Reg Environ Change (2014) 14:895–908
DOI 10.1007/s10113-013-0420-z

ORIGINAL ARTICLE

Evaluating the effect of flood damage-reducing measures: a case study of the unembanked area of Rotterdam, the Netherlands

Hans de Moel · Mathijs van Vliet · Jeroen C. J. H. Aerts

Received: 14 July 2012 / Accepted: 31 January 2013 / Published online: 19 February 2013

Abstract Empirical evidence of increasing flood damages and the prospect of climatic change has initiated discussions in the flood management community on how to effectively manage flood risks. In the Netherlands, the framework of multi-layer safety (MLS) has been introduced to support this risk-based approach. The MLS framework consists of three layers: (i) prevention, (ii) spatial planning and (iii) evacuation. This paper presents a methodology to evaluate measures in the second layer, such as wet proofing, dry proofing or elevating buildings. The methodology uses detailed land-use data for the area around the city of Rotterdam (up to building level) that has recently become available. The vulnerability of these detailed land-use classes to flooding is assessed using the stage–damage curves from different international models. The methodology is demonstrated using a case study in the unembanked area of Rotterdam in the Netherlands, as measures from the second layer may be particularly effective there. The results show that the flood risk in the region is considerable: EUR 36 million p.a. A large part (almost 60 %) of this risk results from industrial land use, emphasising the need to give this category more attention in flood risk assessments. It was found that building level measures could substantially reduce flood risks in the region because of the relatively low inundation levels of buildings. Risk to residential buildings would be reduced by 40 % if all buildings would be wet-proofed, by 89 % if all buildings would be dry-proofed and elevating buildings over 100 cm would render the risk almost zero. While climate change could double the risk in 2100, such building level measures could easily nullify this effect. Despite the high potential of such measures, actual implementation is still limited. This is partly caused by the lack of knowledge regarding these measures by most Dutch companies and the legal impossibility for municipalities to enforce most of these measures as they would go beyond the building codes established at the national level.

Keywords Flood risk · Risk modelling · Damage-reducing measures · Building codes

Introduction

Flood risk management in the Netherlands is largely dominated by technical flood prevention measures such as levees and dikes. Flood management in Europe, however, has increasingly shifted to an integrated risk management approach, including measures that reduce damage and exposure (Büchele et al. 2006; Bubeck et al. 2011). This is exemplified by the European Flood Directive (2007/60/EC), which stimulates EU member states to move towards a risk-based approach in which potential consequences are explicitly considered in flood management. Under this directive member, states are required to, for example, perform risk assessments, draw up flood maps (see De Moel et al. 2009) and set-up flood risk management plans.

H. de Moel (✉) · M. van Vliet · J. C. J. H. Aerts
Institute for Environmental Studies, VU University,
Amsterdam, The Netherlands
e-mail: hans.de.moel@vu.nl

H. de Moel · M. van Vliet · J. C. J. H. Aerts
Amsterdam Global Change Institute, VU University,
Amsterdam, The Netherlands

M. van Vliet
Public Administration and Policy Group, Wageningen
University, Wageningen, The Netherlands

In the Netherlands, the framework of MLS has been introduced to support a risk-based flood management approach (Ministry I&E 2009). This framework addresses three layers: (i) prevention, (ii) damage reduction through sustainable spatial planning and (iii) crisis control and evacuation. The framework can be used to find combinations of measures from the three layers that jointly reduce the overall flood risk (Ministry I&E 2009). Using this framework is by no means common practice yet, and a focus on preventive measures (i.e. layer 1) is apparent in practice. The Dutch Delta Programme continues studying the option of multi-layer safety (Ministry I&E and Ministry of Economic Affairs 2012). One of the main questions concerning the MLS framework is the suitability of measures in the second layer for the Dutch situation. Given the low probability of flooding in the Netherlands due to its high safety standards, the cost-effectiveness of damage-reducing measures on risk may be limited in the embanked part of the Netherlands.

In the area of Rotterdam and its surrounding region large unembanked areas do, however, exist. These unembanked areas have a higher probability of flooding compared to areas protected by the embankments but generally have lower flood levels as they are relatively high grounds (often elevated) (De Kort 2012). Being outside the embankments, measures from the second layer, which aim to reduce the possible consequences of a flood, can potentially be very useful to manage flood risks in these areas (see section "Case study area: larger Rotterdam area"). Such measures can be at the regional level, such as appropriate zoning of functions or the elevation of an area, or at the level of individual buildings, such as wet and dry floodproofing and elevating individual buildings (Aerts and Botzen 2011). Studies related to floods of the Meuse river (Wind et al. 1999) and Elbe river (Kreibich et al. 2005; Kreibich and Thieken 2009) show that implementation of such measures can successfully reduce flood damages.

In order to investigate the effects of damage-reducing measures, a modelling framework is necessary in which building level measures can be incorporated. Such a framework requires a combination of inundation simulations and a flood damage model (e.g. as in De Moel et al. 2012). Referring to the latter, current flood damage models such as HIS-SSM (Kok et al. 2005) and Damagescanner (Klijn et al. 2007; De Moel and Aerts 2011) do not allow for building level assessment studies. In addition, flood damage assessments are still characterised by significant uncertainties associated with stage–damage functions due to generalisations as well as methodological differences in estimating the exposed asset values linked to these curves (Merz et al. 2004, 2010; Apel et al. 2008, 2009; Freni et al. 2010; De Moel and Aerts 2011). One of the few studies that includes estimated flood damage in the unembanked area of the larger Rotterdam region has been performed by Veerbeek et al. (2010). They developed a building level model for residential and infrastructural objects and estimated the effect of different climate change scenarios on the flood risk. Other land-use types were not considered, and the effect of additional damage-reducing measures was not part of their research.

The main goal of this paper is to assess the effect of damage-reducing measures on the unembanked area in the larger Rotterdam area. For this, a new damage model will be developed that enables the evaluation of such measures at the building level. Several measures will be evaluated on its damage-reducing effects, including elevating houses and dry and wet floodproofing. Finally, we explore opportunities and obstacles within the current regulatory framework of building codes and land-use zoning, as implementation is only possible if the rules allow for it.

The remainder of this paper is organised as follows: Chapter 2 provides a brief description of the case study area. Chapter 3 outlines the modelling framework and the underlying data. Chapter 4 provides the results of the modelling set-up and discusses the policy framework related to building level measures. A discussion and conclusions of this paper will be presented in Chapters 5 and 6.

Case study area: larger Rotterdam area

The case study area in this paper concerns the unembanked area of Rotterdam and its surroundings in the Netherlands (Fig. 1). Rotterdam is the largest port in Europe and is situated at the mouth of the "New Meuse" River ("Nieuwe Maas"), one of the river channels in the delta formed by the rivers Rhine and Meuse. Due to its location along the river, and proximity of the sea, this area is vulnerable to flooding. Whereas most of the flood-prone part of the Netherlands is protected from flooding by dike systems, there are also build-up areas between the river and the dikes. These areas are called unembanked and are generally elevated to some extent. The areas feature mostly industrial/harbour activities, but also residential developments have taken place outside the embankments with currently about 64,000 people living in the unembanked areas in the larger Rotterdam area (Meijers et al. 2011). With harbour activities moving towards the sea to accommodate bigger and deeper cargo ships, space is becoming available in the unembanked area for new urban (re)developments. This trend is expected to increase the number of inhabitants in the unembanked areas of the larger Rotterdam area.

