Managing Adaptive REsponses to changing flood risk

MARE3: preparing for extreme events incorporating changing climate conditions

Technical report

R2 121116

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Glossary of terms

Extreme event	An event which exceeds the threshold (the protection level) of the flood system. The volume of water is larger than the drainage system (including e.g. exceedance pathways) can handle, resulting in water flowing where it was not intended or planned to flow
Flood	Temporary covering by water of land not normally covered by water (Flood Directive, 2007)
Flood impact	Economic, social or environmental damage that may result from a flood. May be expressed quantitatively (e.g. monetary value), by category (e.g. high, medium, low) or descriptively. (Samuels and Gouldby, 2009)
Flood Intensity	The flood intensity is a measure of the magnitude of the flood, e.g. expressed as the rainfall duration or flood discharge
Flood protection (measure)	Measure to prevent a certain area from inundating (Samuels and Gouldby, 2009)
Flood risk	The combination of the probability of a flood event and of the potential adverse consequences for human health, the environment, cultural heritage and economic activity associated with a flood event. (Flood Directive, 2007)
FRMP	Flood Risk Management Plan
Impact	See Flood impact
Protection level	Threshold level up to which a drainage system is designed to prevent flooding
Risk	See Flood risk

Executive summary

Traditionally flood risk management for large rivers and coastal areas concentrated on the so-called 'design' events, neglecting opportunities to find synergies with urban design or taking extreme events into account. The MARE project (as part of the EU Intereg IVb program) offers a guidance and climate proofing toolbox (the CPT) which supports cities in developing climate proof flood risk management plans (FRMPs) while integrating Flood Risk Management with urban development. The approach for climate proofing FRMP's, is based on the method developed by Geldof (2007) for design of urban drainage and flooding systems. He concludes that it is not wise to develop a plan that focuses only on defining and meeting standards based on the design event. Two other dimensions need to be considered as well. One is related to a situation of actual flooding (within the context of the MARE project referred to as an extreme event). Responses for such a situation should be found within spatial planning and emergency preparedness. The other dimension is related to the day-to-day situation, the majority of days throughout a year when flood threat is no issue.

This report is one of three reports and focuses on the management of extreme situations (MARE3). The MARE3 method is based on theories on resilience and flood management (De Bruijn, 2005). A central element of the method is the reaction curve which shows the change in impact of an urban area in relation to an increasing flood intensity. The flood intensity is a measure for the magnitude of the flood, e.g. expressed as the rainfall duration or flood discharge. The impact to the urban system is often expressed through damages, casualties or even social disruption. An example of a reaction curve is given in Figure 0.1.

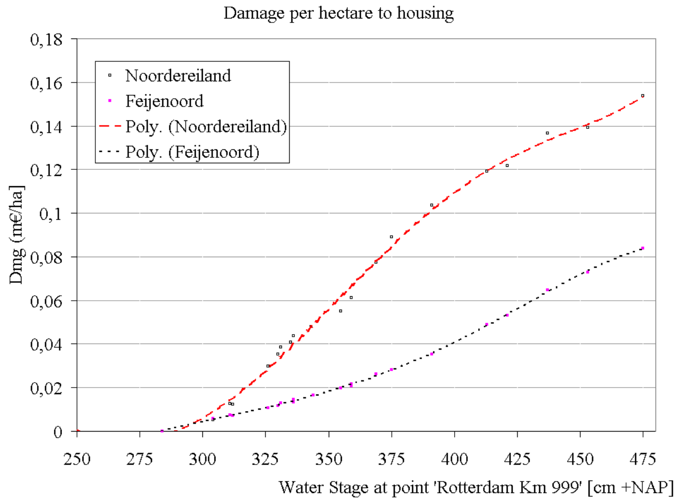


Figure 0.1 Expected damages to housing and interior for the neighborhoods Noordereiland and Feijenoord in Rotterdam associated to the observed water stages in the Meuse River (Exercise executed within the context of the Knowledge for Climate project HSRR 3.1)

The MARE3 method is similar to the adaptation tipping point approach applied in MARE2, with the difference that there are often undefined objectives and threshold values for the impacts of a flood. Examples of such objectives could be a maximum accepted damage or number of casualties, a maximum overall flood risk or even a maximum acceptable social disruption. Setting objectives and thresholds is therefore included within the method (Gersonius et al, 2012).

MARE3 step-by-step

Step 1: Quantify objectives and acceptable thresh-olds.

Comparable to the protection levels for the urban drainage infrastructure, it is recommended to set an attainable standard or threshold as an objective for exceedance events. The ultimate objective would be to reduce damages and casualties to nil under all circumstances. For most situations this will not be feasible e.g. because unexpected or very low probability floods could still occur and because the costs of implementing measures to reach these standards are too high.

Often standards are only defined for the drainage infrastructure while setting a standard for exceedance events will aid in setting goals and layout plans for an area. In addition this provides the possibility to assess the urban impacts for current as well as future climate conditions according to the standard. The process of developing a standard will result in discussion on acceptability of flooding impacts and choices of threshold values.

Step 2: Analyze effects of climate change.

Through impact analysis such as the calculations of damages or casualties for different flood events, a reaction curve is developed. As a result of climate change the return period for a specific event is expected to shift. The reaction curve therefore gives insight into the consequence of this possible future shift.

Step 3: Assess moment in time and where in the system acceptability thresholds will be exceeded.

With use of available climate scenario information, an estimate is made of when in time the threshold is likely to be reached. As for step 3 for MARE2, this results in an earliest and latest time where flood impact on the urban area is likely to exceed the objectives set for the area.

Alternative strategies are then developed and analysed by repeating step 3 and 4. This will result in the definition of a number of most effective adaptive strategies.

Step 4: devise critical set of options.

The final step is to define alternative adaptive strategies to be able to cope with the changing climate conditions if the threshold is expected to soon be exceeded in time or if changing to an alternative adaptation strategy is foreseen to be a lengthy process.

Contents

1 Introduction

1.1 About this report

Flooding can result in a disruption of daily life. Smaller floods cause flooding of roads blocking traffic, delaying goods to be delivered. Houses may become flooded causing damage to the household and damage to or loss of goods. Large floods particularly threaten human life, destroy buildings and can disrupt the daily activity within an area for years as experienced in New Orleans after Hurricane Katrina. Cities are facing an increase in flood threat and thus an increase in flood consequences due to the foreseen climate change. Gaining insight into the possible consequences of current and future flooding is therefore an important step towards climate proofing a Flood Risk Management Plan (FRMP).

Traditionally flood risk management for large rivers and coastal areas concentrated on the so-called 'design' events, neglecting opportunities to find synergies with urban design or taking extreme events into account. The MARE project (as part of the EU Intereg IVb program) offers a guidance and climate proofing toolbox (the CPT) which supports cities in developing climate proof flood risk management plans (FRMPs) while integrating Flood Risk Management with urban development. The approach for climate proofing the FRMP's, is based on the method developed by Geldof (2007) for design of urban drainage and flooding systems. He concludes that it is not wise to develop a plan that focuses only on defining and meeting standards based on the design event. Two other dimensions need to be considered as well. One is related to a situation of actual flooding (within the context of the MARE project referred to as an extreme event). Responses for such a situation should be found within spatial planning and emergency preparedness. The other dimension is related to the day-to-day situation, the majority of days throughout a year when flood threat is no issue. Flood responses designed for the rare situations of a flood are required to integrate within the urban area and even to improve the social and economic state of an urban area. The guidance and toolbox therefore consists of three elements in line with the three dimensions:

(MARE1) focuses on the day-to-day situations and provides guidance for integrated planning and design;

(MARE2) deals with the less frequent situations within design standards (managing flood protection) and gives a method for attaining flood protection standards;

(MARE3) puts emphasis on the infrequent flooding situations beyond design standards (managing the consequence of flooding) and provides a method to deal with extreme events.

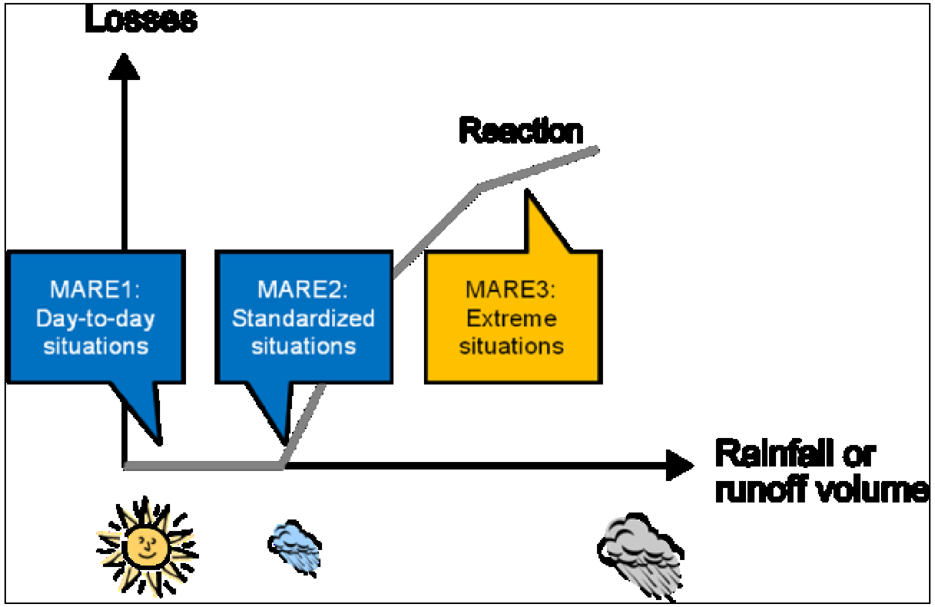


Figure 1.1 The three dimensions to deal with in flood risk management planning

This report is one of three reports and focuses on the management of extreme situations (MARE3). Within the context of this report an *extreme event* is defined as a flood events where the volume of water is larger than the drainage system can handle, resulting in water flowing over surfaces where it was not intended or planned to flow. As it is not possible to guarantee a 100% protection against flooding, there will always remain a risk of an actual flood. Therefore a flood risk management plan should include responses which deal with the consequences of a flood. This report provides a step-by-step method and toolbox to assist in climate proofing FRMP's for those parts of the plan dealing with extreme events.

1.2 The MARE project and the CPT

The overall aim of the Interegg IVb MARE project is to enable widespread implementation of local adaptive measures to reduce and adapt to flood risk. MARE stands for Managing Adaptive REsponses to changing flood risk in the North Sea region.

The project developed a guidance and toolbox for climate-proofing of responses and potential adaptations within FRMPs (the so-called Climate Proofing Toolbox, CPT). Using existing tools and methods, the CPT helps users to take climate change predictions into account in the risk assessment and options planning processes. It helps to answer the questions of if, how and when to adapt to climate change. The CPT aims to help local water managers and urban planners, to achieve timely and effective implementation of managed/adaptive responses. In this regard, it is intended to support the implementation of the EU Floods Directive. The toolbox and guidance may be applied both ex-ante, for developing a new climate-proof FRMP, and ex-post, for assessing the climate-proofness of an already developed FRMP.

