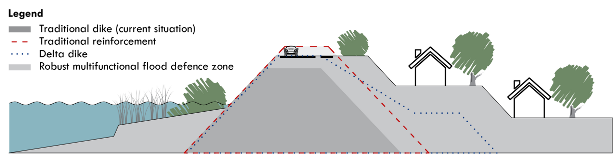


Fig. 3. Cross-section profiles of a current dike, a traditional reinforcement, a Delta dike and an unbreachable multifunctional flood defense (adapted from Silva and Van Velzen, 2008 and Stowa, 2013).

catastrophic flooding by collapsing of the dike (as illustrated by the 1953 flooding in the southwestern delta area in the Netherlands). Traditional dikes have a sharp threshold from no response to a large response, while for broad dikes the damage is far less (Fig. 2). Hence, broad dikes (when applied to the whole dike ring or to the most critical section of the dike ring) could significantly improve the robustness of the flood defense system over a wide range of possible futures and uncertainties, and are feasible as an climate adaptation strategy (Vellinga, 2008; Mens et al., 2011; Klijn et al., 2012). Figure 3 illustrates the physical differences between a traditional dike (with reinforcement), a delta dike and a robust multifunctional dike by comparing cross-sections.

Of course, a robust dike would require more material and space, but it would offer new opportunities for using the space as well (Vellinga, 2008; Hartog et al., 2009). It could be designed as a multifunctional area, combining urban development, transport infrastructure, recreation, agricultural use, and nature conservation or development, thus contributing to the quality of the landscape. These other functions can even help in creating and financing the robust dike.

Apart from forming a structural measure to protect the hinterland, a robust flood defense can also function as a place of safe refuge during a flooding emergency (Pols, 2007), comparable to the historical mounds. In addition, robust dikes could provide part of an evacuation route. Especially in the case of a phased implementation of a robust dike, or a differentiated implementation along the dike section in the dike ring, their function as a refuge area or part of an evacuation route would be a valuable additional strategy. Therefore, robust flood defenses can be incorporated into the recently adopted three-pronged flood protection policy of the Netherlands. That policy requires that in addition to (1) protection against flooding, attention must be paid to (2) flood-proof spatial planning and (3) strategies for early warning and evacuation (Ministerie van Verkeer en Waterstaat, 2009).

Following the advice of the Second Delta Committee and the National Water Plan (Ministerie van Verkeer en Waterstaat, 2009), several studies were carried out exploring the concept of delta dikes and robust multifunctional flood defenses (see, e.g., Hartog et al., 2009; Ellen et al., 2011). Klijn and Bos (2010) explored the potential effects of delta dikes on spatial quality, whereas Knoeff and Ellen (2011) tried to define this concept further with regards to failure mechanisms and failure probability. De Moel et al. (2010) and Van Loon-Steensma (2011) explored the potential for robust multifunctional flood defenses in the rural area and Urbanisten et al. (2010) and Stalenberg (2010) looked at the urban area, whereby the latter developed an adaptable multifunctional design.

Not only scientists, but also regional water boards, municipalities and private companies have expressed interest in robust, multifunctional approaches to flood defenses (e.g., De Moel, 2010). One of the reasons is the long-term character of such an approach. Currently every 10 to 20 years regular reinforcements are needed to maintain the dikes, involving heightening of the dike, strengthening of the revetment or enlargement of the inner berm . This could be avoided with the use of an over-dimensioned dike design. Other reasons are the opportunities the multifunctional approach presents in terms of added values and combining goals and plans. The Municipality of Rotterdam, for example, has initiated explorative studies, and projects to identify opportunities for introducing robust, multifunctional dikes are under way as part of various research programs, including Knowledge for Climate, STW-NWO Perspectief, and the Delta Program (e.g., Urbanisten et al., 2010).

1.5 Aim

This paper reviews possible functions of robust dikes in the rural riverine areas of the Netherlands. It moreover provides an analysis of strengths, weaknesses, opportunities, and threats associated with robust, multifunctional flood defenses in rural riverine areas. It is based on recent ideas and plans for innovative dike reinforcement at five riverine locations in the Netherlands, and a literature review that includes the most relevant Dutch grey literature and policy documents on this topic (Van Loon-Steensma, 2011). The aim is threefold: (1) to make the findings about robust dikes from both the case studies and the literature accessible to an international readership, (2) to expand insights into opportunities for implementing robust, multifunctional flood defense zones and (3) to formulate recommendations concerning strategies for adapting to the effects of climate change in the Dutch riverine area.

2 Exploring the opportunities: an inclusive approach

2.1 Study locations

This study focuses on five locations in the Dutch riverine area where new approaches to dike reinforcement are being explored: Streefkerk, Marsdijk, Arnhem, Grebbedijk, and Munnikenland (Fig. 4). These locations are part of the Dutch program of dike reinforcement that is currently under implementation (the High-Water Protection Program) or are implicated in the current policy to provide more space for the forecast increased river discharges (the "Room for the River" initiative).