From a flood risk management and regulatory point of view, the unembanked areas are of particular interest. They do not fall under the Dutch Water Embankment Act of

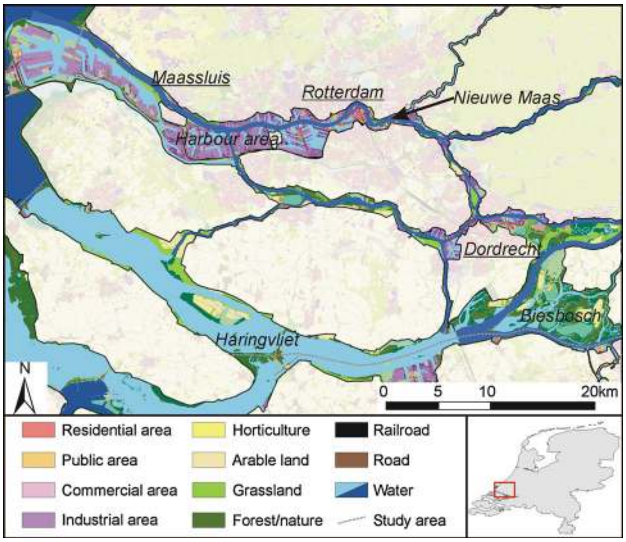

Fig. 1 Map of the study area with some of the main geographic locations. The (*slightly transparent*) white areas are protected by embankments (*black lines*); the areas outside (in *full colour*) are the unembanked areas. The boundary of the area modelled in this paper is delineated by the *grey dashed lines*; going from the mouth of the Nieuwe Maas west of Maassluis to the Haringvliet in the south (colour figure online)

1995, which guarantees a particular level of protection against flood risk for each dike-ring area (Aerts and Botzen 2011). This act has divided the low-lying areas in the Netherlands into 53 dike-ring areas. Each dike-ring area has its own closed flood protection system of dikes, dams and sluices that protect it from floods, with safety standards varying between 1/1,250 per year to 1/10,000 per year. Although the exact flood probabilities are not exactly known for the unembanked area (and differ largely between locations), they are higher than the flood probabilities in the low-lying dike-ring areas.

There are several arguments for developing damage-reducing measures (i.e. layer two) for the unembanked areas of Rotterdam:

1. Since the flood probability of these areas is generally higher than in the dike-ring areas, damage-reducing measures have a higher effect on risk reduction as compared to the areas that already have low flood probabilities.
2. Large parts of the dike-ring areas in the West of the Netherlands are at very low elevations—some even at 6.5 m below sea level. In case of a dike failure, floods may cause potentially large inundation depths. In contrast, the unembanked areas are elevated, resulting in lower inundation depths when flooded. Measures like wet and dry floodproofing are generally effective for relatively low inundation depths (ICPR 2002; Kreibich et al. 2005).
3. A prerequisite for successful dry floodproofing is that there is time to close off doors and other openings in buildings. Flooding in unembanked areas can generally be forecasted quite well, whilst flooding behind embankments is more related to an embankment failure, which is much more difficult to predict.
4. Residential developments on the waterfronts of the unembanked areas have strong potentials to attract higher income groups to the cities; properties near water have significantly higher values (Luttik 2000). This is a major reason for most of the municipalities in the larger Rotterdam area to redevelop old harbour areas. Therefore, measures are needed to decrease damages, while maintaining the view to the river.
5. The Dutch Water Act states that the state will not compensate for flood damages in unembanked areas. As they would not qualify for compensation (unless an exception is made), inhabitants would thus benefit directly from damage-reducing measures.

It should be kept in mind that it is only possible to implement measures in the unembanked area when they fit within the current regulatory frameworks. Therefore, the regulatory framework will also be explored in this study.

Methods

We followed the steps displayed in Fig. 2 to estimate the expected flood damage per year (risk) for (a) the current situation without measures, (b) different climate change scenarios for the years 2050 and 2100 and (c) both the current and future situation with measures. The economic value of buildings and land-use classes have been determined using different data sources (section "Land-use information"). This information on exposed assets determines the potential flood damage in case of a flooding event. Future changes in flood damage were estimated using simulations of inundation depths assuming both sea level rise and changes in peak river discharge. Through combining the flood inundation depth maps (see section "Inundation depths") with land-use information, potential damage was calculated using a damage model (see section "Flood damage model"). With flood damages corresponding to different probabilities, an exceedance probability loss (EPL) curve can be constructed, from which the expected annual damage (EAD) can be calculated (Ward et al. 2011). All flood damage calculations were performed at spatial grids of 5 × 5 m^2. Finally, flood risk measures (section "Damage-reducing measures") were implemented in the damage model in order to calculate their effectiveness in reducing flood risk. The steps used in this method, as well as the data and future scenarios, are described in detail below.

Land-use information

In this study, we use a combination of land use (i.e. a hectare of residential or agricultural use) and individual objects (i.e. residential housing, hospital, etc.). The advantage of land-use-based methods is that there is often more data available on land use, and it usually covers the whole of the area, including infrastructure and public spaces. Object-based methods, on the other hand, allow for a more detailed assessment by circumventing generalisations on the density of buildings, which can have a huge impact on the results (Jongman et al. 2012). Moreover, most of the empirical data available for flood damages are for individual buildings.

In this study, we combined object-based information with land-use information to create high resolution (5×5 m^2) grids, representing the current situation of land use (the year 2010). The land-use information is based on a combination of datasets (Table 1). The CBS land-use dataset, developed by the Dutch statistics agency on the basis of maps, aerial photos and other digital sources (CBS 2008), is the basis of the aggregation procedure as it covers the area entirely and differentiates between different urban uses (i.e. residential, commercial, industrial, public services, horticulture). Moreover, it also provides effective differentiation in green land uses, such as parks, sport areas, garden complexes and recreation. While the CBS data show little detail in agricultural areas and infrastructure, the Top10 dataset (Kadaster 2005), on the other hand, has detailed information on these classes but is less detailed in urban areas. We reclassified the area designated as agriculture in the CBS dataset into five classes based on the Top10 dataset: arable farming, livestock farming, orchard, fruit trees and homestead. In addition, roads and railroads are superimposed from the Top10 dataset onto the new land-use map. Finally, building footprints were derived from the BAG dataset (Kadaster 2011), which differentiates between 11 different uses of buildings: residential, industrial, office, retail, accommodation, healthcare, education, jail, sporting, community buildings and a class of other buildings. These BAG building types replace the land-use classes of the CBS dataset. The aggregation procedure resulted in a new 5×5 m^2 land-use grid map distinguishing 36 types of land use and 11 types of buildings (see Table 2 for classes and Fig. 1 for the map).

Inundation depths

Flood hazard information was available in the form of flood inundation depths at a resolution of 5×5 m^2. The inundation maps used in this study are updates of the maps developed by Huizinga (2010) and show both inundation