MARE has set up platforms of professional stakeholders in flood risk management in four countries to enable collaborative learning. These alliances include local, regional or national level authorities, knowledge institutes and private enterprises. These Learning and Action Alliances (LAAs) are setting out to promote inclusive cooperation between organisations allowing the design of integrated Flood Risk Management solutions and avoiding adverse-impact solutions. The CPT is based on the needs of the members of the four LAAs involved in the MARE project.

1.3 Aims and objectives of MARE3

The objectives of MARE3 are (i) to provide a way to assess the increase in impacts due to climate change, (ii) to identify the most urgent system[1] aspects to tackle and (iii) to define appropriate responses to deal with the increased impacts. The method makes use of existing theory and experiences and makes these operational through a step by step evaluation of the effects of climate change on flood impacts. The MARE3 toolbox is applicable at different scale levels ranging from an urban sewer flooding to larger pluvial, fluvial and coastal floods.

Recent studies (Klijn et al, 2010) show that urban development and economic growth often contribute more towards an increase in flood risk than the effects of climate change do. Although it is important to take these autonomous urban developments into consideration when carrying out a future flood risk assessment, the focus of the MARE toolbox is on taking the effects of climate change onto account within flood risk management planning.

1.4 Guidance to the reader

This report on MARE 3 has been set up similar to the reports on MARE 1 and 2. Chapter 1 gives an introduction on the project and method and describes the aims and objectives. In Chapter 2 a rationale and context gives background information on extreme events. An overview of and introduction to the step-by-step method is provided in chapter 3. A full description of the method is given in chapter 4. In Appendix 1 Techniques tools are listed which can be used in applying the different steps.

[1] Here 'system' means the urban or flooding impacted area, including the recipients affected. Note that this may extend way beyond the local area actually flooded due to disruption and other factors such as economic impact on the city.

2 Rationale

2.1 Why consider other than flood protection measures?

The history of humanity's fight with floods has seen increasingly expensive attempts at protection against flooding by construction of large infrastructure. Recently there has been an increase in the number and severity of flooding throughout Europe, in e.g. Germany, the UK and France, and more frequent and heavier flooding is expected in the future under changing climate conditions, with greater impacts as communities have greater wealth than in the past.

From history it is seen that protection against flooding has not proven to be sufficient. Even with a high flood protection standard in place, there will always remain a residual flood risk because one cannot guarantee for certain that flooding will not occur. Therefore more and more attention is now being given to responses aimed at reducing flood impact. These responses range from spatial zoning, through building regulations to responses such as event management and early warning and can be applied stand-alone or in combination with protection measures. Examples of possible situations where other than flood protection measures are applied are:

- A situation which does not allow for flood protection measures or where enhancing existing flood protection structures is not possible e.g. too costly, no space, technically not achievable.
- When significant risk reduction through measures other than protection against flooding can be achieved either instead of or in addition to flood protection measures.

- A situation where one chooses to be prepared for an extreme event if protection measures were to fail, following the principle that a 100% protection against flooding can not be guaranteed.

2.2 Effects of changing climate conditions on the flood impact

Flood *risk* is generally defined as the multiplication of the probability of flooding and the impact of a flood (Flood Directive, 2007). More frequent and heavier flooding is foreseen under changing climate conditions. The probability (frequency) of flooding is expected to increase and the impact will increase due to a larger volume of water, both resulting in an expected shift in flood risk. In addition autonomous developments in time such as population growth and an increase of asset value will result in an increase of potential damages and casualties over time (autonomous developments are not considered explicitly though within MARE3). Measures to reduce flood risk aim at increasing the level of flood protection and/or reducing the flood impacts. MARE2 deals with the shift in flood probability. MARE3 focuses on maintaining and even reducing potential flood impact levels under changing climate conditions. When planning for the future from a MARE3 perspective, an increase of the flood characteristics such as flood extent, depths and flow velocities and thus an increase of the flood impact will need to be taken into account. Planning for floods will therefore require an insight into the possible increase in impacts due to the climate change effects.

2.3 Stakeholders

MARE3 looks beyond the context of the technical hydraulic system. It considers responses related to buildings and the public space; it has to do with spatial planning and with emergency planning. The method focuses on the technical expert, planners, emergency planners as well as the policy maker.

3 Outline of the method

The overall aim of the *FRM process* is to develop the most effective way of managing flood risks. The outcome of this process will be the establishment and implementation of a FRMP for areas where the risk is deemed significant.

The aim of the *urban planning process* is to find the best solution not only in a technical way of thinking, but the best solution for city development, balancing all social, ecological, aesthetic or spatial aspects in this complex environment.

Both the FRMP and the urban planning process can be described within 4 phases:

1. initial phase;
2. diagnostic studies;
3. design and assessment of options and
4. Decision making and implementation.

Mostly this is not a linear process. It is a complex process in which sometime even a design idea can be the starting point. However, in the process all the phases have to be considered at least once (Richter et al, 2012).

MARE2 and 3 are both related to the flood management planning process while MARE1 is related more directly to land opportunities use within the urban planning process. The relation between the MAREs and between the FRM and urban planning process is illustrated in Figure 3.1

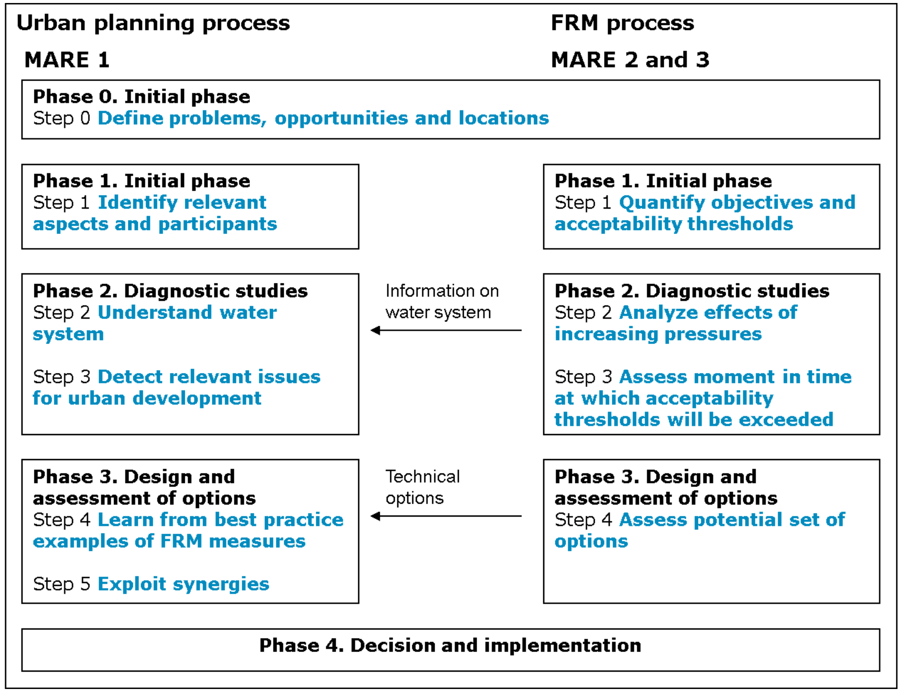


Figure 3.1 MARE 1, 2 and 3 in relation to the FRM and urban planning process.

The MARE3 method is based on theories on resilience and flood management (de Bruijn, 2005). A central element of the method is the reaction curve which shows the change in impact of a system in relation to increasing flood intensity. The flood intensity is a measure for the magnitude of the flood, e.g. expressed as the rainfall duration or flood discharge. An example of a reaction curve is given in **Figure 3.2**

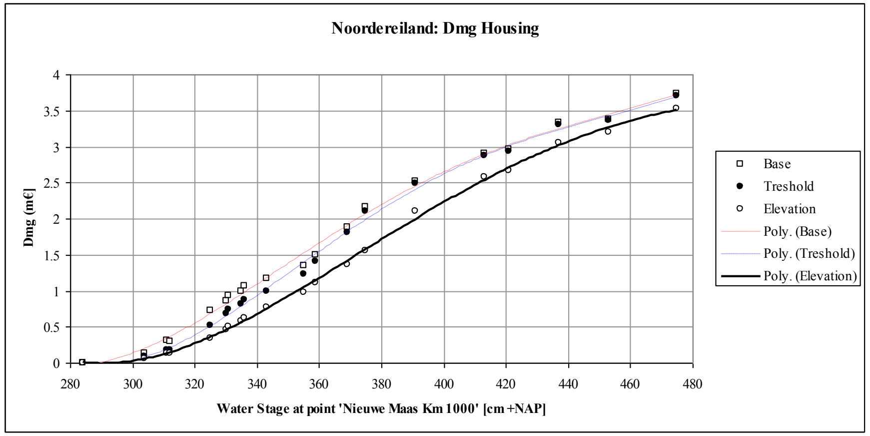


Figure 3.2 Expected damages (to housing and interior assuming three levels for doorstep and ground floor) for the Noorder island area associated to the observed water stages in the Meuse River (Veerbeek et al, 2012)

The illustration shows the impact of a flood in relation to the flood intensity. For this system, up to a water stage of approximately 3.00 m +NAP no damage is expected. Beyond this point the damage increases rapidly with increasing flood intensity. At a water level of approximately 4.40 m +NAP a slight levelling of the graph is noted. The shape of the curve illustrates a concave development of the impact. Initially the flood impact increases rapidly when the flood intensity increases, but the rate of increase of flood impact reduces at higher water stages. Understanding how the impacts develop will give insight into where the impacts occur, which elements are the most vulnerable (i.e. experience the largest impact), and how the impact could change due to climate change.

The MARE3 method is similar to the adaptation tipping point approach applied in MARE2, with the difference that there are often undefined objectives and threshold values for the impacts of a flood. Examples of such objectives could be a maximum accepted damage or number of casualties, a maximum overall flood risk or even a maximum acceptable social disruption. Setting objectives and thresholds is therefore included within the method (Gersonius et al, 2012). The MARE3 method follows four steps equal to the steps followed by MARE 2. An overview of the different steps and how they relate to the FRM planning process is illustrated in **Figure 3.2**;

Step 1: Quantify objectives and acceptability thresholds;

Step 2: Analyse effects of climate change;

Step 3: Assess moment in time at which acceptability thresholds will be exceeded;

Step 4: Devise critical set of options.

In phase 4, decision and implementation balancing between MARE2 and MARE3 is applied through e.g. cost-benefit analysis. This phase is described in (Veelen, 2012).

4 Applying the method step by step

4.1 Step 1: Quantify objectives and acceptability thresholds

Flood protection systems are designed to prevent flooding up to a certain water level or flood frequency. This level is defined as the flood protection standard and in some countries the standard is constitutionalized through legislation. Examples are the design level for the sewer system or coastal flood defences. A standard can be interpreted as an objective or performance level which the flood protection system must meet. Often standards are only defined for the flood protection system while in addition setting a standard for flood impacts, will provide the possibility to assess the urban impacts for current as well as future climate conditions compared to the set standard. Setting a standard for the flood impacts will also aid in setting goals and plans for an area and the process of developing a standard will result in thought and discussion on acceptability of flooding impacts.