The locations at Streefkerk, Marsdijk, and Arnhem were selected based on their challenging boundary conditions. These locations were also the subject of an earlier explorative study on the practical aspects of building a robust dike in the riverine region (De Moel et al., 2010), and in Van Loon-Steensma (2011) a more in-depth look at technical and societal feasibility issues was taken. The other two locations provide additional illustrations of current initiatives exploring robust, multifunctional approaches to flood protection in a rural riverine context.

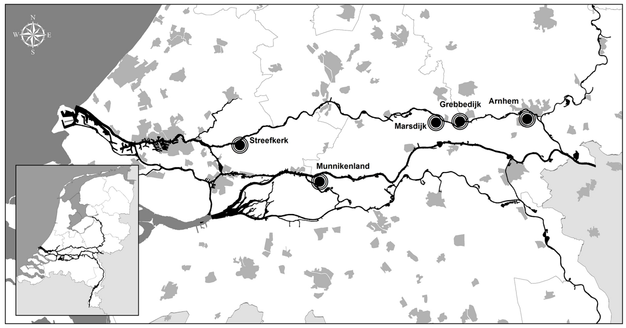


Fig. 4. Locations: **(a)** Streefkerk, **(b)** Marsdijk, **(c)** Arnhem, **(d)** Grebbedijk, and **(e)** Munnikenland.

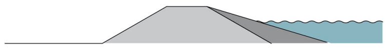
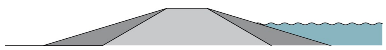
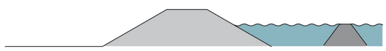
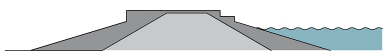
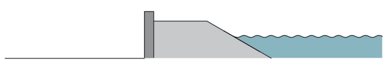
2.2 Profiles of robust, multifunctional flood defenses for the five locations

For the five locations, this study determined the flood protection task to be accomplished, characteristics of the area, boundary conditions, current function, values, plans and ambitions. Based on this information, suitable robust, multifunctional flood defenses were identified for each location. Table 2 presents an overview of all robust, multifunctional flood defenses, alongside their possible functions and values and the flood-protection strategy utilized (based, e.g., on Hartog et al., 2009; Klijn and Bos, 2010; Van der Zwan and Tromp, 2010). Over-dimensioning of the inner berm leads to an erosion-resistant structure. The over-dimensioned inner berm offers space for various functions (see also Fig. 3), which may however not interfere with the profile required from the flood protection perspective. A shallower slope of the outer berm, or a foreland, dampens the incoming waves. This over-dimensioned outer berm also offers space for other functions that can cope with occasionally high water levels in this outer dike area. A parallel lower dike in front of the dike (as is the case for many rivers) prevents flooding of the floodplains or polders during normal discharges and offers possibilities for several functions that can cope with occasional flooding. The over-dimensioned inner and outer sides of the camouflaged dike offer special opportunities for urban-related functions, as well as more technical constructions such as buildings with water-retaining walls or sheets; however, the latter will not automatically form a more robust defense than a traditional dike profile.

2.3 Interviews about chances and constraints

Thirty-three stakeholders (varying from representatives of the central and local government and experts to inhabitants and entrepreneurs) were interviewed to gain insight into the main opportunities and constraints for robust, multifunctional flood defenses in the rural riverine area. Due to the novelty of the dike concepts being explored, an open, semi-structured interview method was employed. Stakeholders

Table 2. Overview of robust multifunctional flood defenses (based on Klijn and Bos, 2010), with associated possible functions and water safety strategies.

Concept	Profile	Possible functions[1]	Water safety strategies[2]
(A) Over-dimensioned inner berm		Flood safety Housing Transport Recreation Energy Nature Landscape	Erosion resistant Refuge area Evacuation route
(B) Over-dimensioned outer berm		Flood safety Transport Recreation Energy Nature Landscape	Wave attenuation Extra stability
(C) Over-dimensioned inner and outer berm		Flood safety Housing Transport Recreation Energy Nature Landscape	Erosion resistant Refuge area Evacuation route Wave attenuation Extra stability
(D) Parallel dikes		Flood safety Recreation Energy Nature Landscape Agriculture	Extra space for discharge Controlled overflow Wave attenuation
(E) Camouflaged dike		Flood safety Housing Transport Recreation (Urban) landscape	Erosion resistant Refuge area Evacuation route Wave attenuation
(F) Technical construction		Flood safety Housing Transport Energy Urban landscape	

[1] In all cases the flood safety function is of primary importance; the other functions are not put in a particular order of importance (the importance of these depends on the local context).
[2] The water safety strategies are not put in any particular order.

were asked about their roles, interests, and activities concerning dike reinforcement projects, along with background information. Their views were also solicited concerning adaptations to the effects of climate change, functions of flood defenses, and opportunities and constraints for robust, multifunctional flood defenses. In addition, the interviewees were asked to sketch a picture of the range of interests and stakeholders involved and pathways to realizing synergy.