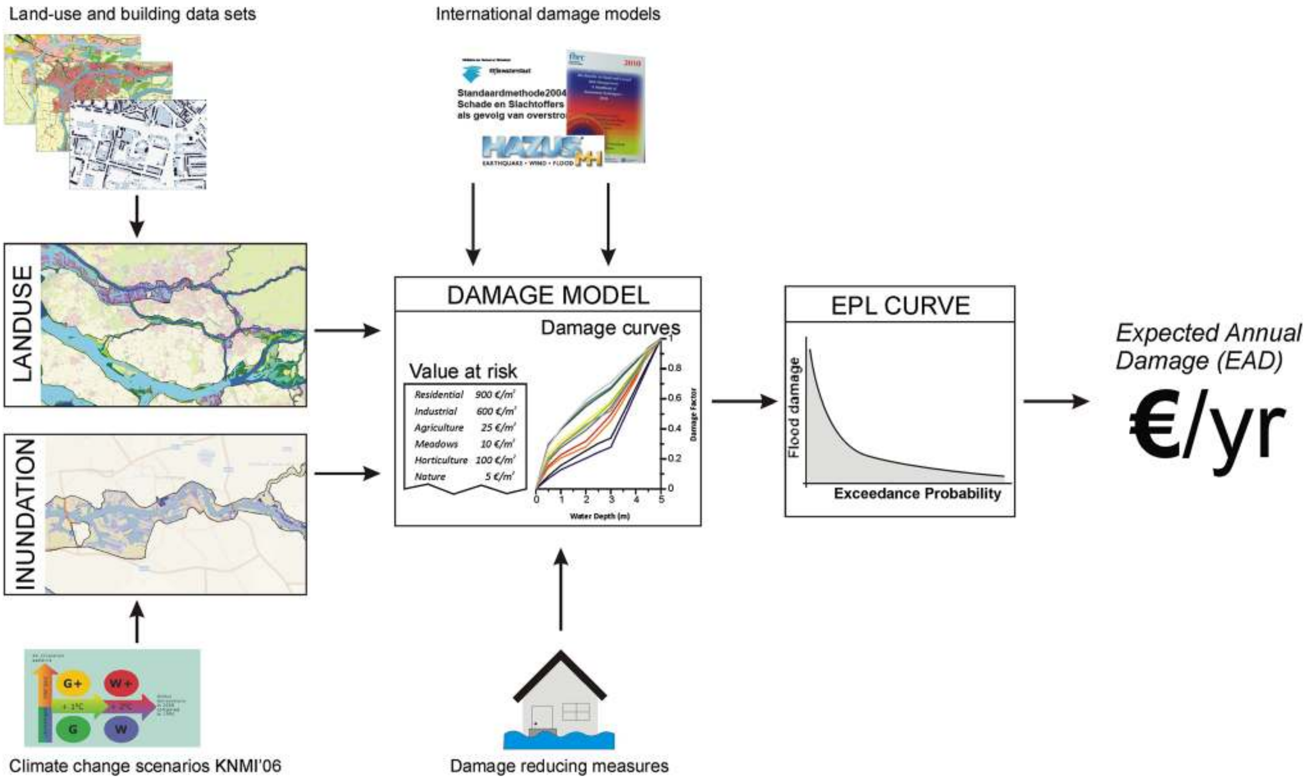

Fig. 2 Schematic overview of the methodology used in this study. Note that the values and curves depicted in damage model box are hypothetical. See Table 2 and Fig. 4 for the values and curves used in this study

Table 1 Description of the datasets on which the land-use map is based

Name	Source	Type	Full cover	Reference year
BAG	Municipalities	Points (function) and polygon (building footprint)	No	~2008
Top10 vector	Kadaster	Polygon (roads, buildings, etc.)	Yes	~2007
CBS land use	Central Bureau of Statistics	Polygon (use)	Yes	~2010

Table 2 The 36 land-use classes distinguished in this study, the source of the land-use information from which each class is derived, and their associated maximum damage values

Group Land use Building	Source	Value (EUR/m^2) Area/building	Content	Group Land use	Source	Value (EUR/m^2) Area/building
Urban				*Recreation and green*		
Residential area	CBS (2008)	50		Parks	CBS (2008)	0.04
House	BAG	1,600	800	Sport fields	CBS (2008)	0.04
Garden shed/unknown	BAG	1,000	100	Garden complex	CBS (2008)	0.04
Rural residential area	Top10	20		Recreation (day)	CBS (2008)	0.04
Public and social services area	CBS (2008)	50		Holiday accommodation	CBS (2008)	100
Community house	BAG	1,400	800	Forest	CBS (2008)	0
Jail	BAG	1,000	100	Dry nature	CBS (2008)	0
Healthcare	BAG	2,500	2,500	Wet nature	CBS (2008)	0
Education	BAG	2,000	1,200			
				Infrastructure		
Sport	BAG	1,600	600	Railroads	CBS (2008)	2,500
Miscellaneous	BAG	1,000	100	Highways	Top10	55
Commercial area	CBS (2008)	50		Major roads	Top10	55
Office	BAG	5,000	1,200	Roads	Top10	40
Shop	BAG	1,400	1,200	Unpaved roads	Top10	20
Accommodation	BAG	1,600	800	Parking lot	Top10	40
Miscellaneous	BAG	1,000	100	Airport	CBS (2008)	110
Industrial area	CBS (2008)	40				
				Miscellaneous		
Industry	BAG	1,800	1,200	Waste site	CBS (2008)	0.04
Shed (industrial)	BAG	1,200	1,000	Wreck storage	CBS (2008)	0.04
				Cemetery	CBS (2008)	0.04
Agriculture						
Horticulture	CBS (2008)	40		Mining	CBS (2008)	0.04
Greenhouse	BAG	100	1,000	Building lot	CBS (2008)	0.04
Arable land	Top10	0.8		Miscellaneous paved	CBS (2008)	0.04
Shed/stable	BAG	100	1,000	*Water*		
Livestock farming	Top10	0.1		Freshwater reservoir	CBS (2008)	10
Orchard	Top10	10		Dredging storage	CBS (2008)	0
Fruit trees	Top10	10		Inland water	CBS (2008)	0
				Major river	CBS (2008)	0
				Sea	CBS (2008)	0

Maximum damage values have been derived from various sources

levels for the current climate and for two projections of climate change. For the current climate situation and climate change projections, inundation depth maps for 6 different return periods (1/10; 1/100; 1/1,000; 1/2,000; 1/4,000; 1/10,000) are used and combined into an estimate of expected annual damage (see for the procedure e.g. Meyer et al. 2009; Ward et al. 2011). An example of a 1/1,000 inundation map for 2100 is shown in Fig. 3.

The two climate change projections are derived from the Dutch KNMI’06 scenarios (Van den Hurk et al. 2006) and labelled 2050 and 2100. Both scenarios assume an increase in river discharge of 13 % for the Rhine and 21 % for the Meuse river, as well as a slight increase in storm duration (35 h instead of 29 h). The probability of failure of the storm surge barrier in the Nieuwe Maas (near Maassluis) is estimated to be once every hundred times it should be closed. The 2050 scenario further assumes a sea level rise of 35 cm, in line with the upper estimates of the W scenarios of KNMI’06 (based on a global temperature increase of +2 °C). The 2100 scenario assumes a sea level rise of 60 cm, which is the middle of the range of the W scenarios of KNMI’06. Given the uncertainties related to future projections of climate change, these scenarios should be considered as explorative what-if scenarios, with the labelled years being indicative of when such conditions may occur.

Flood damage model

Potential flood damage is calculated using so-called damage curves (Smith 1994, Merz et al. 2007). A stage–damage curve shows, for a particular land-use category, how much of a fraction (‘damage factor’) of the maximum value at risk is reached at a particular inundation depth (see Fig. 4). Flood damage models based on stage–damage curves are used in many countries, including USA (Scawthorne et al. 2006), UK (Penning-Rowsell et al. 2010) and Germany (Thieken et al. 2008; Kreibich et al. 2010). Damage curves, as well as associated maximum values at risk, have to be assigned to each land use and building type. As a new land-use map has been developed, curves and associated maximum values had to be assigned to all 36 land-use classes. These have been determined by combining information of various damage models from the Netherlands and other countries: The US-based HAZUS model (Scawthorn et al. 2006), the UK-based Multi-Coloured Manual (MCM, Penning-Rowsell et al. 2010) and the Dutch HIS-SSM (Kok et al. 2005, Briene et al. 2002). In addition, insights of studies from Vanneuville et al. (2006), Dutta et al. (2003), Hoes (2007) and information from Statistics Netherlands have been used.

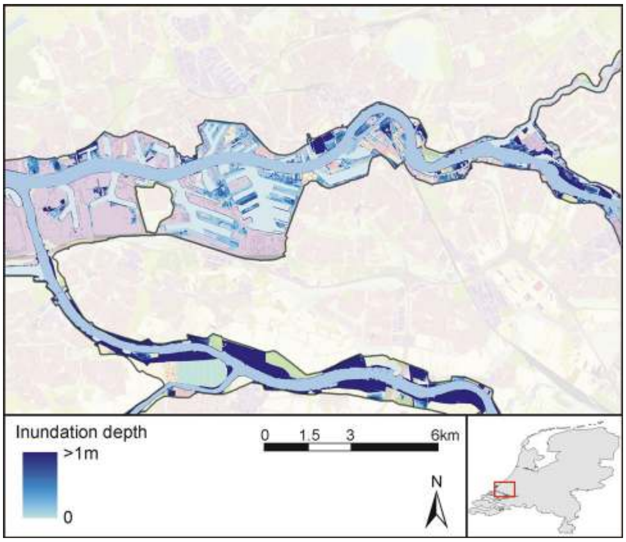

Fig. 3 Part of an example inundation map for the Rotterdam area. Water levels correspond to a 1/1,000 year event in 2100. Background is the same land-use map as depicted in Fig. 1

The stage–damage curves and associated maximum values at risk for residential *building structure* are mainly based on curves from HAZUS, the MCM and Dutta et al. (2003). These models and studies all show that the shape of damage curves for residential building structure rises fastest at low inundation depths and slows down at higher inundation depths (i.e. upwards convex shaped). Moreover, the relative curves of Dutta et al. (2003) and HAZUS show that the maximum damage factor reached for structural damage to residential buildings generally does not exceed 0.6–0.7 of the total value at risk. It is expected that many structural components will not be completely damaged after a flood (FEMA 2009: p. 5-3). Correspondingly, an upwards convex curve that flattens out at a damage factor of 0.6 has been used for building structure (Fig. 4). The maximum value at risk for residential building structure has been estimated at EUR 1,600 per m^2, based on building cost data from Statistics Netherlands (CBS 2012).