To be able to assess the climate proofness of an area or a FRMP, it will be required to set attainable standard for flood impacts. These standards act as objectives which should be met now and in future. The ultimate objective would be to reduce damages and casualties to nill under all circumstances. For most situations this will not be feasible; e.g. because even unexpected or low probability situations can still occur, because the costs of implementing measures to reach such standards are too high or because this would require that the current buildings and infrastructure need to be removed and rebuilt to be flood proof or the population relocated. Examples of attainable standards for flood impacts are:

- A maximum number of damage and/or casualties per event.

- A maximum flood frequency to be prepared for (note that preparation does not necessarily entail structural defences, but alternative preparations). Up to this level no damages or casualties are acceptable.

- A combination of these standards where a maximum annual risk is defined (flood probability x impact), e.g. in the Netherlands a standard exists for individual risks in relation to public security ($< 10^{-6}$ per year per person).

- A minimal graduality (further explained in paragraph 4.3)

4.2 Step 2: Analyse effects of climate change

Step 2 assesses the food impacts for a range of flood events with increasing flood intensities. From these results a reaction curve is built and the shift in flood impact due to climate change is plotted. For step 2 the following activities need to be undertaken:

- Choose the flood intensities for which the impacts will be assessed.

- Develop flood hazard maps.

- Calculate the impact per event.

- Build the reaction curve.

- Plot the shift in flood probability due to climate change.

These activities are illustrated in **Figure 4.1**.

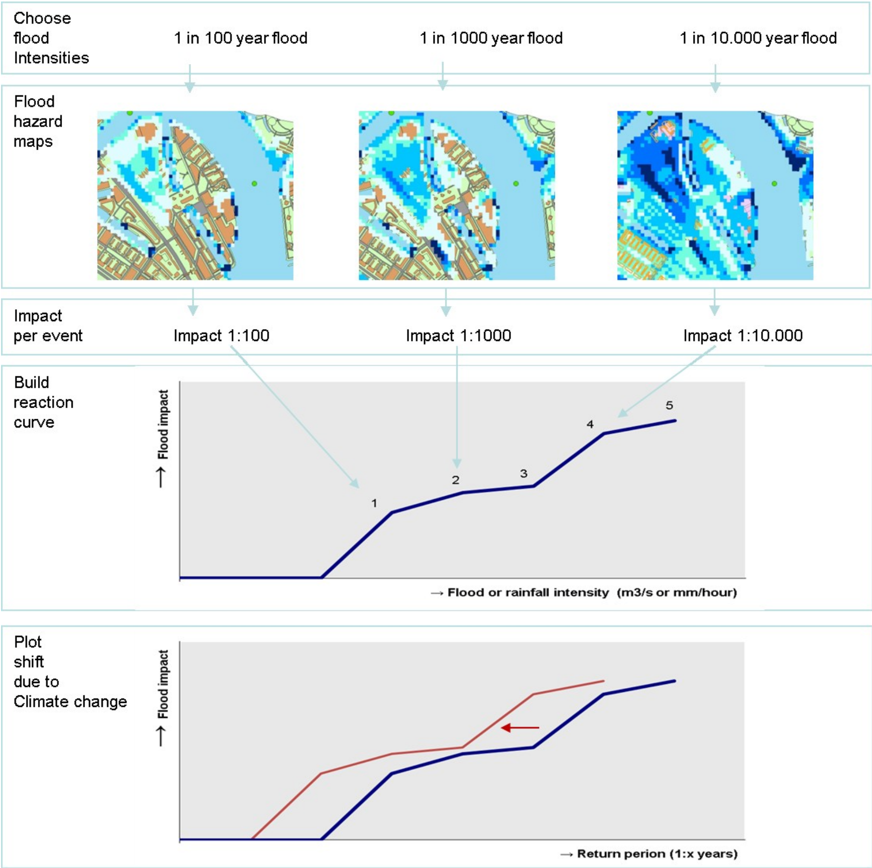


Figure 4.1 Illustrated overview of the activities in step 2.

Choose flood intensities to evaluate

It is recommended that the impacts for a minimum of four flood intensities are used to build the reaction curve. A larger number of intensities will give more insight into how the system reacts to increasing intensity of a flood. It is therefore recommended that sufficient intensities are selected to ensure that the variations in the response (impacts) of the system are defined adequately. Note that it is not possible to know '*a priori*' where and under what intensities the system will be critically impacted. Starting with a minimum of 4 intensities, the response curve should be built up, with impacts at additional intensities being assessed for intensities where it is possible that there may be critical impacts.

Some information will already be available from application of the MARE2 method and will provide a baseline as to what events the system can cope with without flooding. For Mare3 a maintaining of this protection level, the level up to which the system is protected against flooding, is assumed as this is dealt with in Mare2.

Escuder Bueno et al (2010) recommend for the evaluation of fluvial flooding:

- Undefended systems: return periods between 20 and 1000 years.
- Defended systems (defence systems designed for return periods up to 75 – 100 years): return periods between 100 and 1000 years.
- Highly defended systems (e.g. large dam or levee): return periods between 1000 and 10,000 years.

For pluvial flooding Escuder et. al. (2010) recommend a series in the range of 5 to 500 years as drainage systems are often designed up to a return period of 10 years. However, in many urban areas, much lower return periods are used where impacts are expected to be confined to roads and not property.

Develop flood hazard maps

Flood impacts are calculated with use of impact assessment models. These models relate the expected impact to flood variables such as the expected water depths, flow velocity, flood duration etc. The choice of impact assessment method (see next step) defines which information on the flood characteristics is required. Flood hazard maps show the information on flood characteristics.   Different techniques are available for the development of flood hazard maps ranging from GIS to hydrodynamic flood models. Appendix XX gives examples of tools for the development of flood hazard maps.

Calculate the Impacts per event

Each point on the reaction curve shows the total impact related to a certain flood intensity. The first step in building the reaction curve is therefore to calculate the impacts for several flood intensities.

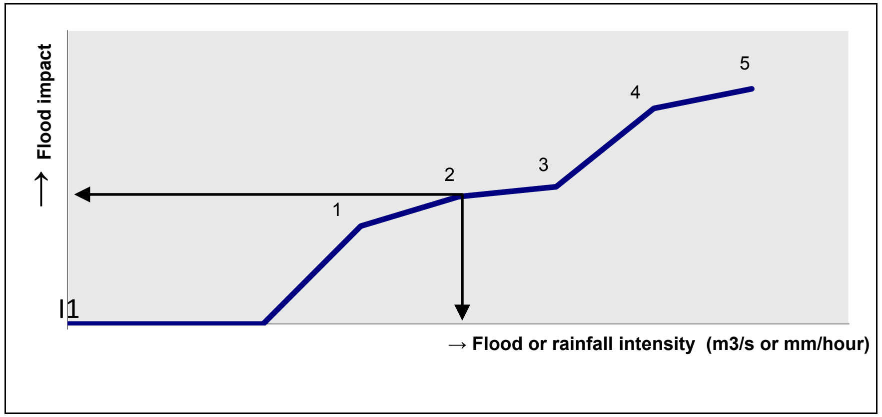


Figure 4.2 Example of a reaction curve. A point on the curve shows the impact corresponding to a flood event with a specific flood intensity.

The impact of a specific flood event encompasses the costs, the number of casualties and injured (expressed monetary or in numbers) and other impacts such as loss of ecological or cultural value.

The impact of a flood is multi-faceted and can be broken down into the aspects given in Table 4.1 (several other classifications and categories exist). Where feasible it is preferable to determine the impacts in monetary terms. However, for many of the flood impacts expressing the impact monetarily is not possible or subject to debate: e.g. pollution, damage to ecosystems etc. The last column in **Table 4.1** indicates to what extent the impact type can be quantified in monetary terms.

Table 4.1 shows to what extent the specific impact can be quantified with use of available methods ranging from 'not likely to be expressed monetary' (--) to 'generally expressed monetary' (++).

Table 4.1; Flood impact categories

Impact category	Impact type	explanation	Quantifiable
Economic impact			
	Direct costs	Costs of repair of material damages within the flooded area	++
	Indirect costs	Business interruption within the flooded area	+
	Secondary costs	Business interruption outside of the flooded area	+/-
	Induced costs	costs of relief aid	+
Impact on health and safety			
	Loss of life		+
	Injuries		-
	Stress and trauma		--
	Secondary health risk (e.g. caused by bacteria)		-
Other impact			
	Ecological damages		+/-
	Cultural losses		--
	Social impact		--

The most obvious impact in this list is the direct damage to buildings, belongings, infrastructure and cars, but it is necessary to also consider other impacts e.g. the indirect damages caused by business interruption within the flooded area, the secondary damages due to business interruption outside of the flooded area and the costs for relief aid.

Figure 4.3 illustrates a hypothetical example of the development of the flood impact during a flood event. This figure shows an initial impact which occurs during the actual flooding, e.g. by damage to buildings and infrastructure, but, depending on the extent and duration of the flood, aspects such as economic losses caused by loss of jobs or business interruption also contribute to the total impact during the time of recovery. In general, the longer time that an area is flooded, the larger the impact will be. Often preparation is made for an actual flood even, but without consideration of the possible duration of a flood or the required responses to reduce the recovery time (this is what happened in New Orleans after Katrina).

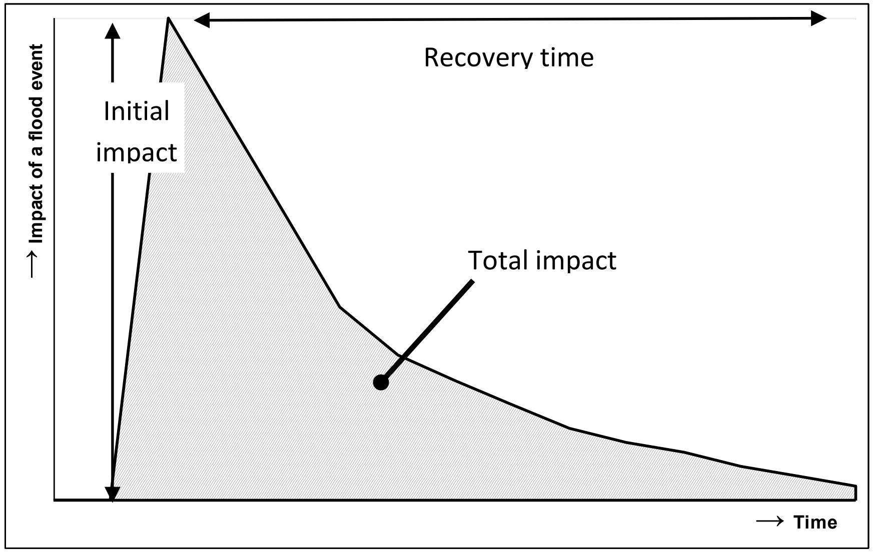


Figure 4.3 flood impact in time

It is usually necessary to make a choice as to the types of impact to be assessed. The choice is limited by the availability of information and methods available for the impact analysis as well as the type of flood and expected impacts upon the system. For example, a single day of urban flooding due to heavy rainfall is not expected to cause significant ecological damage or loss of life and probably only minimal secondary damage, whereas severe fluvial flooding can result in injuries and in the worst case even loss of life.