3 Results

3.1 Analysis of the five locations and the robust multifunctional approaches identified

For each of the five locations, the flood-protection task to be accomplished, characteristics of the area, boundary conditions, plans and ambitions for the location, envisaged functions, and suitable robust multifunctional approaches were identified (see Supplement 1 for an impression of the locations by aerial and ground photographs).

3.1.1 Streefkerk

Streefkerk is a small town located east of the city of Rotterdam on the south bank of the Lek River. The flood-protection task to be accomplished at Streefkerk and adjacent dike stretches, according to the latest assessment, is reinforcement of the river dike to prevent shear stress of the inner berm. A common solution in such a situation would be to raise and enlarge a stretch of the inner berm.

Housing in and near the village of Streefkerk is built in an elongated pattern just behind the dike along the roads (*lintbebouwing* in Dutch) that are on top of the dike. Beyond the dike, part of the floodplains is a nature conservation area. The population of Streefkerk is aging, and village shops, businesses, and local activities are slowly disappearing. Streefkerk has a shortage of housing for young people.

The weak underground, consisting of layers of clay and peat on top of a Holocene sand layer, has caused the macrostability problems of the dike and is an impediment to traditional dike reinforcement. As a result of past dike reinforcements, many historic and characteristic houses are now situated right up against or partly on and in the current dike. Without removal of a substantial number of houses, no further reinforcement is possible.

The marina of Streefkerk would like to expand, and the municipal government has identified a number of objectives for improving the social facilities of the village and enhancing landscape quality as well. It has therefore initiated a process to develop an integrated, long-term planning vision that connects these objectives with plans for dike reinforcement and third-party plans.

Table 3 lists envisaged functions for the Streefkerk location.

Table 3. Envisaged functions for the Streefkerk location.

Functions	Ambitions for Streefkerk
Flood safety	Robust, in order to avoid the need for future adjustments
Housing	Affordable housing for young people; preferably oriented towards the river; accommodations for the elderly
Transport	Local road to connect villages; entrance to houses along the dike; accessibility of local businesses
Economy	Expansion of the recreational harbor
Recreation	Bicycle path; walking path; boating (entrance to marina); touring
Nature	Riverine nature (floodplains)
Landscape	Conservation and strengthening of the typical Dutch riverine landscape
Urban quality	Improved urban quality; space provided for facilities; strengthened connection between the village and the river and adjacent floodplains
Cultural heritage	Conservation and strengthening of the typical Dutch riverine landscape, the traditional housing pattern, and houses
Energy	–

3.1.2 Marsdijk

Marsdijk is located along the south bank of the Rhine River in the central part of the Netherlands between the cities of Utrecht and Arnhem. Most of the dike does comply with current safety standards. Small sections, however, need to be heightened and strengthened, due to problems of macrostability and piping (waterflow through the dike that may destabilize the structure).

The landscape around the dike shows many remnants of former riverbeds, historic dikes, dike breakthroughs, and polders. The building of the dike in the 19th century transformed the riverine area between the historic "*Bandijk*" and the newer Marsdijk into the Mars Polder. The Mars Polder is used for agricultural purposes (fruit and dairy farming), and a few farms and houses are located there. As a result of sand mining, nature has developed during the past 15 years around extraction pits on the Mars Polder.

In 2005, the idea was launched to use the Mars Polder to give the Rhine River more space. The suggestion met with staunch resistance from both inhabitants and the municipal government. Ultimately, it was rejected by the ministry.

Table 4 presents envisaged functions for the Marsdijk location.

3.1.3 Arnhem, south of the Rhine River

Along the south bank of the Rhine River, the city of Arnhem has steadily expanded since the 1940s onto the extensive floodplains that carry the marks of former riverbeds. Some sections of the dike here do not comply with the prescribed norms and must be adapted. The location is close to the bifurcation of the Rhine and IJssel rivers, and measures are being taken here to give the river enough additional space to realize a 7 cm reduction in its water level. For this reason, the dike in the Bakenhof district was relocated in 2000 to broaden the floodplains. The floodplains are now used for recreation and parts of the area east of the urban zone are used for agricultural purposes.

On the floodplains south of the river, the groundwater system is complicated, as sandy layers in the subsoil connect low-lying areas here to both the "*Veluwe Massief*" north of the river and to the Rhine River itself. The connection with the river results in desiccation during periods of low river levels in summer and to excess water in the housing areas during high water levels in winter.

Table 4. Envisaged functions for the Marsdijk location.