For residential *building content*, also a curve rising fastest at low inundation depths is used. The technical report of HAZUS (FEMA 2009: p. 5-12) mentions that there is roughly a 60/40 split in content damage between the first and second floor. Moreover, both HAZUS and MCM use upwards convex curves to represent the damage curve for content, which rises even more sharply than damage to the building structure. Therefore, a damage curve for building content has been created that rises quickly to 0.6 at 3 m (1st floor) and then proceeds to 1 (maximum damage) at higher inundation depths (2nd floor, see Fig. 4). With respect to the value at risk, many studies state that the value at risk of building content is roughly half of the value of the building structure (Kok et al. 2005; Vanneuville et al. 2006; Penning-Rowsell et al. 2010). In addition, estimates of the content values from inventories of insurance companies (e.g. http://www.berekenhet.nl/modules/wonen/inboedelwaarde.html) show that building content values are roughly 40–50 % of the average building structure value. Correspondingly, a maximum value at risk of EUR 800 per m^2 has taken for residential building content.

The same stage–damage curves for both building structure and building content have been used for the non-

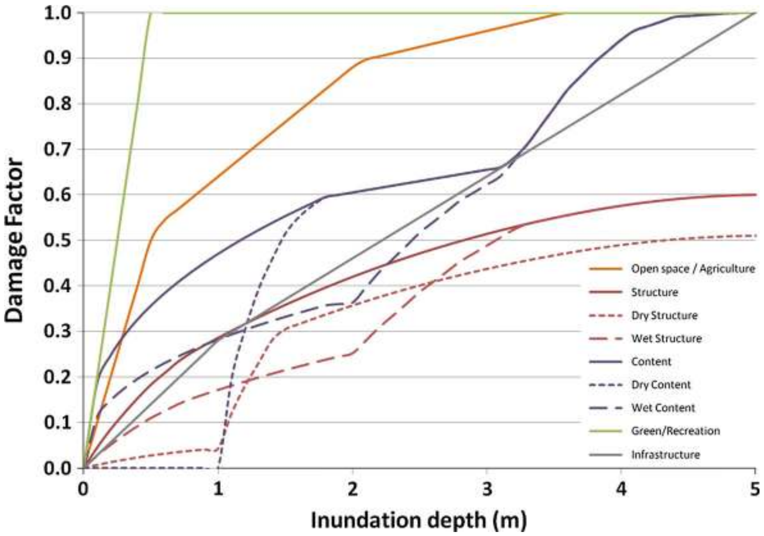

Fig. 4 Damage curves used in this study. Note that building damage is divided into damage to building structure and damage to building content. The *dashed lines* illustrate the effect of dry proofing and wet proofing on the damage curve

residential buildings (Table 2). However, the associated maximum value at risk has been adjusted using information from HAZUS and MCM, who also distinguish several different building types. For example, the maximum value at risk for healthcare buildings is considerable higher regarding both structure and content. The maximum value at risk for sheds is, however, much lower.

Furthermore, for the non-building land uses such as agriculture, recreation and infrastructure, curves and associated values at risk have been taken from various sources depending on applicability to the classes distinguished in our land-use map. For urban land use (i.e. open space between the buildings), maximum values at risk have been taken from Briene et al. (2002) and the stage–damage curve from HIS-SSM (Kok et al. 2005). For agricultural uses, the curve from the HIS-SSM has been used, but maximum values at risk have been taken from a variety of sources, such as HIS-SSM and national statistics data for horticulture and greenhouses, Briene et al. (2002) for arable land and Hoes (2007) for cattle farming and orchards/fruit trees. For recreation and green and miscellaneous land-use classes, only clean-up costs have been taken into account, in line with Vanneuville et al. (2006). Only for intensive recreation (holiday accommodation) has a different curve been used based on expert judgement. The damage curve for infrastructure has been taken from HIS-SSM (Kok et al. 2005), and values at risk have been recalculated to m^2 from Briene et al. (2002). Finally, damage to water classes has been set to zero, except for freshwater basins. The maximum value at risk for these basins has been based on conservative estimates of the costs of drinking water, which are assumed to be lost when lower quality flood waters enter the storage basin.

Damage-reducing measures

Various types of damage-reducing measures can be implemented in the model in order to estimate their effects on flood damage. Table 3 shows the damage-reducing measures considered in this study, including their effects.

Elevating buildings or an entire housing block reduces flood damage in quite a straightforward way in that it requires higher inundation depths before it gets flooded. This measure has been implemented in the model by reducing the inundation depth of an area or buildings by the amount with which is elevated. This has been done for three elevations: +0.5, +1 and +2 m. In a similar way, *elevating area* has been modelled, in which case not only the buildings, but the entire area including open spaces is elevated +0.5, +1 and +2 m.

Dry proofing concerns sealing a building so no water can enter it. This includes the closing of openings (doors, windows), waterproofing the outside wall and making sure no water enters the house through the sewer systems through installing back stop valves (Manojlovic and Pasche 2007). As dry proofing keeps the water out, it can considerably reduce damage from flooding, up to a certain water level. Dry proofing walls above a certain level is not useful, as the pressure difference between water outside and lack of water inside the building would make it structurally unstable and could result in failure of the outside walls. In this study, we therefore assumed dry proofing up to an elevation of 100 cm, in line with Bubeck and De Moel (2010) and Poussin et al. (2012). The stage–damage curves have been adjusted to account for dry proofing in the damage assessment (Fig. 4). Both content and structural damage of buildings have been reduced with 85 % for inundation depths lower than 1 m, in line with the

Table 3 Damage-reducing measures considered in this study and their effect

Measure	Effect
Elevating area	Decrease in inundation depths for entire area
Elevating building	Decrease in inundation depths for buildings
Dry proofing	Large reduction in damage factor up to 1 m
Wet proofing	Medium reduction in damage factor up to 3 m
Warning/ communication	Reduction in content damage

findings from ICPR (2002) and DEFRA (2008). Above the 1 m inundation depth threshold, content damage quickly rises to its normal level. The curve for structural damage also rises sharply after 1 m inundation depth, but remains 15 % lower than the normal curve as the water-resistant material will still result in less damage, as shown by Kreibich et al. (2005).

In contrast to dry proofing, *wet proofing* is a measure that allows water to enter the building, but aims at reducing the damaging effects when it does. This can be achieved by various alterations or changes such as moving vulnerable functions and installations to higher floors or the use of elevated electricity sockets. It has been shown by Kreibich et al. (2005) that such adaptations reduced the damage to building structure and content by roughly 40–50 % during the 2002 Elbe floods. This is in line with the estimates of ICPR (2002) and DEFRA (2008), who reported reductions of 30–40 % and roughly 50 %, respectively. Correspondingly, we created stage–damage curves that are 40 % lower than the normal level for both building structure and content (Fig. 4). As wet proofing involves moving functions to another level or raising them to a certain elevation, this reduction effect wears off after 3 m of inundation depth, at which point the second floor will also be flooded.

Finally, the effect of adequate warning, communication and response of people was simulated. The rationale is that when people are properly warned in time, they have the opportunity to move valuable items to safe elevations (i.e. the attic) and thus reduce damage to content. In HAZUS, a curve is used that indicates the reduction in damage as a function of the warning time (Scawthorne et al. 2006). This function rises to about a 35 % reduction in 48 h. At 24 h, the reduction is around 30 %. In this study, we also performed analyses with such a reduction to illustrate the possible effects of an adequate warning and communication system. This reduction is only applied to content damage of residential buildings, as it is assumed that people will take care of their homes before their place of work when warned.