Flood impacts are calculated with use of impact assessment models. These models relate the expected impact to flood variables such as the expected water depths, flow velocity, flood duration etc. This information is then combined with information on e.g. land use, number of inhabitants, economic activity. Most of the existing methods are based on original works by Kates (Escuder Bueno, 2010), using water depths as a basic parameter and water depth-damage curves to estimate direct economic losses depending on the land use. In general, the indirect costs are calculated as a fraction of the direct costs (Escuder Bueno, 2010). Appendix 1 gives an overview of available impact assessment methods and models.

Build the reaction curve

The reaction curve is built using the impact assessment for the different flood intensities. There are different types of reaction curves. The simplest form gives the impact as a function of the flood intensity in hydrological terms such as rainfall duration, flood discharge. If information is available on the return period corresponding to the hydrological variable, then the corresponding return period can be plotted on the horizontal axis. To gain insight into effects of climate change, information on how these return periods change due to climate variation is required as well.

The Intensity – impact reaction curve

The simplest form of a reaction curve is the intensity-impact curve. This curve can be developed for a single flood source as illustrated in **Figure 4.4**. In this hypothetic example the impact has been assessed for five different river discharge rates increasing in intensity from Q1 to Q5 resulting in an impact I1 to I5. The corresponding reaction curve is illustrated in **Figure 4.2**. The example illustrates flooding from an embanked river, but a similar reaction curve could be developed for other types of floods; e.g. urban flooding due to exceedance of sewer system capacity. The horizontal axis would then represent the rainfall intensity or duration.

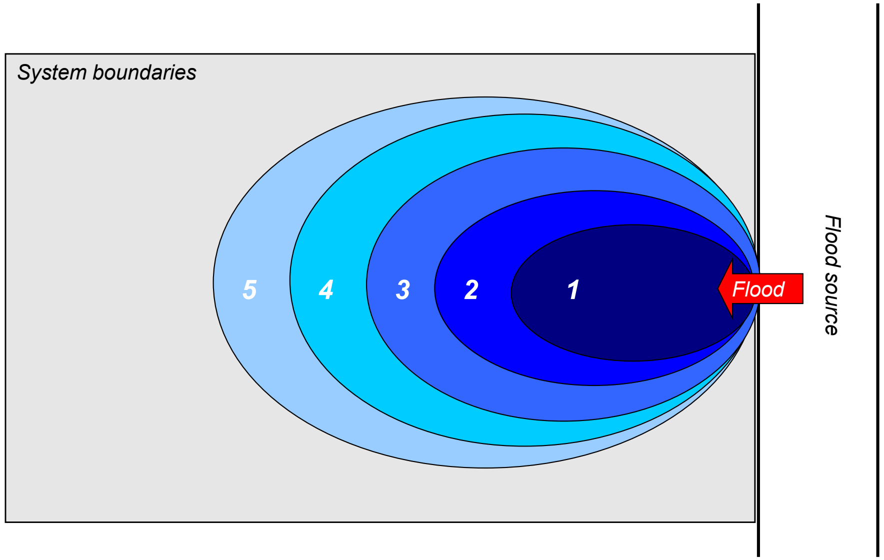


Figure 4.4 Illustration of floor from a single flood source.

Where flood water can enter the system from multiple locations, it is recommended to weight the relative impact according to the probability of flooding for the different locations (**Figure 4.6**). In this example a river with a discharge Q1 could cause a flood 1A and/or a flood 1B. Because it is impossible to know ahead which location will flood, it is assumed for this example that each location has an equal probability of flooding, thus the impact is weighted equally for each in this example:

Impact 1 = 0.5*Impact1A + 0.5*Impact 1B

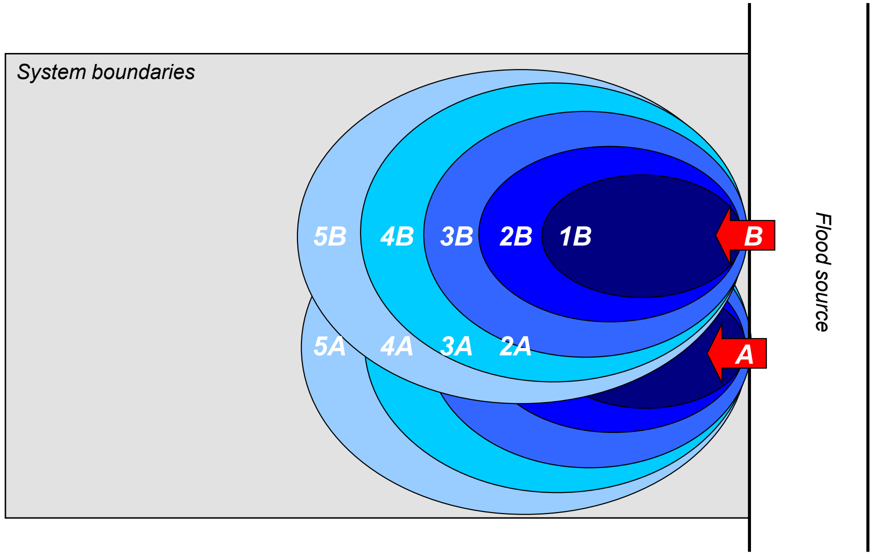


Figure 4.5 Illustration of floor from a multiple flood source.

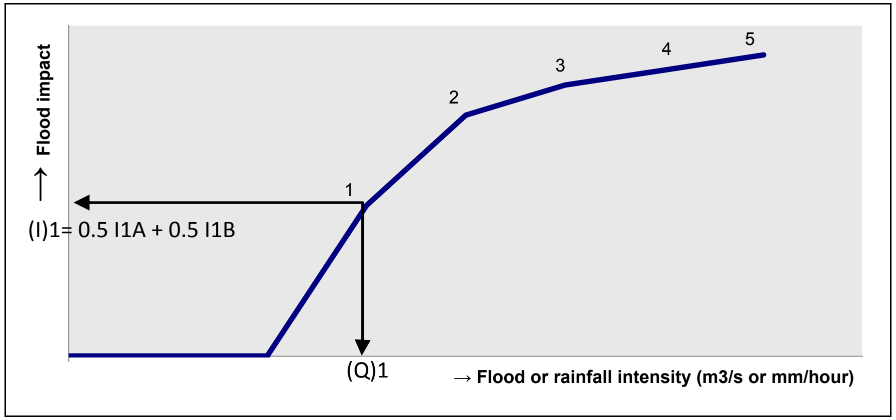


Figure 4.6 Example of a reaction curve for a system with possibility of multiple flooding locations

Probability – impact reaction curve

If the frequency or probability related to the particular floods events are known, these can be plotted on the horizontal axis instead of the flood intensities.

Plot the shift in flood frequency due to climate change

More frequent and intense flooding is foreseen due to climate change across most of Europe. A flood with a return period of e.g. 10 years and a corresponding flood impact A, will occur more frequent in future, e.g. with a return period of 5 years, as is illustrated in **Figure 4.7**.

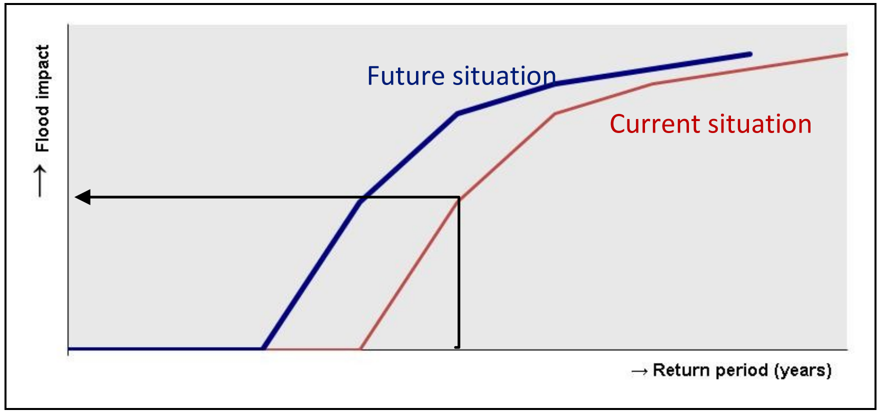


Figure 4.7 more frequent and intense flooding due to climate change

Insight into possible climate change effects requires an understanding of the possible shift in return periods for a given intensity. The shift can be plotted in the reaction curve as is illustrated in **Figure 4.7**. **Figure 4.8** gives an illustrative example of change in pluvial flooding impacts from current conditions (dotted line) compared with future potential impacts by the 2080s for a UK catchment for climate change based on medium greenhouse gas emissions and a National Enterprise economic scenario (Evans et al, 2004). Note that only 3 return periods were selected for the analysis.

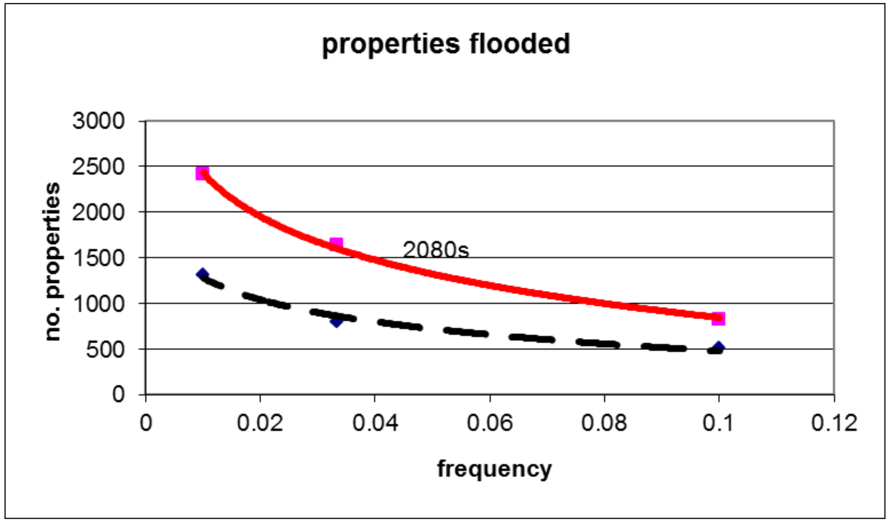


Figure 4.8 Change in pluvial flooding impacts from current conditions (dotted line) compared with future potential impacts by the 2080s for a UK catchment (Evans et al, 2004).

An alternative is to plot multiple return periods for each climate change scenario on the horizontal axis as is illustrated in **Figure 4.9**.