Functions	Ambitions for Marsdijk
Flood safety	Comply with current standards; avoiding nuisance
Housing	Maintain current housing
Transport	Local road for use by residents and local businesses
Economy	–
Recreation	Bicycling and touring
Nature	Strengthening nature development near sand extraction pits
Landscape	Conservation of the typical Dutch riverine landscape
Urban quality	–
Cultural heritage	Conservation of the typical Dutch riverine landscape, the traditional housing pattern, and houses
Energy	–

Table 5. Envisaged functions for the Arnhem location.

Functions	Ambitions for Arnhem
Flood safety	Comply with current standards; preferably robust to avoid the need for further adjustments in the short term
Housing	Providing up-to-date housing in the suburbs; limiting building in natural parts
Transport	Local transport to suburbs
Economy	–
Recreation	Bicycle path; walking paths in the floodplain area
Nature	Riverine nature (floodplains)
Landscape	Strengthening the typical Dutch riverine landscape
Urban quality	Provision of high-quality residential areas; connection with river and adjacent floodplains
Cultural heritage	–
Energy	–

There are plans to rebuild some areas of the suburbs. Furthermore, after long deliberation, the municipality recently decided to allow limited building in the eastern rural area and to develop a "green river". The latter implies that the area could be used as an extended riverbed during periods of high discharge.

Table 5 lists envisaged functions for the Arnhem location.

3.1.4 Grebbedijk

Grebbedijk is located along the north bank of the Rhine River west of the city of Wageningen. The dike here protects an extensive low-lying and densely populated area between two natural heights. Extraction of clay from local floodplains to reinforce the dike has produced new riverine nature and wetlands, which are now key nature conservation areas in the Netherlands. Former brick factories located here have been granted cultural heritage status. Grebbedijk meets current safety standards. However, the provincial government and local water board are exploring opportunities to make the dike more robust.

A 2004 modeling study underscored the strategic importance of the dike. If it would breach a huge area would be affected, with water levels reaching up to 3 m in Veenendaal and damage of more than 10 billion Euros (Wouter, 2004). The city of Wageningen has expressed interest in adapting the dike here, to take advantage of opportunities to relocate the unattractive industrial harbor and run-down industrial area away from the city.

Table 6 lists envisaged functions for Grebbedijk.

3.1.5 Munnikenland

Munnikenland is a rural region in the center of the Netherlands along the south bank of the Waal River. The government's "Room for the River" Program (Ministerie van Verkeer en Waterstaat, 2007) mandates that measures be undertaken here to reduce the river level and relocate and improve the dike. The location has a long history of land reclamation, and many remnants of historic dikes can be traced in the landscape. Near Loevenstein Castle is a nature conservation area, while dairy farming is still prominent in other parts of Munnikenland.

The local water board initiated a process to develop a comprehensive planning vision for Munnikenland, including flood defenses. A range of local stakeholders, experts, and artists contributed to an integrated vision for improving flood safety while strengthening the area's cultural, historical, natural, and recreational value. The plan envisages the use of the excavated material from the floodplains to over-dimension a newly relocated dike. The planned over-dimensioning will create a dike suited for use for recreational purposes and also provide a place for cattle to take refuge during high-water events.

Table 7 lists the envisaged functions for the Munnikenland location.

3.1.6 Suitable robust, multifunctional flood defenses

Based on the envisaged functions, local boundary conditions, and the plans and ambitions expressed for the five locations, Table 8 lists the most appropriate dikes identified (see Table 2 for a description of these dikes). In order to safeguard the historic and characteristic homes behind the current dike in Streefkerk, the dike should be reinforced into the direction of the river. A camouflaged dike by over-dimensioning the crest gives the best chances to combine flood protection with all other ambitions and plans. It offers space for new accommodation or even a new town center oriented towards

Table 6. Envisaged functions for the Grebbedijk location.

Functions	Ambitions for Grebbedijk
Flood safety	Protection of the extensive hinterland with a robust flood defense
Housing	Maintain current housing
Transport	Local road for accessibility of local business
Economy	Creating housing facilities for knowledge companies (spin offs of Wageningen UR); relocation of industrial harbor and industrial area
Recreation	Bicycle path; walking paths on floodplains; touring; recreation along riverside
Nature	Strengthen riverine nature (floodplains)
Landscape	Conservation and strengthening of the typical Dutch riverine landscape
Urban quality	Relocation of industrial harbor and outdated industrial area; strengthening the connection between the town, the river, and the adjacent floodplains
Cultural heritage	Conservation and strengthening of riverine landscape; conservation of industrial heritage in the form of the remnants of brick factories
Energy	–

Table 7. Envisaged functions for the Munnikenland location.