Results and discussion

Current flood risk

Table 4 shows the land use affected by flooding for an event with a return period of 4,000 years. This is mostly nature/recreation (~43 %) and agriculture (~32 %). With a lot of industrial areas and harbour-related activities in the unembanked areas, the share of industrial land use in the potentially affected parts is relatively large: ~5 %. Residential and other urban land use is not so common, roughly 1 % each (Table 4).

Figure 5 shows the EPL curves illustrating the probability that a certain amount of damage will be exceeded (Grossi et al. 2005). The curves show that for extreme events (return periods <1/4,000 per year) damages increase drastically. Flood damage for a flood event with a return period of 1/10,000 per year (the highest safety standard of the embanked part of the Netherlands) is estimated at more than 2 billion euros under current climate conditions. With a changing climate, damages of such extreme events increase up to almost 4 billion (2050 scenario) and over 6 billion (2100 scenario). By taking measures, like elevating buildings 100 cm (grey curve in Fig. 5), damages can be reduced substantially. Where the EPL curve combines losses from events with different return periods, the area under the curve corresponds to the EAD: an aggregate measure of the risk. For the current situation (i.e. the solid black line in Fig. 5), this corresponds to 36 million euro per year (Table 4). A large share of this results from damage to industrial assets and land (Table 4). Other large contributors to the total EAD are infrastructure, residential and other urban land use. It should be noted that industry has not been differentiated between different types of industry,

Table 4 Area affected and expected annual damage (EAD, mln EUR/year) of different land-use types

	Area	EAD	
	%	10^6 EUR/year	%
Residential	1	3.3	9
Other urban	1	5.9	16
Industrial	5	21.7	60
Agriculture	32	1.4	4
Nature/recreation	43	0.9	2
Infrastructure	2	2.8	8
Miscellaneous	8	0.0	0
Water	8	0.0	0
Total		36.0	

Note that the numbers given for the area correspond to the inundation extent corresponding to a 1/4,000 per year event. The relative area affected may be different for other return periods even though it is a very heterogeneous land-use class. Overall, ∼33 % of the total EAD can be attributed to damage to building structure, and ∼44 % can be attributed to damage to building content. Together, damage to buildings consequently constitutes about 77 % of the total EAD, indicating the potential of building level adaptation measures to reduce flood risk.

Considering the limited area outside embankments, our estimate of EAD is quite large for Dutch standards. Estimates of flood risk for the embanked part of the Netherlands have, for instance, been estimated at 88 million per year (Aerts et al. 2008) and 140 million per year (Klijn et al. 2007). However, these estimates for the embanked part are based on the design standards, which are very high for the embanked part (1/1,250–1/10,000 per year). Ward et al. (2011) shows that especially the high frequency (i.e. not so extreme) events contribute relatively substantially to the total EAD. To illustrate, Ward et al. (2011) estimated the EAD of the upstream Dutch Meuse area at 34 million euros annually, even though this is a far smaller area than the embanked part. Similarly, Bouwer et al. (2010) estimated the EAD of a single dike ring (dike ring 36) on 20 million euros per year, taking into account flooding before design conditions (as a result of dike failure rather than overtopping). As events with a relatively high frequency do occur in the unembanked area, the EAD becomes therefore relatively high.

Effect of damage-reducing measures and climate change

The results of the various risk calculations with measures and climate change scenarios are shown in Table 5. From this, the effect of various types of damage-reducing measures (when implemented in the entire area) and the effect of climate change can be inferred (the % change in Table 5). When considering the current climate conditions, the results show that measures implemented at the building level result in considerable damage reduction. Elevating all buildings would result in a risk reduction of 50 % (50 cm elevation) to about 74 % (200 cm elevation). Dry floodproofing would result in a reduction of ∼61 % and wet floodproofing in ∼29 % reduction. The effect of dry floodproofing is relatively large in comparison with elevating buildings and wet floodproofing. Dry floodproofing all buildings has an effect about as large as elevating all buildings with 50–100 cm. As dry floodproofing is particularly effective at low (<1 m) inundation depths, where wet floodproofing is more effective at medium (100–250 cm) inundation depths, these results illustrate that the inundation depth for many buildings is relatively low in the unembanked areas considered in this study. This is further supported by the relatively small difference in risk reduction between elevating buildings 100 and 200 cm, indicating that inundation levels for buildings are generally low (up to 100 cm) in the unembanked area. The largest overall effect is achieved when the entire unembanked area is elevated. This would result in a large decrease in flood risk: elevating the entire area 50 cm will reduce risk by 61 % and elevating it by 200 cm would reduce the risk 95 %.

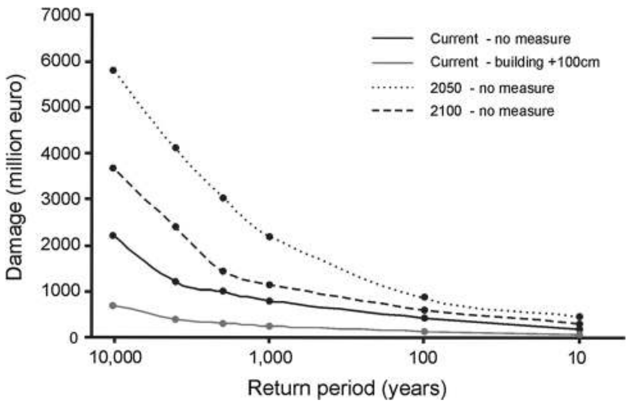

Fig. 5 Exceedance probability loss curves for the current situation, future situations and a situation in which all buildings would be elevated 100 cm

Adequate warning and response of people are found to only have a limited effect on the total risk of the area (1 % reduction). This is largely due to the fact that it only reduces damage to the content of homes, which in itself accounts for only 3.5 % of the total EAD. When looking at the EAD of residential buildings only, adequate warning would result in a risk reduction of about 16 % (Table 6). Table 6 also shows the risk reduction of all other building level measures on the risk of only the residential buildings. As can be seen, this effect is quite substantial. Wet proofing would reduce the flood risk of residential buildings in the area by about 40 %, and dry proofing by about 89 %. Elevating buildings 100 cm or more would virtually eliminate the entire EAD of residential buildings. The total EAD of residential buildings, 2.5 million euros per year, is substantially higher than Veerbeek et al. (2010), who estimated the risk in the unembanked part of the larger Rotterdam area at 0.16 million euros per year. This difference may be due to different (synthetic) depth-damage curves and values at risk or slightly different inundation depths and extent. An important difference is furthermore that Veerbeek et al. (2010) corrected for elevated floor levels in the area, as floors can be several decimetres above the ground level. Our result for elevating residential buildings by 50 cm, which resulted in 0.5 million euros per year, shows that this can have a large effect.

Our results related to the effect dry and wet proofing are higher than the findings of Poussin et al. (2012), who

Table 5 Total EAD corresponding to risk calculations with various types of damage-reducing measures and climate change scenarios

Total EAD	Current		2050		2100	
	EAD	% Change	EAD	% Change	EAD	% Change
No measure	**36.0**		52.1	+45	76.2	+112
Warning	35.6	−1	51.4	+43	75.2	+109
Wet proofing	25.5	−29	36.6	+2	53.2	+48
Dry proofing	14.1	−61	20.1	−44	29.8	−17
Building +50 cm	18.0	−50	25.7	−29	37.8	+5
Building +100 cm	11.7	−67	16.5	−54	24.2	−33
Building +200 cm	9.4	−74	12.8	−65	18.0	−50
Area +50 cm	14.1	−61	20.3	−44	29.6	−18
Area +100 cm	5.8	−84	8.5	−76	12.5	−65
Area +200 cm	1.8	−95	2.5	−93	3.3	−91

Simulated estimates of EAD for the different measures and/or climate change scenarios are given in mln EUR/year. The percentual changes are related to the baseline situation of no measures and the current climate (bold value)

investigated the effect of dry and wet floodproofing in the upstream part of the Dutch Meuse river. They reported decreases in EAD of 10–15 % for wet proofing and 15–25 % for dry proofing. Both studies consequently agree on dry proofing being particularly effective. The larger risk reduction estimated in this study is probably related to the relatively low inundation depths that buildings would experience in our study area. Both our estimates and those of Poussin et al. (2012) are higher than those reported by Bubeck and De Moel (2010) for the Rhine basin, who reported risk reductions of ~7 % (wet proofing) and ~5.5 % (dry proofing). This is likely also related to different flood characteristics of the studies, as the flooded area in the study of Bubeck and De Moel (2010) comprises many deep polder areas with large inundation depths where building level measures are not as effective.