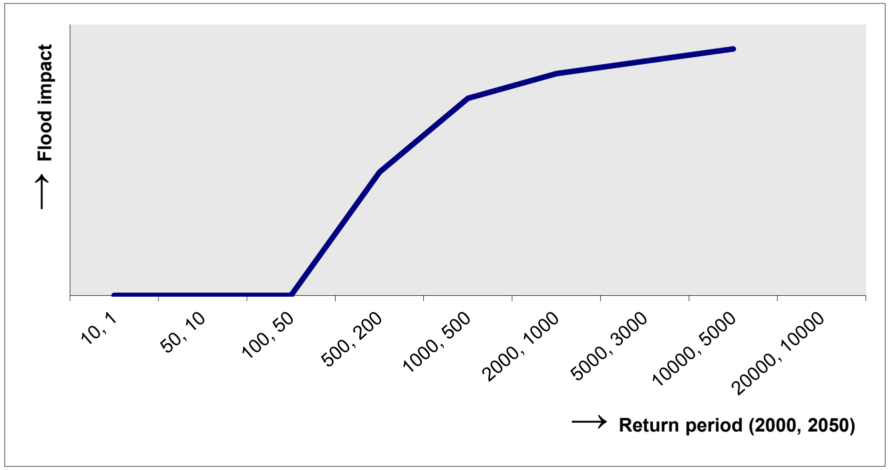


Figure 4.9 Illustrating the shift in return periods and flood impact due to climate change by plotting multiple return periods on the horizontal axis (numbers are fictive).

The time horizon to consider should be in accordance with the life span of the system, the responses and the FRMP. The time frame should also take into account investment cycles and other urban utility timings as well as city planning horizons.

4.3 Step 3: Assess moment in time at which acceptability thresholds will be exceeded

The next step is to assess to what extent a system or a FRMP is climate proof. The evaluation consists of assessing the characteristics of the reaction curve and tests the system or FRMP according to a pre-defined standard for the current as well as future climate conditions. From this evaluation, the weak points of the system are extracted giving direction to the choice and implementation of responses. Step 3 comprises the following activities:

- Interpretation of the reaction curve.
- Assessing to what extent the system or FRMP is climate proof.

Interpretation of the reaction curve

This section explains how to interpret the reaction curve by a simple visual assessment. The curve is interpreted by assessing the aspects: *amplitude* including the underlying impacts, and *graduality*. These assessment aspects are based on the method to assess resilience of a flood system given by (de Bruijn, 2005).

Amplitude (magnitude) of the impact

The amplitude of the reaction curve is defined by the height of the impacts. When assessing the effect of climate change, the amplitude is of interest because it shows to what extent the impacts will increase due to climate change. The amplitude can also be used to compare between areas or compare the effectiveness of different responses (see step 4).

The total impact is the sum of the amplitudes from the different impact causes (**Table 4.1**). The reaction curve can give insight into the contribution of the individual underlying impacts as a proportion of the total impact on the system, which aids in giving direction to the choice of measures. It is therefore recommended plot the underlying impact types which contribute to the total impact separately; e.g. structural damages, economic damage etc.. An example is shown in **Figure 4.10**.

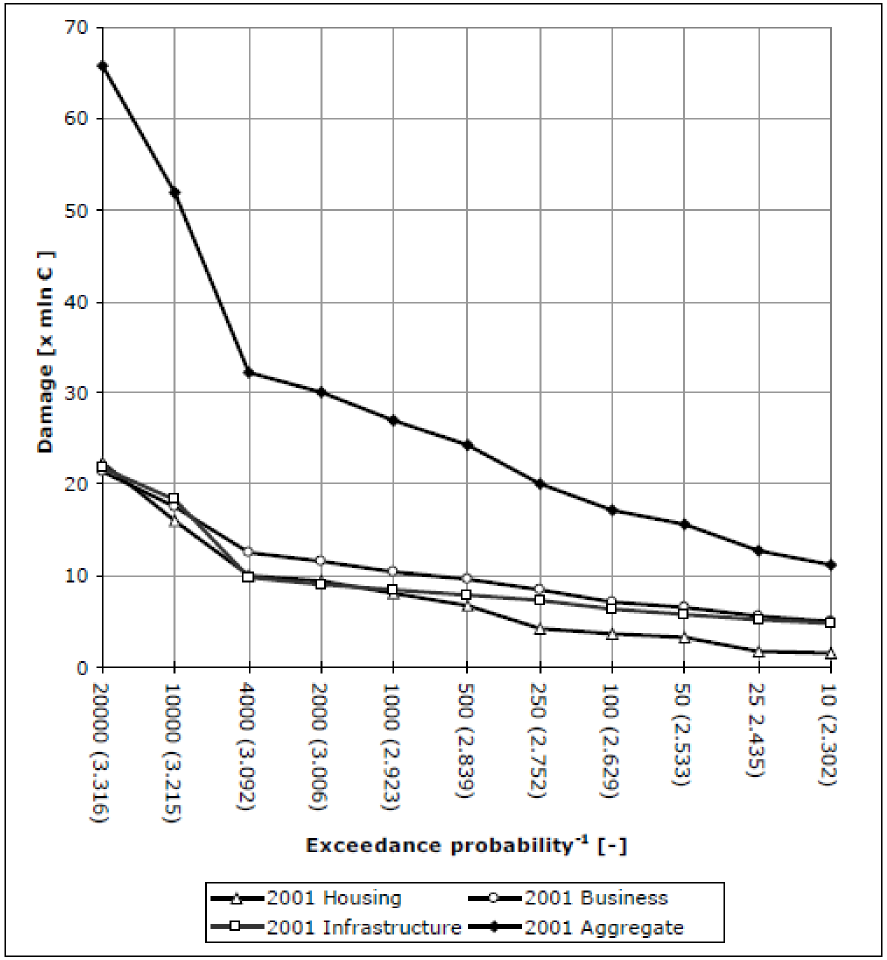


Figure 4.10 Damage curves for housing, businesses and infrastructure and aggregate levels within the unembanked areas of the Island of Dordrecht for annual Exceedance Probabilities between 10-1 and 20000-1 (Veerbeek et al, 2008). Corresponding river water levels are indicated within brackets.

In **Figure 4.10** the total damage as well as the underlying damage for three impact categories are plotted. This shows that the damage to business is the largest, although the three categories do not differ greatly.

Similar to plotting the underlying impact categories, it is recommended to make a distinction between the initial impact and the impact which accumulates during the recovery time, e.g. material damages can be categorized as time independent whereas economic damages due to e.g. business interruption will accumulate in time. This will show to what extent the total impact is the cause of initial damages or by impacts developed during the recovery time.

Gradients or discontinuities in the curve; graduality

The slope of the curve defines the graduality, i.e. the relative change in impact. Graduality therefore indicates the rate of increase in impact with increasing flooding event severity (de Bruijn, 2005). Previous examples of the reaction curves showed a consistent concave line (e.g. **Figure 4.6**). Reaction curves are, however, not likely to be as smooth as the illustrations. Often up to a certain flood extent an area will not be flooded, but if a larger flood would occur, the area will suddenly become flooded and the flood impact will increase considerably. The sudden increases in gradient or discontinuities in the curve reveal the critical and often, sudden, increases in impacts within the system. **Figure 4.11** illustrates several non-gradual reaction curves.

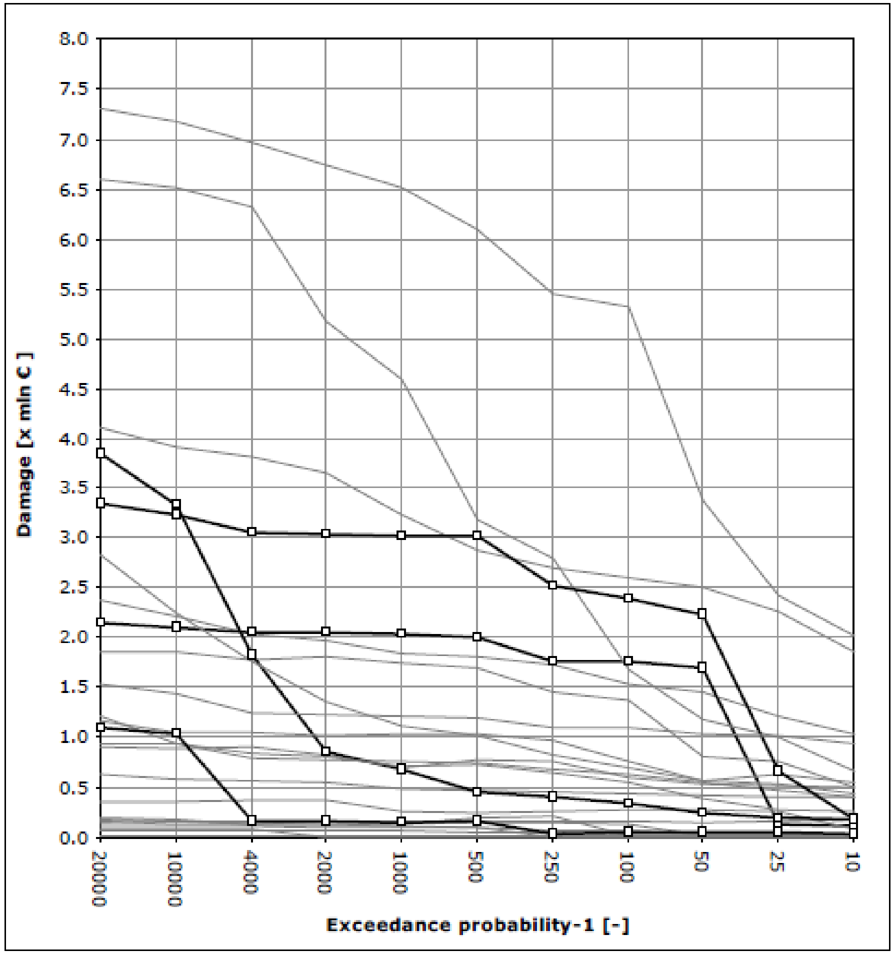


Figure 4.11 Damage curves for individual neighbourhoods within the unembanked areas of the Island of Dordrecht for annual Exceedance Probabilities (EP) between 10-1and 20000-1 (Veerbeek et al, 2008).

In **Figure 4.11** the results of the aggregate damages are plotted per individual neighbourhood. While many of the curves show gradual increases in damage over the range of EPs, some of the curves show different behaviour. The damage curves depicted in bold all have in common that their levels shift upwards substantially after some threshold value is reached (depicted in bold). Below this threshold the expected damages are increasing only by a small amount with change in EP. The discontinuity observed in some of the damage curves can be attributed to a sudden increase of flood extent; when a threshold value is passed. A relatively large number of buildings are inundated by a relatively small change in flood water level resulting in a rapid increase in rate of change of flood damage (Veerbeek et al, 2008).

Assess to what extent the system or FRMP is climate proof

After defining the standard for the system, the standard can be plotted in the reaction curve. Read from the curve at what point the standard will be exceeded. If the shift due to climate change has also been plotted, this will show to what extent the point at which the standard will be exceeded will also shift.

Not only the system should be tested for future climate conditions, but it will also be necessary to consider if the standard is maintainable in future situations. If this is not the case, the standard will need to be reconsidered (step 1).