Functions	Ambitions for Munnikenland
Flood safety	Robust, as part of an integrated plan for the area, including floodplain excavation to supply material for robust reinforcement
Housing	–
Transport	Local road (mainly for recreation)
Economy	–
Recreation	Enjoying the riverine nature and the historic area; walking; cycling; touring
Nature	Riverine nature (floodplains)
Landscape	Conservation and strengthening of the historic riverine landscape
Urban quality	–
Cultural heritage	Conservation and strengthening of the cultural heritage, including Loevestein Castle as well as the landscape
Energy	–

the river and the marina. To prevent removal or damage of the new buildings due to future flood protection tasks, the design has to be very robust. Both an over-dimensioned outer berm and water-retaining walls can be used to improve the connection of the build environment with the river, the marina and the adjacent floodplains.

Only small sections of the Marsdijk have to be heightened and strengthened, and therefore besides traditional reinforcement, expensive measures such as sheets are also feasible for the sparse locations with houses just behind the dike. On the other hand, the historic "*Bandijk*" forms a parallel defense, and may allow some overflow or more wave overtopping than the current norm under the condition of an erosion-resistant inner berm.

In Arnhem, the plan to rebuild the outdated suburbs near the river and the ambition to strengthen both the quality of the urban and riverine landscape and to improve recreation facilities offer excellent chances for multifunctional solutions. In order to use the flood defense for housing and infrastructure, the dike has to be over-dimensioned. This may result in a camouflaged dike. The existing houses will be removed, and thus do not impede landward reinforcement, or even a landward shift of the flood defense. Because there seem to be no spatial constraints, technical constructions (which are expensive) are not very likely.

Over-dimensioning of the outer berm and the crest of the Grebbedijk offer chances to relocate and integrate the current industrial harbor and industrial area with the flood defense and strengthen the connection of the city with the Rhine River and floodplains. Integrating buildings with water-retaining walls into the flood defense offer possibilities to create housing facilities for small businesses and can contribute to the urban quality. However, to improve the protection of the extensive hinterland, the Grebbedijk over its entire length of 5 km would have to be reconsidered. The largest stretch of the Grebbedijk comprises a rural area and scattered houses just behind the dike. Over this rural stretch other functions such as a road come into play, to meet and co-finance the envisaged robustness.

A robust dike with an over-dimensioned inner and outer berm meets the ambitions for Munnikenland (Table 7) because it fits excellently into the typical Dutch riverine landscape and allows recreational use. Moreover, it facilitates nature development in the flood prone outer dike area by providing a refuge during high-water events for cattle grazing in this nature area.

3.2 Opportunities and constraints of robust, multifunctional approaches to flood defense

The interviews revealed that all stakeholders are basically positive about combining functions in a dike, provided this does not compromise the primary flood protection function of the defense. However, all see from their own background and experiences various opportunities as well as points of concern and constraints with regards to technical, economic, governance and spatial aspects.

Technical aspects

Over-dimensioning of the flood defense prevents the nuisance of repeated adaptations to the latest insight and norms, as is the current practice, and can better deal with the uncertainty in the effects of climate change. However, even robust flood defense may need future adjustments. Integrating buildings in or on the flood defense impedes such future adaptation. Furthermore, it was stressed by several stakeholders that design and assessment criteria in the Netherlands do not yet account for innovative solutions. The implementation of robust multifunctional flood protection will in practice involve in the first instance some (strategic) parts in the dike ring, whereas the flood policy in the Netherlands is based on entire dike rings. Therefore further exploration is needed into how a stepwise implementation will affect the risk in the hinterland. Most stakeholders share the opinion that multifunctional flood defenses are more feasible in urban than in rural areas, because the limited space in urban areas stimulates the search for integrated measures. However, every location needs a tailor-made design based on local environmental conditions and that considers spatial as well as temporal aspects.

Economic aspects

A robust flood defense is more expensive than a traditional reinforcement, therefore additional funding is needed as the Dutch national flood protection program finances only the cheapest solution to meet the required flood safety norm. Offering space to other functions encourages support of other parties (e.g., municipalities, nature or culture heritage conservation programs, entrepreneurs or residents) and the willingness and ability for co-financing the over-dimensioned flood defense. However, organizing co-funding is very challenging because all participants have different interests and criteria in making funds available and have different time horizons in their goals. Besides weighing the construction costs against the immediately visible benefits, it is also important to assess cost-effectiveness in the long term. Regular adaptation of the flood defense, as is the current practice, is very unattractive in view of co-funding, therefore over-dimensioning is effectively a prerequisite for co-funding of a multifunctional flood defense.

Governance aspects

Multifunctional flood defenses offer an excellent chance to realize tasks and ambitions in fields other than flood protection. However, as was already mentioned in the previous section, all different stakes (and their spatial and temporal aspects) make the implementation of a multifunctional flood defense a complex and often lengthy process. Therefore an enthusiastic and strong initiator is needed. Moreover, a suitable governance structure has to be developed, for the initial planning part and the implementation part of the project as well as for the period afterwards when management, maintenance and assessments become important issues. When dike reinforcements are called for, local water boards (who are responsible for maintaining flood defenses and meeting lawful flood safety standards) start by collecting information about hydraulic and physical boundary conditions, planning tasks, and noting constraints, while involving stakeholders in the process. They must also take landscape, nature, and cultural values into consideration. However, they have no mandate to realize goals other than flood safety, and the legislative framework within which they work is based on evolving safety standards. If other parties propose initiatives to combine functions in a flood defense zone, it is the water board's responsibility to set the preconditions based on the water act. Even if such a plan for a multifunctional flood defense does meet these preconditions, opponents can make the implementation stop by court as over-dimensioning goes further than meeting the standards. Furthermore, expropriation of needed space for over-dimensioning is not feasible.