Tables 5 and 6 also show the adverse impacts of climate change (sea level rise and increased peak river discharge) on flood risk in the unembanked area. The results show that the EAD may increase with 45 % by 2050 and 112 % by 2100 (Table 5). Many of the measures considered in this study could offset this increase in risk. For instance, elevating all buildings 50 cm towards 2100 would almost nullify the adverse effects of climate change on the total flood risk (Table 5).

When only looking at the flood risk of residential buildings (Table 6), we see that the risk increases more than the total risk (82 % by 2050, 180 % by 2100). It is found that with the exception of wet proofing under 2100 climate conditions, all investigated measures could offset the negative impacts of climate change on flood risk. These results indicate that building level measures can successfully mitigate the adverse effects of climate change on the flood risk of those buildings. The effect of climate change on flood risk as estimated in this study is at first glance lower than those of Veerbeek et al. (2010), who reported a doubling of EAD in 2050, and a four time increase by 2100. This may again be related to the correction for floor level elevations that was performed by Veerbeek et al. (2010), as our results for the risk of residential buildings with 50 cm elevation of those buildings shows an increase that is very similar: from 0.4 to 0.9 million euro per year in 2050 and to 1.6 million euro per year in 2100 (Table 6).

Regulatory framework

Although the results show that building level measures can successfully lower damages, most of these measures are still little used. Up to now, new developments are normally

Table 6 EAD corresponding to risk calculations for residential buildings with various types of damage-reducing measures and climate change scenarios

EAD residential buildings	Current		2050		2100	
	EAD	% Change	EAD	% Change	EAD	% Change
No measure	**2.5**		4.5	+82	6.9	+180
Warning	2.1	−16	3.8	+54	5.9	+138
Wet proofing	1.5	−40	2.7	+11	4.2	+71
Dry proofing	0.3	−89	0.6	−76	1.0	−60
Building +50 cm	0.4	−83	0.9	−63	1.6	−34
Building +100 cm	0.1	−97	0.2	−90	0.4	−82
Building +200 cm	0.0	−99	0.1	−96	0.2	−93

Simulated estimates of EAD for the different measures and/or climate change scenarios are given in mln EUR/year. The percentual changes are related to the baseline situation of no measures and the current climate (bold value) elevated to reduce damages. In currently build-up areas, however, this is problematic as it results in height differences (Van Veelen 2012). There are a number of reasons why adaptive building techniques are still little used (see Van Vliet and Aerts 2012). One of them is the current regulatory framework. Van Vliet (2012) made an inventory of Dutch policies, rules and regulations related to spatial planning, building codes and water management. He showed that the implementation of new adaptive measures at the building level is possible but needs concerted action across different governance tiers.

On the *national level*, some water regulations include rules for the use of unembanked areas (Ministry I&E 2006, 2011). For example, building development and other new activities are only allowed when they do not decrease the rivers' discharge capacity. However, the policy does not address any regulations that guarantee the safety of the new activities. The state will compensate for flood damages in the embanked areas but *not* for damages in unembanked areas.

In terms of *zoning* regulations, municipalities have to develop land-use zoning plans every 10 years. They are legally binding, for civilians as well as governments. Relocating critical and flood-sensitive functions (which decreases both direct and indirect damages) can be included in new zoning plans (see for instance Van Veelen 2012), for instance on the basis of flood maps. Land-use zoning plans, however, cannot enforce changes. This makes flood zoning in existing build-up areas difficult. If a municipality wants to move a critical function, they cannot simply rezone the plot and designate it a non-critical function. Rezoning is only possible when it is clear that the current function will cease within 10 years (Van Vliet 2012). The government could buy the sensitive function and then move it, or offer them a new location elsewhere. Only for extremely urgent and important causes that serve the general public interest is the government entitled to force people to sell their property. The possibility of flood damage will most likely not qualify as such.

Given the good results of dry floodproofing (reducing damage to buildings by ~88 %), municipalities might want to enforce dry proofing in unembanked areas. This is, however, not possible. The state has developed *building codes* to ensure that buildings are built safely and can be used safely (Ministry of Internal Affairs 2011). These contain, among others, rules for the building process, fire safety, electricity, heating, rainwater discharge and isolation of the building. They also include standards for the water resistance and absorption of facades, but these are not aimed at flood situations (van Vliet 2012). Other government levels such as municipalities cannot enforce standards that are stricter than the building codes. Enforcing wet and dry floodproofing is consequently not possible as it requires municipalities to apply standards that are stricter than the current standards on water resistance and water absorption in the national building codes. These codes would have to be changed in order to allow this. Therefore, at the moment, municipalities can only make voluntary agreements with building companies.

The process of entering into voluntary agreements can be stimulated by communicating the current and future flood risks and associated costs (Baan and Klijn 2004; Terpstra and Gutteling 2008). Communication can also create awareness, which might make flood warning more effective, which, according to our calculations, may have the potential to reduce damages to residential buildings by 15 %. Policies on flood risk *communication* differ between municipalities. Rotterdam does not actively warn its citizens. A recent study in Rotterdam showed that only half of the people that live in the unembanked areas know that they live in an unembanked area (De Boer et al. 2012). Another reason for better communication, besides raising awareness, is to lower the liability of municipalities (Van Vliet and Aerts 2012). If municipalities do not warn their inhabitants, the inhabitants are unaware of the risk and that they should take measures. Therefore, they could sue the municipality. When they are aware, the municipality is less liable, as owners could have taken measures themselves.

Discussion

Flood risk assessments, as carried out in this study, comprise of various different models and many different sources of input data. As a consequence, results are surrounded by uncertainties that should be considered when interpreting the results. Various studies have assessed such uncertainties in flood risk assessments (e.g. Apel et al. 2008; De Moel et al. 2012). Important uncertainties exist in the calculation of inundation depths in the unembanked area. Key assumptions like the duration of a flood event, closure of surge barriers, redirecting of flood waters, etc., can greatly influence resulting risk estimates (see e.g. De Moel et al. 2012; De Moel 2012). Moreover, there are also considerable uncertainties associated with the damage calculation itself in flood risk assessments (see e.g. Merz and Thieken 2009; Freni et al. 2010; De Moel et al. 2012). Though not explicitly considered in this study, these factors cause substantial uncertainties in flood risk estimates. Especially absolute estimates of flood risk are affected by this (i.e. the 40 million euro p.a.). Relative estimates, like the % change shown in Tables 5 and 6, have been found to be more robust (De Moel and Aerts 2011; Bubeck et al. 2011). Nevertheless, under- or overestimation of, for instance, inundation depths, could seriously impact the effectiveness of measures addressed in this study as building level measures are typically effective up to a certain water level. Slootjes et al.

(2011) performed a sensitivity analysis of water levels in the Rijnmond region, including our study area. They show that the location in the region is very important with respect to how uncertainty in boundary conditions affect water levels. The effect of design river discharge on water levels is, for example, quite limited in the area considered in our study (generally less than a decimetre), whilst varying sea levels and the probability of failure of the storm surge barrier in the Nieuwe Maas have much more pronounced effect on water levels (several decimetres).

In this study, different types of measures have been applied on the current building stock of the entire area. Given the size of the area and the amount of buildings, this should not be considered a realistic option, but it rather illustrates the effectiveness of said measures and thus supports considerations surrounding the development of new urban areas in this unembanked region. Of course, the effectiveness of a measure should directly be related to the costs of said measure, though a full cost-benefit analysis is outside the scope of this paper. The costs of taking building level measures could very well be manageable, especially when considering that taking measures when developing new buildings is considerable less costly. For instance, the costs of mining and transporting a cubic metre of sand are in the range of 5–15 euro (Van Vliet et al. 2012). Jones et al. (2006) report that, for the USA, the extra costs of elevating a building at construction time with 1 m vary between 0.75 and 9 % of the original building costs. Ideally, cost-benefit analyses should be performed spatially, to allow for a distinction of where a measure may be most cost-effective.