4.4 Step 4: Devise critical set of options

Step 4 of the MARE3 method comprises two activities:

- Choosing appropriate measures
- Evaluating the effectiveness of the measures

Choosing appropriate measures

The assessment of the reaction curve gives insight into the critical points of the system in terms of external flood drivers. These results aid in making a first choice of responses. It shows where the largest gain can be accomplished in lowering flood risk now and in the future. Reduction of flood impacts can be reached by implementation of measures. Measures can be grouped into the categories as described in **Table 4.2** (based on de Bruijn et al, 2008). The columns 'Amplitude',' Graduality' and 'Recovery time' have been added and indicate if the response is expected to have a positive effect (+), negative effect (-) or no effect (+/-) on the respective aspects. This only gives an indication as every flood system is unique. The appropriate choice of responses will therefore be specific to an area and often it will be seen that a selection of measures are applicable. The choice will therefore also depend on aspects such as costs and benefits, local preferences, the possibility to link to other developments and the flexibility of a response to future climate changes. These aspects are discussed in MARE1.

Table 4.2; Overview of flood impact reduction responses (based on de Bruijn et al, 2008)

				Amplitude	Graduality	Recovery time
Flood impact reduction	Control of flood patterns	Structural	Compartmentalisation of areas Detention areas/calamity polders Floodway Ring dikes along villages/cities Mounds	+	-	+/-
	Adaptation & regulation of use of flood-prone area	Structural	Flood proofing	+	+	+
		Regulatory	Building restrictions Land use zoning Regulations on storage of toxics/chemicals Adaptation of recreation functions Adaptation of agricultural practices	+	+	+/-
		Financial	Fines for damage increasing behaviour Subsidies for flood proofing or other measures	+	+	+
	Distribution of flood impacts	Financial	Damage compensation Governmental relief funds Insurances	+/-	+/-	+
	Preparedness	Communicatiion	Crisis management Education of inhabitants Evacuation plans Flood forecasting Flood risk maps Flood warning systems Radio/Television information channel	+ (for casualties)	+/-	+/-

Evaluating the effectiveness of the measures

The effectiveness of a single measure or a collection of measures is evaluated by building a reaction curve for the system which includes the implementation of the selected measures. Plotting these using a new reaction curve provides insight into the effects of the different measures. This is illustrated in **Figure 4.12**. The implementation of the measures is then tested according to the standard set in Step 1. Through an iterative process different strategies can be developed.

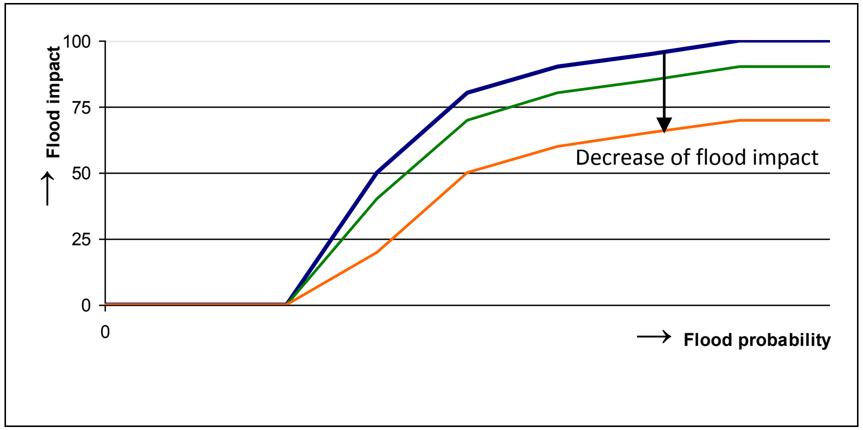
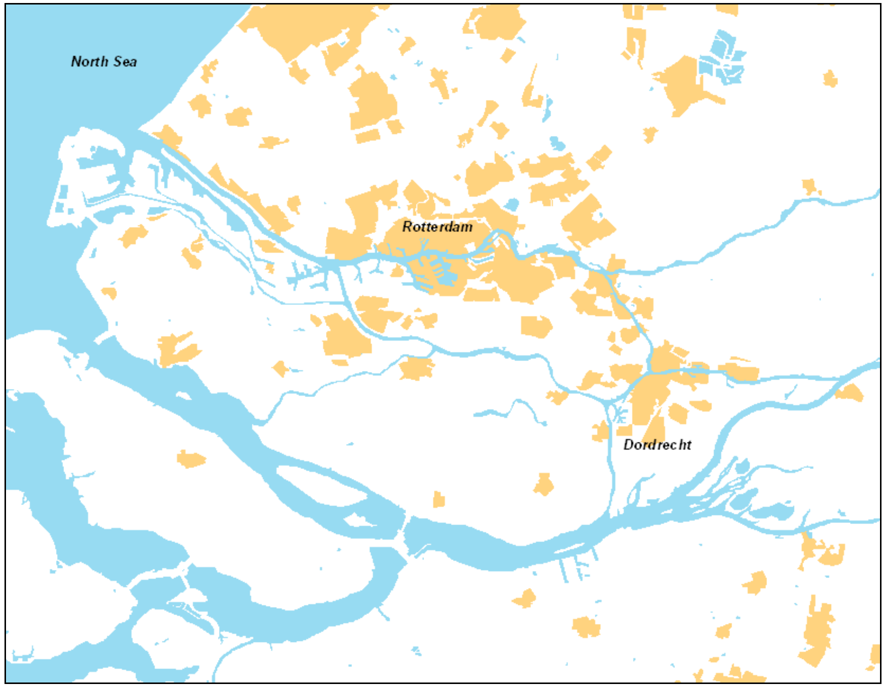


Figure 4.12 Decrease of flood impact when implementing responses (assuming that the protection level is maintained).

5 Case study examples

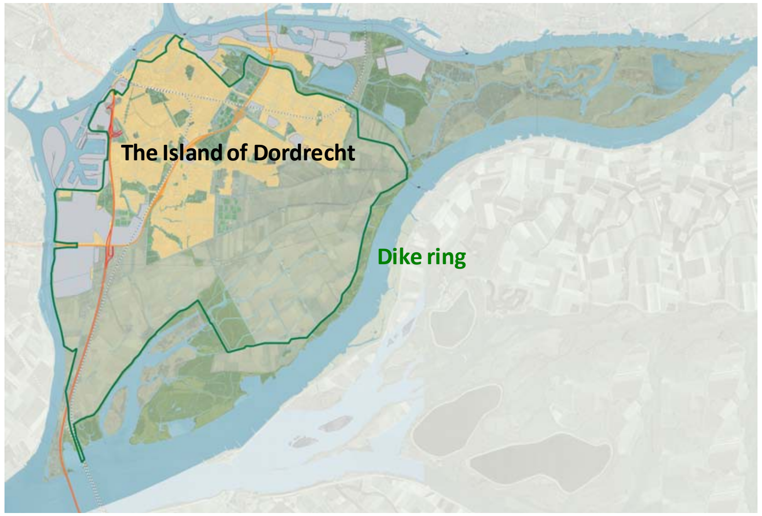
5.1 Introduction to the case study areas

Two very different case studies have been chosen to illustrate the application of the steps as described in the method. The first focuses on the Island of Dordrecht, the second on a neighbourhood in Rotterdam. Both areas are situated at the lower reach of the Rhine and Meuse river systems.



Case 1; Evaluation of climate dikes for the Island of Dordrecht

The Dordrecht case study looks at an area with a high protection level through an extensive system of dikes. A large part of the city is protected by a 37km long enclosed dike ring . These dikes are designed to withstand a flood event with a probability of 1 in 2000 years. The water level corresponding to this protection level is reached through a combination of high river discharges and sea levels. Flooding of the Island of Dordrecht could occur through overtopping and/or breaching of the dike ring during high water level conditions. Breaching of the dike would cause a rapid flood with significant water depths up to 4 meters. A flood will cause great damage and could cause considerable casualties as it is extensively urbanised with a high population density. Because of the limited exit points from the Island, risks of casualties are high in the event of a flood. The case evaluates the flood risk for different water levels and compares this base case to the flood risk when implementing several alternative dike construction options.



Case 2; adaptive strategies for the Feijenoord neighbourhood' (Veelen, 2012)

The Rotterdam case study focuses on the Kop van Feijenoord neighbourhood. This is an area only protected against flooding by the Maeslant sea barrier, which closes when sea levels reach 3 meters above average sea level. Parts of the neighbourhood are expected to flood quite frequent (more than once in 50 years) and due to climate change it is expected that flooding will occur even more frequent. At these frequencies, water depths for most of the parts are small, in the range of 10 to 50 cm. The case evaluates the effectiveness of a range of urban flood management strategies for this area unprotected by flood defences. The case was carried out within the context of the Knowledge for Climate project 'Adaptive strategies for the Rotterdam unembanked area' (Van Veelen, 2012).

Figure 5.1 Aerial view of the case study area Rotterdam Feyenoord and Noordereiland.

5.2 The Dordrecht case, step by step

Step 1; Quantify objectives and acceptability thresholds

For the Dordrecht case, no objectives or standards were developed on flood impact.

Step 2; Analyse effects of climate change

In an evaluation of the flood impact for the Island of Dordrecht flood impacts have been assessed for three flood probabilities. The flood scenarios and impact calculations were obtained from the VNK2 project (Piek, 2007). The representative boundary conditions for these flood scenarios are given in **Table 5.1**.

Table 5.1 Overview of the applied flood probability scenario's.

Probability Scenarios	**Seaside flood defences (Maeslant/Hartelkering) "Open" or "closed"**	**Rhine Discharge (m^3/s)**	**Sea level at Maasmond (m)**
Up to 1 in 2000	*No flooding assumed*		
1 in 2000	Closed	8000	3.5
1in 20000	Closed	9500	3.75
1 in 200000	closed	10000	4.25

The VNK2 project evaluated the effects for 13 representative dike breach locations for the Island of Dordrecht. For each dike breach location three flood maps have been developed each describing a flood corresponding to one flood probability, resulting in 39 (3x13) flood maps.

Direct and indirect economic impacts have been considered as well as the number of casualties. The total impact was defined by the sum of the direct damage that occurs to buildings, infrastructure and capital goods, the indirect damage caused by business failure and secondary costs due to business interruption outside of the flooded area (Subhan, 2010). The damages were calculated using The Netherlands Damage and Casualties module (HIS SSM). The module combines information on land use (roads, housing, railroads, agricultural and other land use types, etc.) with flood information through damage functions. Inputs for the module are the maximum water depth, maximum flow velocity and rate of rise of water levels for various flood scenarios (Subhan, 2010). Impacts which could not be expressed monetary were not considered due to lack of information and method.

The total impact for each probability scenarios was defined by the sum of the weighted impact for each breach location assuming equal probability of breaching (1/13 = 0.077).

Impact Sc1 = 0,077*ImpactBreach1-Sc1 + 0,077*ImpactBreach2-Sc1 + … + 0,077*ImpactBreach13-Sc1

From the impact assessments of the dike breaches, two Impact - Probability relation curve were built illustrating the damages in MEuros and the number of casualties. **Figure 5.2** and **Figure 5.3** show the Impact – Probability curves for the Island of Dordrecht. Within this case study these curves are defined as the base case (alternative 0). In step 4, devise critical set of options, measures are evaluated and compared with the base case.