Spatial aspects

Multifunctional use of the flood defense is attractive for densely populated areas; however, in such areas the available space is normally already fully occupied. The removal of, e.g., historical buildings or the affecting of historical urban patterns might not be feasible. Plans and tasks on spatial planning of other parties encourages the development of integrated plans. However, when the flood defense does already meet the standards, then it is difficult to add other functions. Temporarily assignment of other functions to the space reserved for future adaptations might then give an opportunity for multifunctional use of this space. The ambition to improve the spatial quality of the riverine (urban and rural) area offers chances for additional functions. Both national and local policy on spatial planning can hinder the implementation of robust multifunctional flood defenses, because the additional space they require may already be assigned to functions other than flood protection.

These opinions about opportunities, constraints, points of concern, and recommendations for achieving synergy are reported in more detail in Van Loon-Steensma (in Dutch) (2011). Figure 5 presents a summary in a Strengths, Weaknesses, Opportunities, and Threats (SWOT) framework.

3.3 Opinions about adapting flood defenses to the effects of climate change

Table 8 summarizes the views of the interviewed stakeholders about suitable timeframes for dike reinforcement and on how the effects of climate change and uncertainties about future conditions could best be taken into account. The opinions voiced can generally be categorized into three groups. The first group of stakeholders considered current flood safety policy to be appropriately based on scientific insights about the effects of climate change and recent engineering know-how (but did not reject the idea of integrating more functions into the flood defense). The second group of

Strenghts	Weaknesses
- Optimized use of limited space - Focus on long term (fewer adjustments necessary) - Greater flood protection	- Over- dimensioning is expensive - Dutch government finances only adjustments to current safety norms - Development of an integral plan for a multifunctional flood defense zone is complicated and will involve much time and efforts - The legislative framework is based on adjustments to current safety standards - Instruments to judge safety status are still lacking
Opportunities	**Threats**
- Tasks and problems in the field of infrastructure, land- use planning, nature and landscape protection, and development - Ambitions and plans of various stakeholders, such as municipalities, civil society, entrepreneurs, and inhabitants - Obligation to improve flood protection - Attention for innovative approaches to flood protection - On-going projects on integrated area development	- Deadline of 2015 of the on-going regular dike reinforcement program and "Room for the River" Program - Time horizon of nature restoration programs and other plans

Fig. 5. SWOT analysis based on the interviews.

stakeholders considered it wise to make flood defenses more robust than is currently done to avoid the need for new adjustments in the short term. They pointed out that most dikes have to be reinforced far before the end of their lifetime due to changed insights, new norms or boundary conditions, and appear not te be over-dimensioned during their planned lifetime. A third group of stakeholders called for an intensified search for other solutions, arguing against making the dikes more robust before better insight was available into the effects of climate change (Table 9).

4 Discussion

The current terminology for robust flood defenses is confusing; various names refer to the same concept, whereas comparable terms also refer to subtly different concepts (see Table 1). This is a consequence of the novelty of the concept. The robust multifunctional flood defense is not yet a dominant design in the Netherlands, hence various new ideas are still emerging (see Geels, 2004).

In each of the five case studies several suitable multifunctional robust flood defenses could be identified that would contribute to the envisaged functions and ambitions for the area. However, not every dike design would be compatible with the local opportunities and constraints. A thorough analysis was required to consider all opportunities and constraints, alongside a cost-benefit analysis that also considered long-term trade-offs on a broad range of aspects. Analysis of the stakeholders' responses provided an indication of the full range of considerations at play, as well as insights into the pros and cons of robust, multifunctional flood defenses in riverine areas.

The interviews revealed that there is basically a broad positive attitude towards robust multifunctional defenses among stakeholders from different backgrounds based on (1) the optimized use of limited space, (2) fewer adjustments, and (3) more safety. Although multifunctional use of space was

Table 8. The most appropriate approaches for the five locations. Refer back to Table 1 for an overview of the different approaches

Robust multifunctional approach	Streefkerk	Marsdijk	Arnhem	Grebbedijk	Munnikenland
(A) Over-dimensioned inner berm			+	+/–	+
(B) Over-dimensioned outer berm			+	+	+
(C) Over-dimensioned inner and outer berm	+/–		+	+	+
(D) Parallel dikes		+		+	+/–
(E) Camouflaged dike	+		+	+	
(F) Technical construction	+	+		+	

Table 9. Opinions of interviewed stakeholders on how to deal with climate change concerning dike reinforcement (+ = share this view, 0 = share this view more or less.