It is acknowledged that other considerations than just (cost-) effectiveness would play a role in such a case as well. For instance, elevating the entire unembanked region would severely limit the storage and discharge capacity of the river, which would result in increased water levels and endanger the embanked parts of the region. Moreover, considerations related to the appropriateness at a certain location would also play a role in decision-making. Allowing areas to be flooded once in a while can have additional benefits like maintaining the view on the river, preserving the atmosphere of historical area and creating interesting new living environments. Historical areas like the waterfront in Dordrecht show that inhabitants can tolerate hinder of floods. In the end, it is up to decision makers to make a final choice between measures from the different layers. This should ideally be based on a thorough analysis of various measures from all layers and their pros and cons using a common framework.

Conclusions

The MLS framework has been proposed in the Netherlands as a possible approach to effectively address flood risk management issues. This MLS framework distinguishes three layers of measures to reduce flood risk: (1) flood prevention, (2) smart spatial planning to reduce flood damage and (3) proper disaster risk management to limit casualties. In order to support such an approach, this paper explored the regulatory framework to implement damage-reducing measures (i.e. layer two measures) and presented a methodology to estimate the effect of such measures. This methodology has been applied to the unembanked region of the larger Rotterdam area and includes projections of climate change on the flood hazard.

Our results show that the current flood risk in the unembanked larger Rotterdam area is substantial: EUR 40 million p.a. A large part of this risk can be attributed to industrial land use. Industrial land use was modelled rather crudely, however, using only a single class despite the known large heterogeneity. Future flood risk estimates would thus benefit from a more detailed consideration of this land-use category. Furthermore, climate change has been found to have a profound negative impact on flood risk in the region, doubling the total flood risk in 2100. This change in flood hazard combined with possible future residential developments in the region calls for the consideration of risk-reducing measures. The results of this study show that damage-reducing measures (layer two of the MLS framework) can substantially reduce flood risks in this unembanked region. It was found that dry proofing all buildings up to 1 m would reduce the total flood risk of the region by 56 %. Also, the elevation of buildings has a considerable effect. Elevating all buildings by only 0.5 m would already result in reducing the total flood risk of the entire region by half. When focusing only on the flood risk of the buildings, it was found that elevating buildings by more than 100 cm would virtually remove the entire risk, indicating that inundation levels of buildings in the unembanked region rarely exceed 1 m.

These results imply that the characteristics of the unembanked region (often elevated, possibility of issuing warnings) are favourable for building level flood risk-reducing measures. It is consequently warranted to consider building level measures when contemplating new residential developments or retrofitting existing buildings in the unembanked area. The existing regulations on building codes do not prevent the implementation of such measures. However, at the moment they can only be achieved by voluntary agreements between the municipality and developers. Municipalities cannot force developers to implement specific building level damage-reducing measures as that would go beyond the requirements of the national building code.

Acknowledgments This research was carried out in the framework of the Dutch National Research Programme “Knowledge for

Climate” (theme 1) and the EU TURAS project. The authors would like to thank Jan Huizinga for providing the inundation data that was used in this study. We would like to thank the editors and two anonymous reviewers for their constructive comments.

References

Aerts JCJH, Botzen WJ (2011) Flood-Resilient Waterfront Development in New York City: a study of flood insurance, building codes, and flood zoning. Ann NY Acad Sci 1227:1–82

Aerts JCJH, Sprong T, Bannink BA (2008) Aandacht voor veiligheid. 009/2008, Leven met Water, Klimaat voor Ruimte, DG Water. http://www.adaptation.nl

Apel H, Merz B, Thieken AH (2008) Quantification of uncertainties in flood risk assessments. Int J River Basin Manage 6(2):149–162

Apel H, Aronica GT, Kreibich H, Thieken AH (2009) Flood risk analyses-how detailed do we need to be? Nat Hazards 49(1):79–98

Baan PJA, Klijn F (2004) Flood risk perception and implications for flood risk management in the Netherlands. Int J River Basin Manage 2(2):113–122

Bouwer LM, Bubeck P, Aerts JCJH (2010) Changes in future flood risk due to climate and development in a Dutch polder area. Global Environ Change 20:463–471. doi:10.1016/j.gloenvcha.2010.04.002

Briene M, Koppert S, Koopman A, Verkennis A (2002) Financiele onderbouwing kengetallen hoogwaterschade. *I7435*, Netherlands Economic Institute (NEI), Rotterdam, The Netherlands (in Dutch)

Bubeck P, de Moel H (2010) Sensitivity analysis of flood damage calculations for the river Rhine. 32 Report IVM, DG Waters, The Netherlands

Bubeck P, de Moel H, Bouwer LM, Aerts JCJH (2011) How reliable are projections of future flood damage? Nat Hazards Earth Syst Sci 11:3293–3306

Büchele B, Kreibich H, Kron A, Thieken A, Ihringer J, Oberle P, Merz B, Nestmann F (2006) Flood-risk mapping: contributions towards an enhanced assessment of extreme events and associated risks. Nat Hazards Earth Syst Sci 6(4):485–503

CBS (2008) Bestand bodemgebruik 2008. Den Haag, Centraal Bureau voor de Statistiek. http://www.cbs.nl/nl-NL/menu/methoden/dataverzameling/bodemgebruik.htm

CBS (2012) Statline. http://statline.cbs.nl/statweb/. Accessed January 2012

De Boer J, Botzen W, Terpstra T (2012) Percepties van burgers over binnen- en buitendijks wonen. Rotterdam, Gemeente Rotterdam (Rotterdam Climate Initiative) (in Dutch)

De Kort R (2012) Kwetsbaarheid in het buitendijks gebied, analyse van de gevolgen van overstroming op vitale infrastructuur en stedelijke functies in Rotterdam. Stadsontwikkeling gemeente Rotterdam (in Dutch)

De Moel H (2012) Uncertainty in flood risk. PhD dissertation thesis, VU University Amsterdam. http://dare2.ubvu.vu.nl/handle/1871/38274

De Moel H, Aerts JCJH (2011) Effect of uncertainty in land use, damage models and inundation depth on flood damage estimates. Nat Hazards 58(1):407–425

De Moel H, van Alphen J, Aerts JCJH (2009) Flood maps in Europe—methods, availability and use. Nat Hazards Earth Syst Sci 9(2):289–301

De Moel H, Asselman NEM, Aerts JCHJ (2012) Uncertainty and sensitivity analysis of coastal flood damage estimates in the west of the Netherlands. Nat Hazards Earth Syst Sci 12:1045–1058

Defra (2008) Developing the evidence base for flood resistance and resilience: summary report. R&DTechnical report FD2607/TR1. Environment Agency and the Department for Environment Food and Rural Affairs (DEFRA), London

Dutta D, Herath S, Musiakec K (2003) A mathematical model for flood loss estimation. J Hydrol 277:24–49. doi:10.1016/S0022-1694(03)00084-2

FEMA (2009) Hazus MH MR4 Technical manual. Federal Emergency Management Agency, Washington, DC. Available at online at: http://www.fema.gov/library/viewRecord.do?id=3726

Freni G, La Loggia G, Notaro V (2010) Uncertainty in urban flood damage assessment due to urban drainage modelling and depth-damage curve estimation. Water Sci Technol 61(12):2979–2993

Grossi P, Kunreuther H, Windeler D (2005) An introduction to catastrophe models and insurance. In: Grossi P, Kunreuther H (eds) Catastrophe modeling: a new approach to managing risk. Springer Science+Business Media, Inc., Boston, pp 23–42

Hoes OAC (2007) Aanpak wateroverlast in polders op basis van risicobeheer. PhD dissertation, Technische Universiteit Delft (in Dutch)

Huizinga HJ (2010) HSRR02: water safety: flood depth and extent. Available online at: http://knowledgeforclimate.climateresearchnetherlands.nl/nl/25222818-Knowledge_transfer.html

ICPR (2002) Non-structural flood plain management: measures and their effectiveness. International Commission for the Protection of the Rhine

Jones CP, Coulbourne WL, Marschall J, Rogers SM Jr (2006) Evaluation of the National Flood Insurance Program’s building standards. Christopher Jones and Associates, Durham, USA