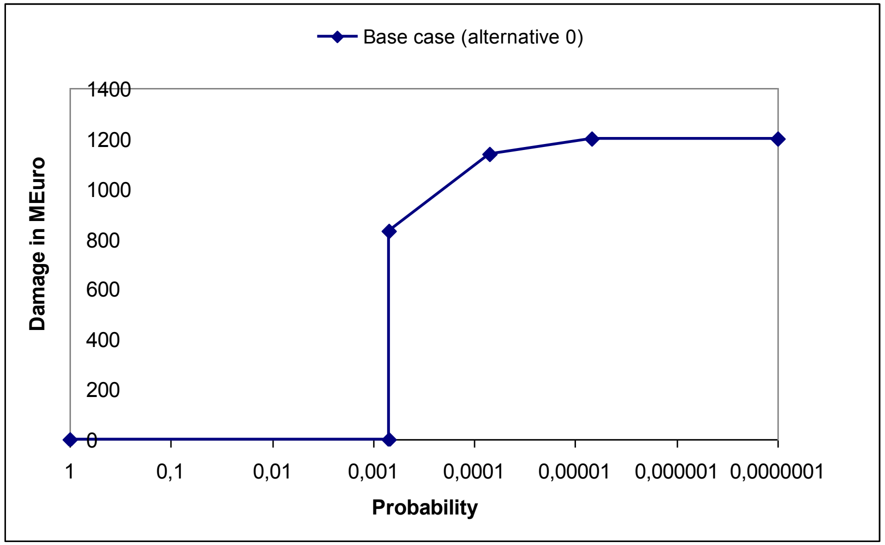


Figure 5.2 Impact - Probability curve for base case Island of Dordrecht (Damage in MEuro) (Gersonius et al, 2011).

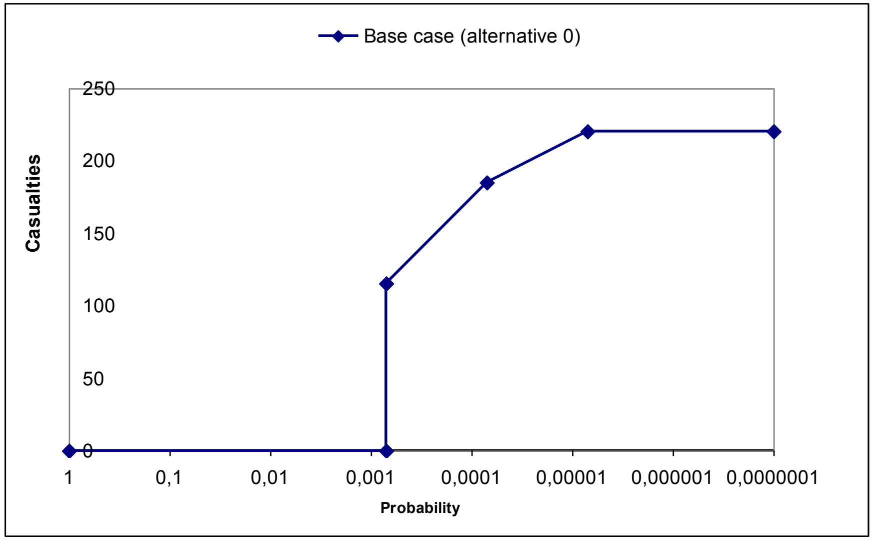


Figure 5.3 Impact - Probability curve for base case Island of Dordrecht (Number of casualties) (Gersonius et al, 2011).

Step 3; Assess moment in time at which acceptability thresholds will be exceeded

From interpretation of the reaction curve it is seen that this highly protected system shows a very large increase in impact after passing the protection level. A high protection level is implemented for the island, but if the flood defences fail the island will be flooded very rapidly and large water depths are expected. At this point the graduality is low. The reaction curve shows that this is one of the critical points in the flood risk management for the Island of Dordrecht. The impact only increases minimally subsequently compared with the large increase in impact after initial failure of the flood defences. A significant increase in impact due to climate change is therefore not foreseen although, the predicted impacts would occur at a much lower return period if the protection level it not maintained.

For the Dordrecht case only a visual assessment was executed.

Step 4; Devise critical set of options

From the assessment of the reaction curve for the Island of Dordrecht it was seen that the impact due to climate change is not expected to increase largely. It was seen though that the graduality was very low at the point where the protection level was passed. Two alternative dike constructions have been evaluated. These responses aim at reducing the inundation depths. The following alternatives were considered (Gersonius et al, 2011).

1. Making the existing dike ring overtopable. It is assumed that the probability of failure of an overtopable dike is 100 times smaller than for the current design standard (Gersonius et al, 2011).

2. Implementation of an overtopable dike in combination with compartimentalisation. In this alternative, the Northern part of the dike ring is converted to an overtopable dike. The Southern part of the island is protected by two sequential dikes.

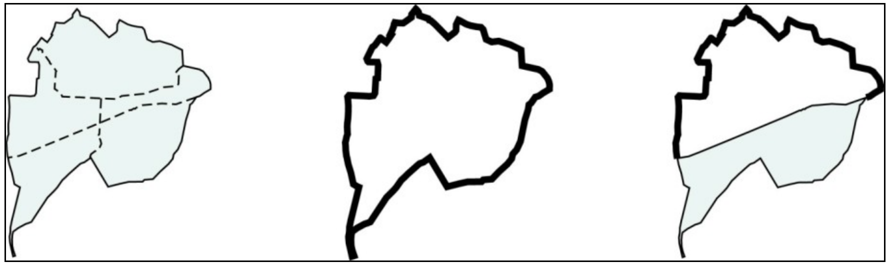


Figure 5.4 Illustration of base case (left) and two alternative dike constructions for the Island of Dordrecht. Middle: overtopable dike ring, right: combination of overtopable dike and compartment dikes (Gersonius et al, 2011).

The flood impacts for the alternative dike constructions were evaluated using the Netherlands damage and casualties module (HIS SSM). The results are illustrated in **Figure 5.5** and **Figure 5.6**.

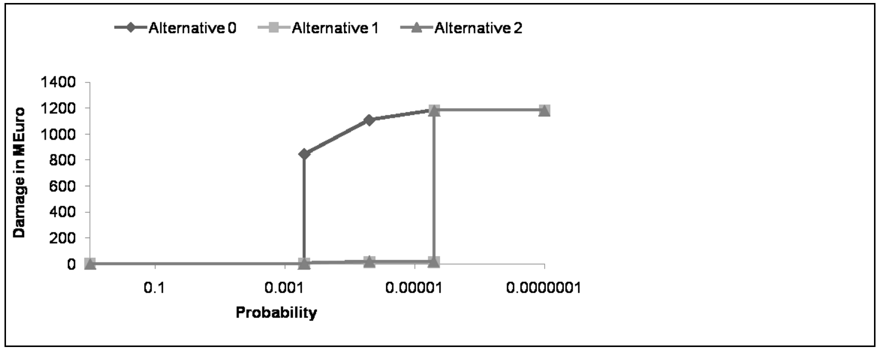


Figure 5.5 Expected damages over a range of return periods for the three alternatives (Gersonius et al, 2011).

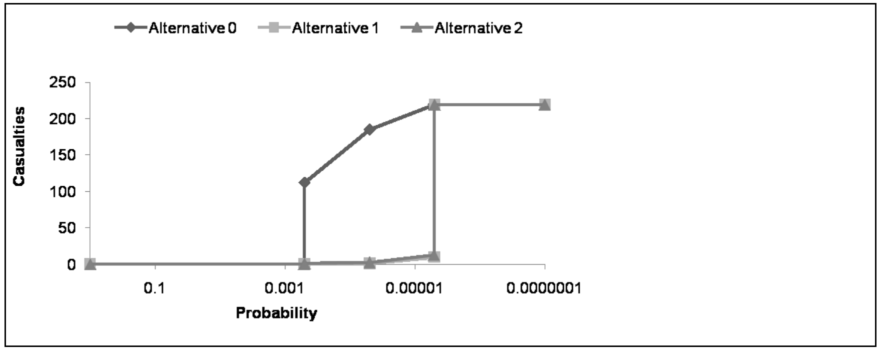


Figure 5.6 Expected number of casualties over a range of return periods for the three alternatives (Gersonius et al, 2011).

The figures show that the alternatives result in a damage and casualties decrease when comparing to the base case. Large damages and casualties are only foreseen for very rare flood event with a probability smaller than 1 in 100.000.

5.3 The Rotterdam case, step by step

Step 1; Quantify objectives and acceptability thresholds

For the Rotterdam case study area objectives were defined on the topics Social disruption and Damages. For the topic social disruption critical urban functions and objects were identified which should be maintained or not cause an impact during a flood. This criterion was set for floods with a frequency of up to 1 in 10.000 years. The urban functions and objects are: Electricity (substation), Communication, Evacuation and emergency services routes, Metro including the metro stations, Train including the train stations, Ground floor bound living (single floor), Hazardous activities and 24-hour medical care.

For the topic Damages, a distinction was made for existing buildings, to develop buildings and the public space. For each category no damages are tolerated up to a certain flood frequency, respectively 1 in 100, 1 in 1000 and 1 in 100 years.

Step 2; Analyse effects of climate change

Within the context of the KvK 3.1 project, a vulnerability analysis was performed, looking into the flood damages to buildings and infrastructure and into critical infrastructure (Veerbeek and Gersoinius, 2012). Use was made of the flood hazard maps developed for the unembanked areas (Huizinga, 2010) which are illustrated in **Figure 5.7**. A series of flood frequencies was analysed ranging from a 1 in 10 years flood to a 1 in 10.000 years flood.

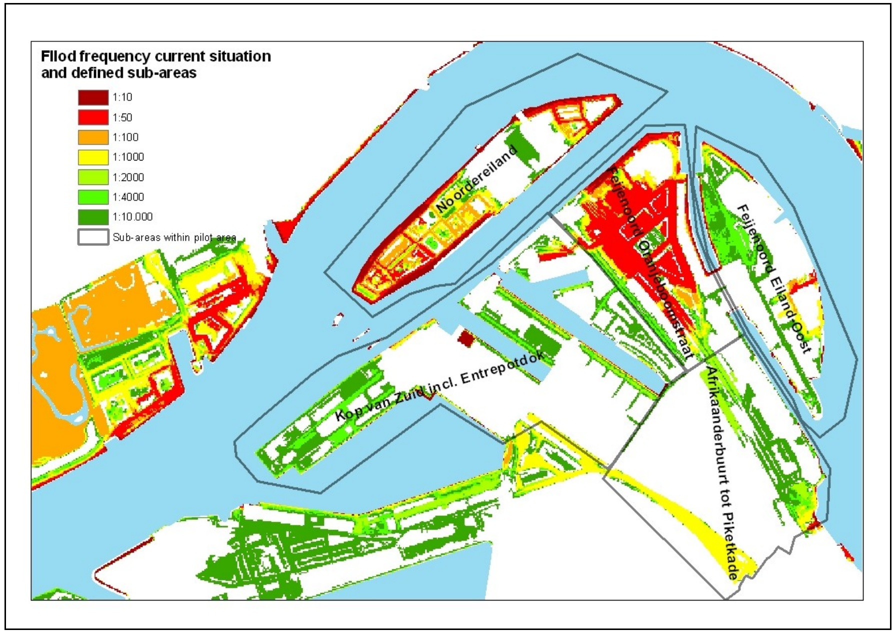


Figure 5.7 Flood extent for a series of flood frequencies. The red colors are used to indicate the areas with highest probability of flooding. The case study focusses on the areas Noordereiland and Feijenoord Oranjeboomstraat (Kop van Feijenoord).