Opinion	Central government	Rijkwaterstaat	Province	Water board	Municipality	Inhabitants	Entrepreneurs	Nature conservation and environmental protection	Cultural heritage
A	+	+	+	+	0			0	
B			+	+		+	+	0	
C						+	+		+

A: Recent insights concerning the effects of climate change are already integrated in the current water safety policy.
B: It would be wise to anticipate more than is currently done for the effects of climate change and other changes.
C: More robust flood defenses are not desirable.

identified as an important strength, the (lack of) space forms a severe constraint as well. According to Silva and Van Velzen (2008), an unbreachable dike based on current norms requires at least a 1 : 3 inner-berm slope. Most existing sea defenses meet this requirement already. Klijn and Bos (2010) estimate based on the assumptions of Silva and Van Velzen (2008) that only some 140 ha is needed to make the 1000 km of Dutch sea defenses unbreachable delta dikes. However, some 3000 ha would be needed to transform the country's 1400 km of river dikes into unbreachable delta dikes. In general, a multifunctional flood defense zone requires even more space, to avoid the need for further adjustments in the coming 50 to 100 years. Integrating more functions into the flood defenses will therefore lead to an over-dimensioned flood defense that needs less future adaptations (as was identified as another strength). A robust multifunctional flood defense provides potentially more protection; however, the reduction in risk should be assessed on the level of the dike ring. Over-dimensioning of a small section in the dike ring may not affect the risk in the hinterland at all. On the other hand, De Bruijn and Klijn (2009) found that building delta dikes could substantially reduce flooding risks, preventing extensive fatalities and economic damages at "risky" locations with densely inhabited areas adjacent to flood defenses and a relatively short warning time of potential breaches and evacuation difficulties. Unbreachable flood defenses have also been recommended by the Netherlands Environmental Assessment Agency as an appropriate measure to reduce future risks of flooding (Ligtvoet and Van Gerwen, 2011). Klijn et al. (2012) found that these can effectively reduce the fatality risk at even lower net societal costs than continuation of the present policy.

Moreover, robust dikes form a refuge during flooding and provide time to prepare and evacuate. Although a robust flood defense is primarily meant to protect the hinterland against flooding, this is consistent with the second and third prongs of the new flood protection policy, and forms an additional argument to explore the potential of robust multifunctional flood defenses to improve flood protection. The importance of such an exploration of additional, non-structural, protection values was illustrated by the disastrous effects of the tsunami after the Great East Japan Earthquake in 2011. Although Japan has opted for very robust dikes at some critical locations, the flood defenses were not prepared for floods far beyond prior assumptions (see Van Alphen et al., 2011). Although over-dimensioned flood defenses are expensive, their simultaneous performance of structural and non-structural properties may be attractive as it enlarges the portfolio of flood risk management measures (see Hall and Solomatine, 2008).

The challenging idea that integrating functions helps to create more robust flood defenses also forms the weaknesses of this concept. Over-dimensioning is expensive, and when there are no other tasks or opportunities to combine functions it may become extremely difficult to find funds to build an over-dimensioned flood defense. Knoeff and Ellen (2011) estimate that transformation of all flood defenses in the Netherlands into delta dikes would cost 20 billion Euros. To transform dikes along the rivers, space would be needed to enlarge the inner berms, whereas the transformation of coastal dikes mainly requires replacement of the revetment. To save costs they advise combining the transformation into delta dikes with regular dike reinforcements (Knoeff and Ellen, 2011). Such an approach would imply incremental adaptation to the effects of climate change (Vellinga et al., 2009).

Another weakness is that the development of an integral plan is complicated and will require a lot of time (see also Tromp et al., 2012). In the Netherlands, all space is legally designated and utilized for specific functions. Broadening the flood defense in favor of flood protection would in all cases compromise other functions and values. In the rural area, many floodplains are used for agricultural purposes or are valued for their nature and landscape qualities. Yet these functions do not automatically conflict with robust, multifunctional flood defenses. Therefore, it is important to explore the conditions under which nature and agricultural land can be made part of flood defense zones. The Dutch legislative framework is based on current safety standards and provides no rules concerning over-dimensioning of flood defenses. Broadening the outer berm is prohibited in most riverine locations because of the obligation to maintain the riverbed's discharge capacity. The "Room for the River" program even aims at widening the riverbeds (Ministerie van Verkeer en Waterstaat, 2007). Moreover, extensive tracts of river floodplains are part of the Netherlands' Ecological Network and the EU Natura 2000 network. They are thus protected by both national and international legislation (Ministerie van Economische Zaken, Landbouw and Innovatie, 2013). A number of Dutch riverine areas have been granted National Heritage Landscape status in recognition of their natural, cultural, or historic. Up to now, there has been little exploration of how and under what conditions a robust multifunctional flood defense fits within the legal framework for nature and landscape conservation, or may even strengthen natural, landscape, and cultural values.