Jongman B, Kreibich H, Apel H, Barredo JI, Bates PD, Feyen L, Gericke A, Neal J, Aerts JCJH, Ward PJ (2012) Comparative flood damage model assessment: towards a European approach. Nat Hazards Earth Syst Sci 12:3733–3752. doi:10.5194/nhess-12-3733-2012

Kadaster (2005) Top10vector. Topografische Dienst Kadaster, Apeldoorn

Kadaster (2011) Basisregistraties adressen en gebouwen. Topografische Dienst Kadaster, Apeldoorn. http://www.kadaster.nl/window.html?inhoud=/bag/

Klijn F, Baan PJA, De Bruijn KM, Kwadijk J (2007) Overstromingsrisico’s in nederland in een veranderend klimaat. *Q4290*, WL|delft hydraulics, Delft, Netherlands (in Dutch)

Kok M, Huizinga HJ, Vrouwenvelder ACWM, Barendregt A (2005) Standaardmethode2004—schade en slachtoffers als gevolg van overstromingen. *DWW-2005-005*, RWS Dienst Weg- en Waterbouwkunde (in Dutch)

Kreibich H, Thieken AH (2009) Coping with floods in the city of Dresden, Germany. Nat Hazards 51:423–436

Kreibich H, Thieken AH, Petrow Th, Müller M, Merz B (2005) Flood loss reduction of private households due to building precautionary measures—lessons learned from the Elbe flood in August. Nat Hazards Earth Syst Sci 5:117–126

Kreibich H, Seifert I, Merz B, Thieken AH (2010) Development of flemocs—a new model for the estimation of flood losses in the commercial sector. Hydrol Sci J 55:1302–1314. doi:10.1080/02626667.2010.529815

Luttik J (2000) The value of trees, water and open space as reflected by house prices in the Netherlands. Landsc Urban Plan 48:161–167

Manojlović N, Pasche E (2007) FLORETO-web based advisory tool for flood mitigation strategies for existing buildings. In: Ashley R, Garvin S, Pasche E, Vassilopoulos A, Zevenbergen C (eds) Advances in Urban Flood Management. Taylor and Francis, New York

Meijers E, Hendriks M, de Greef P (2011) Regionale deltascenario’s Rijnmond-Drechtsteden. Deltaprogramma Rijnmond-Drechtsteden

Merz B, Thieken AH (2009) Flood risk curves and uncertainty bounds. Nat Hazards 51(3):437–458. doi:10.1007/s11069-009-9452-6

Merz B, Kreibich H, Thieken A, Schmidtke R (2004) Estimation uncertainty of direct monetary flood damage to buildings. Nat Hazards Earth Syst Sci 4(1):153–163

Merz B, Thieken AH, Gocht M (2007) Flood risk mapping at the local scale: concepts and challanges. In: Begum S, Stive M, Hall J (eds) Advances in natural and technological hazards research. Springer, Dordrecht, The Netherlands, pp 231–251

Merz B, Kreibich H, Schwarze R, Thieken AH (2010) Review article 'assessment of economic flood damage'. Nat Hazards Earth Syst Sci 10:1697–1724. doi:10.5194/nhess-10-1697-2010

Meyer V, Scheuer S, Haase D (2009) A multicriteria approach for flood risk mapping exemplified at the Mulde river, Germany. Nat Hazards 48:17–39

Ministry I&E (2006) Spatial planning key decision Room for the river: explanatory memorandum. Ministry of Infrastructure and the Environment, The Netherlands

Ministry I&E (2009) National water plan. Ministry of Infrastructure and the Environment, The Netherlands (in Dutch)

Ministry I&E (2011) Besluit algemene regels ruimtelijke ordening. Ministry of Infrastructure and the Environment, The Netherlands (in Dutch)

Ministry I&E and Ministry of Economic Affairs (2012) Deltaprogramma 2013—werken aan de delta. Ministry of Infrastructure and the Environment and Ministry of Economic Affairs, The Hague, The Netherlands

Ministry of internal affairs (2011) Bouwbesluit 2012. *Stb. 2011, 416* (in Dutch)

Penning-Rowsell EC, Viavattene E, Pardoe J, Chatterton J, Parker D, Morris J (2010) The benefits of flood and coastal risk management: a handbook of assessment techniques—2010. Flood Hazard Research Centre, Middlesex University Press, London

Poussin JK, Bubeck P, Aerts JCJH, Ward PJ (2012) Potential of semi-structural and non-structural adaptation strategies to reduce future flood risk: case study for the Meuse. Nat Hazards Earth Syst Sci 12:3455–3471. doi:10.5194/nhess-12-3455-2012

Scawthorn C, F.ASCE, Flores P, Blais N, Seligson H, Tate E, Chang S, Mifflin E, Thomas W, Murphy J, Jones C, Lawrence M (2006) HAZUS-MH Flood loss estimation methodology. II: Damage and loss assessment. Nat Hazards Rev 7(2):72–81

Slootjes N, Jeuken A, Botterhuis T, Gao Q (2011) Resultaten MHW berekeningen t.b.v. probleemanalyse en verkenning hoekpunten voor het Deltaprogramma Rijnmond-Drechtsteden. 1204302-000, p 71, HKV lijn in water, Deltares (in Dutch)

Smith DI (1994) Flood damage estimation—a review of urban stage–damage curves and loss functions. Water Sa 20:231–238

Terpstra T, Gutteling JM (2008) Households' Perceived Responsibilities in Flood Risk Management in The Netherlands. Int J Water Resour Dev 24(4):555–565

Thieken AH, Olschewski A, Kreibich H, Kobsch S, Merz B (2008) Development and evaluation of flemops—a new flood loss estimation model for the private sector. In: Flood recovery, innovation and response I. WIT Press, Chichester, pp 315–324

Van den Hurk B, Klein Tank A, Lenderink G, van Ulden A, van Oldenborgh GJ, Katsman C, van den Brink H, Keller F, Bessembinder J, Burgers G, Komen G, Hazeleger W, Drijfhout S (2006) KNMI climate change scenarios 2006 for the Netherlands. KNMI scientific report WR 2006-01, De Bilt

Van Veelen P (ed) (2012) Adaptieve ontwikkelingsstrategieën in buitendijks gebied in de Regio Rotterdam, report WP2, HSRR3.1 (in Dutch)

Van Vliet M (2012) Deelrapport ruimtelijke ordening en bouwvoorschriften—Juridische haalbaarheid van maatregelen Kop van Feijenoord. Amsterdam, Institute for Environmental Studies, VU University Amsterdam (in Dutch)

Van Vliet M, Aerts JCJH (2012) Adaptation to climate change in urban water management—flood management in the Rotterdam Rijnmond Area. In: Grafton RQ, Daniell KA, Nauges C et al (eds) Understanding and managing urban water in Transition. Springer, New York

Van Vliet M, Huizinga J, de Moel H, Eikelboom T, Vreugdenhil H, Koene W (2012) Meerlaagsveiligheid buitendijks—uitkomsten van de workshop in regio Rotterdam Drechtsteden. KfC 85/2012, Knowledge for Climate, Institute for Environmental Studies, HKV lijn in water

Vanneuville W, Maddens R, Collard C, Bogaert P, De Maeyer P, Antrop M (2006) Impact op mens en economie t.g.v. overstromingen bekeken in het licht van wijzigende hydraulische condities, omgevingsfactoren en klimatologische omstandigheden. *MIRA/2006/02*, Vakgroep Geografie, Universiteit Gent, Gent, Belgium (in Dutch)

Veerbeek W, Zevenbergen C, Gersonius B (2010) Flood risk in unembanked areas part C: vulnerability assessment based on direct flood damages. KfC report number 022C/2010. National research programme Knowledge for Climate

Ward PJ, De Moel H, Aerts JCJH (2011) How are flood risk estimates affected by the choice of return periods? Nat Hazards Earth Syst Sci 11:3181–3195. doi:10.5194/nhess-11-3181-2011

Wind HG, Nierop TM, de Blois CJ, de Kok JL (1999) Analysis of flood damages from the 1993 and 1995 Meuse floods. Water Resour Res 35(11):3459–3465