The damage was assessed for the different neighbourhoods with a differentiation between damage to buildings and to infrastructure and reaction curves were developed based on this information. The results are summarised in **Figure 5.8** and **Figure 5.9** (Stone, 2012) and (Veerbeek and Gersonius, 2012).

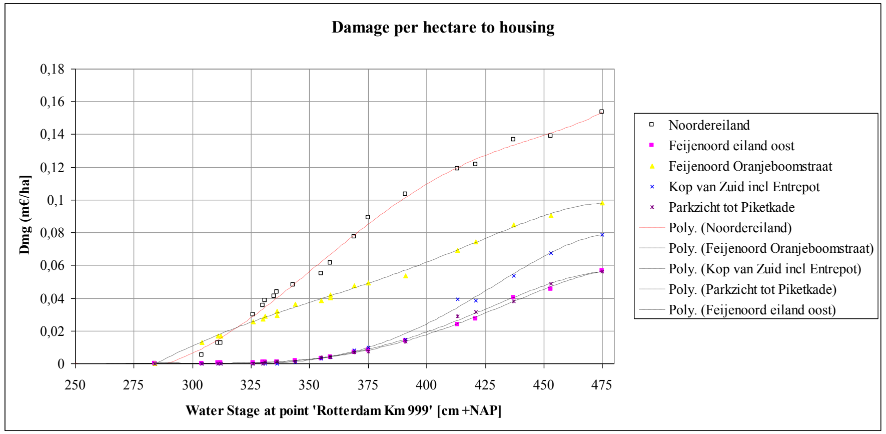


Figure 5.8 Damage to housing for different river water levels in MEuros/ha (Stone, 2012).

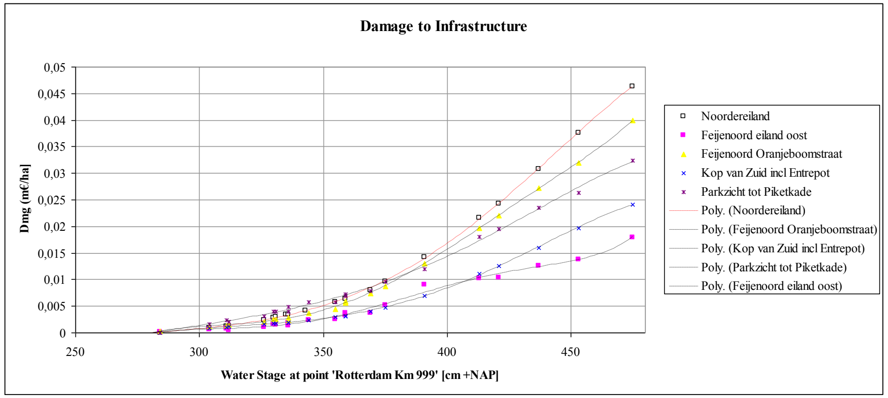


Figure 5.9 Total damage to infrastructure for different river water levels in MEuros/ha with equal vertical scale range as for damage to housing (Stone, 2012).

The shift in flood probability due to climate change was not plotted in a graph. Insight into the effects of climate change on the river water levels is available though (**Table 5.2**).

Table 5.2 Corresponding water levels at the current situation and sea level rise for river section KM 999, Rot-terdam (Veelen, 2012).

Sea level rise (cm)	0	35	60	85	130
Corresponding climate scenario's	Current situation	KNMI W/W+ 2050 KNMI G/G+ 2100 lower limit	KNMI G+ 2100 upper limit	KNMI W/W+ 2100	Veerman 2100
Frequency (1:X years)					
10	284	299	312	319	336
25	296	308	320	326	345
50	304	314	326	331	355
100	311	320	331	337	369
250	319	327	339	348	389
500	325	333	347	360	405
750	328	337	353	370	414
1000	330	339	359	377	421
1250	332	342	364	382	426
2000	336	348	375	394	437
2500	338	352	380	399	442
4000	344	362	391	410	453
5000	346	368	396	415	458
7500	353	378	406	425	468
10000	359	385	413	432	475
20000	377	403	431	449	492
50000	402	427	455	472	514

Step 3 and 4; Assess moment in time at which acceptability thresholds will be exceeded and devise critical set of options

For the Noordereiland and Kop van Feijenoord area the extent of sea level rise was assessed at which the objectives could not be met anymore. Three strategies were developed each encompassing a package of measures (PoM) to reduce the flood risks in the area. Each set of measures was assessed on their effectiveness. The outcomes are shown in **Figure 5.10** and **Figure 5.11** (Stone, 2012).

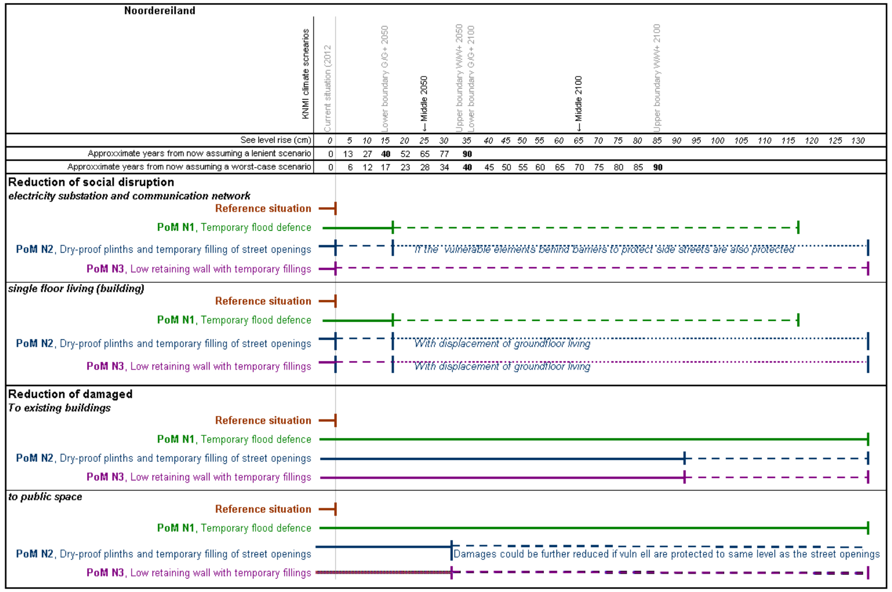


Figure 5.10 Overview of the effectiveness of the PoM's for Noordereiland in regard to the objectives. The dashed lines illustrate the effectiveness of the PoM's if the maximum variant for the measures is implemented (Stone, 2012).

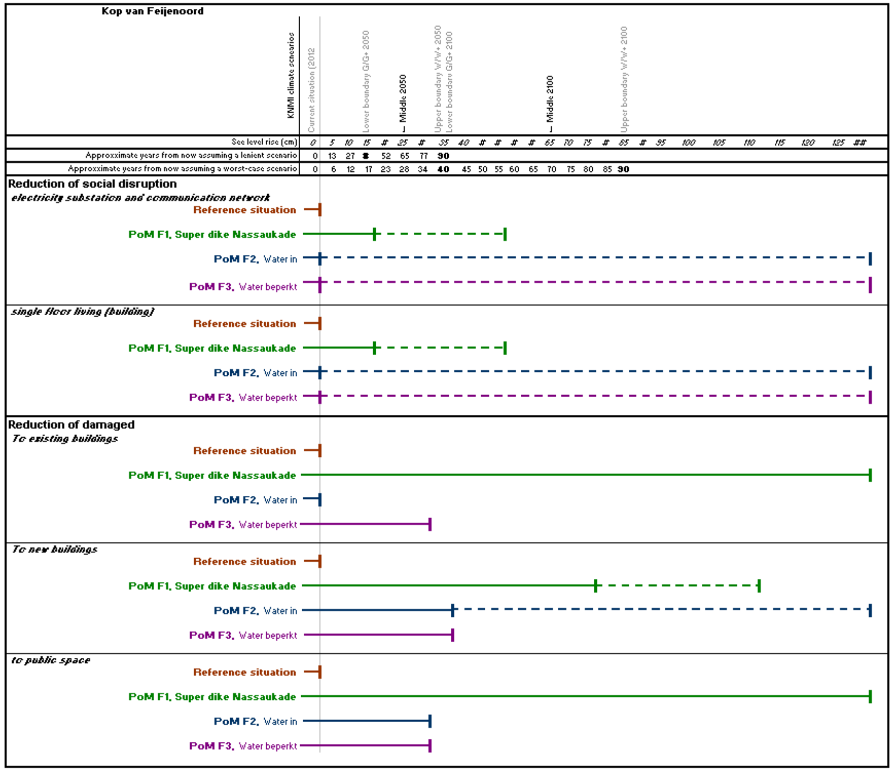


Figure 5.11 Overview of the effectiveness of the PoM's for kop van Feijenoord in regard to the criteria objectives. The dashed lines illustrate the effectiveness of the PoM's if the maximum variant for the measures is implemented (Stone, 2012).

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Appendix 1 Techniques and tools

Step 1: Quantify objectives and acceptability thresholds;

No specific techniques and tools.

Step 2: Analyse effects of climate change;

An extensive overview of methods and tools for flood mapping and impact assessment has been developed within the context of the FLOODSite project (Samuels et al, 2009).

Flood modelling:

- Sobek 1D2D (software)
- Mike FLOOD
- TUFlow

Impact assessment

- The Netherlands: damage and casualties module (HIS SSM) for calculation of flood impacts
- UK: Multi coloured manual. The insurance tables.
- Determination of recovery capacity: method de Bruijn (2005)

Probability assessment:

- HYMOS (statistical analysis of historical data)
- The Netherlands: PC Ring

Climate change scenarios:

- The Netherlands: KNMI klimaat scenario's

Step 3: Assess moment in time at which acceptability thresholds will be exceeded;

- More information on interpretation of reaction curve can be found in (de Bruijn, 2005)
- More information on developing adaptation pathways, can be found in (Haasnoot et al, 2012) and (Te Linde and Jeuken, 2011)

Step 4: Devise critical set of options

Overview of possible responses:

- The Netherlands: waterrobuust bouwen (3BW, 2009)

Effectiveness of responses:

- EU CRUE-Era-net project FIM Frame: framework for improvement of Flood Emergency Plans
- LEM and Evacuaid: evacuation models