The legislative framework concerning flood protection implies furthermore that water boards have no mandate or financial resources to realize goals other than flood safety. Therefore, expropriation of rights and property is not feasible, and subsequently over-dimensioned multifunctional flood defenses can only been implemented if the additional space can be obtained voluntarily.

Many stakeholders share the view that the implementation of multifunctional dikes requires an initiator and manager capable of galvanizing and persuading involved parties and, if necessary, influencing existing plans and planning processes. Those interviewed furthermore suggested that the initiator of such a complex and innovative approach would need to facilitate exploration of pathways beyond the usual policy. Water boards and municipal governments are generally obliged to follow national policy lines; they are thus poorly positioned to play this role.

Although the current lack of design standards, an assessment framework, and management standard were identified as a weakness, Knoeff and Ellen (2011) note that the current legal framework does not hinder implementation of delta dikes. This is reflected in the current status of the five locations. In Streefkerk the building of a robust multifunctional flood defense (as a camouflaged dike) has recently started, after an intensive three-year process initiated by the water board and adopted by the municipality to realize their ambitions concerning the improvement of Streefkerk. The province of South Holland and the marina provide the additional funding needed for over-dimensioning the flood defense. At the Marsdijk location, the water board has opted for traditional reinforcement. In Bakenhof in Arnhem, houses were built on top of and up against a newly relocated dike. The robust dike forms an integral part of the landscape and connects the neighborhood with the adjacent floodplains and river. The Delta Program has indicated its intention to choose Grebbedijk as a pilot location for a delta dike. At the Munnikenland location, an over-dimensioned dike is currently being built to meet the safety norm and to create additional recreational value. All described situations form illustrations of the identified opportunities.

Finally, the stakeholders were also asked about their views concerning suitable timeframes for dike reinforcement and on how the effects of climate change and uncertainties about future conditions could best be taken into account. Climate change and its related uncertainty was, to our surprise, for none of the groups of stakeholders the main reason to support the introduction of the more robust multifunctional flood defenses.

Even though one can never achieve complete safety (e.g., Kundzewics, 2004), in view of climate adaptation policy the robustness of an over-dimensioned dike by combining functions is very attractive in view of the uncertainties regarding the effects of climate change (Hall and Solomatine, 2008) and a changing world (Merz et al., 2010).

5 Conclusions and recommendations

We analyzed the pros and cons of robust, multifunctional flood defenses in riverine areas of the Netherlands, based on both plans and ideas described in (mainly) Dutch grey literature and opinions expressed by stakeholders involved in five locations with a reinforcement task. The overall conclusion is that in many situations a robust multifunctional dike is a viable design option.

Another important conclusion is the notion that every location has its specific design criteria as a result of the varying strengths, weaknesses, opportunities, and threats in each location.

With regard to attitudes of stakeholders we conclude that stakeholders from different backgrounds think generally positively about robust multifunctional dikes due to (1) the optimized use of limited space, (2) fewer adjustments, and (3) higher safety standards.

A final conclusion is that the inclusion of multiple functions (i.e., in addition to flood defense) seems to be a prerequisite for realizing a robust dike due to the high financial investments that have to be made in the preparation and construction phase.

Our findings lead to several recommendations.

First, the concept of a robust multifunctional flood defense is promising as a climate adaption measure and therefore all aspects should be explored more in depth by a thorough analysis of scientific literature and of experiences in other countries. Additionally, the process of establishing a robust multifunctional dike, from initial idea through to implementation, should be monitored at challenging and appropriate pilot locations to learn from experiences. Designation of these pilot locations and support by the Delta commissioner would help, as he could facilitate exploration of pathways beyond the usual policy. The pilot locations should be chosen to include complex boundary conditions and a wide range of ambitions and stakeholders, and preferably be located in three distinct areas (e.g., a riverine location, a location in the Southwest Netherlands Delta, and a Wadden Sea location).

Second, as the integration of other functions into the flood defense leads to a more robust system, benefits in the longer term should be investigated more in depth. Questions that may then be answered are if and under which conditions robust multifunctional flood defenses can offer greater security per Euro invested than traditional flood-defense systems, and how the benefits for the other functions can be incorporated into a comparative analysis against, e.g., traditional dike reinforcement.

Third, in order to facilitate the implementation of robust multifunctional flood defenses, attention should be paid to the development of appropriate design standards, assessment frameworks, and management standards, specifically for these robust dikes.

Finally, research should explore under what conditions robust multifunctional flood defenses can contribute to nature and landscape values and fit into Natura 2000 aims and legislation.

Supplementary material related to this article is available online at http://www.nat-hazards-earth-syst-sci.net/14/1085/2014/nhess-14-1085-2014-supplement.pdf.

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