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Vulnerability to Climate Change:

Appraisal of a vulnerability assessment method in a policy context

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Vulnerability to Climate Change: Appraisal of a vulnerability assessment method in a policy context

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Content

Summary

This report presents the outcomes of a review, choice and application of vulnerability assessment methodologies in the context of natural hazards. Since the outcomes are especially aimed at policy and decision makers from municipalities, the criteria and use have been aimed to fit into a more strategy oriented context that is flexible, communicative and usable for experts as well as non-experts. The adaptation tipping point method is identified as the best assessment methodology since it focuses on the temporal dimension, acts as a 'meta-method' on top of existing vulnerability methods and is able to incorporate multiple climate change scenarios. The method has been applied in two case study locations, Rotterdam-Noord and Nijmegen for the problem of pluvial flooding. This report covers a review of vulnerability assessment models, a rational for the choice of the adaptation tipping point method, the application and observations as well as a discussion on strengths, weaknesses, opportunities and threats of using the method.

Samenvatting

In dit rapport worden de uitkomsten gepresenteerd van het onderzoek naar de keuze een optimale methode voor het bepalen van de kwetsbaarheid voor klimaateffecten. Aangezien de doelgroep voor een dergelijke methodiek bestaat uit gemeentelijke beleidsadviseurs en bestuurders, moet de methodiek vooral strategisch van aard zijn. Daarnaast moet zij inpasbaar zijn in zowel de organisatie als binnen het huidige instrumentarium dat gebruikt wordt binnen de gemeentelijke diensten om klimaat gerelateerde problemen te modeleren en meten. De 'Adaptation Tipping Point' methodiek lijkt hiervoor de beste keuze. De methodiek is toegepast in Rotterdam-Noord en Nijmegen voor het evalueren van een mogelijk toenemende wateroverlast als gevolg van klimaatverandering. Dit rapport presenteert een uitgebreide beschouwing van beschikbare methodieken voor het bepalen van kwetsbaarheid, de criteria en keuze van een methodiek, de uitkomsten van de toepassing alsmede een sterkte-zwakteanalyse van de methodiek.

Extended summary

Urban areas are vulnerable to climate change. It is expected that the amount and intensity of extreme rainfall events, drought and heat will increase, resulting in increased pluvial flooding, groundwater flooding, drought and heat stress. Scientists indicate that pro-active adaptation policies in combination with extensive vulnerability assessments help reducing the costs of the impacts of extreme weather events. At this moment, quantitative vulnerability assessments on municipal level are scarce. The objective of this study is formulated as follows:

To develop and pre-test a method for municipalities for assessing the current and future vulnerability of urban areas to climate change quantitatively regarding pluvial flooding, and explore its potential for groundwater flooding, heat and drought.

Vulnerability can be measured in terms of its outcomes, referred to as outcome vulnerability, and in terms of “the state of a system before the hazard acts”, referred to as contextual vulnerability. This study uses an integrated definition of vulnerability, that refers to both contextual and outcome vulnerability:

Vulnerability is “the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity” (McCarthy et al., 2001, p.995)

An analysis is made of the ways in which urban areas or municipalities are vulnerable to pluvial flooding, groundwater flooding, drought and heat stress on the basis of literature research. An analysis is made of the need for vulnerability assessment on municipal scale and what methods for vulnerability assessment would be useful, both referring to contextual vulnerability and outcome vulnerability on the basis of interviews with a number of municipalities in the Netherlands (Rotterdam, Amsterdam, Nijmegen, Arnhem, Utrecht and Den Haag) and literature research. Finally, the Adaptation Tipping Point (ATP)-method (e.g. Jeuken and te Linden, 2011) has been selected for pre-testing in Rotterdam-Noord and Nijmegen. This pre-test only addressed pluvial flooding.

Applied to the context of vulnerability assessment, the ATP-method uses the results of climate change impact and damage analyses to determine under what conditions the vulnerability of areas exceeds a certain threshold value. It expresses vulnerability in terms of the time that is left until the threshold value is exceeded. It is a method that indicates outcome vulnerability. Important features of the model comprise flexibility regarding vulnerability indicators, such

as monetary values of damages, casualties and ecological damage, and a strong temporal focus, which allows municipalities to determine the urgency of management of their vulnerability.

The ATP-method has been pre-tested in Rotterdam-Noord and Nijmegen in regard to the municipal need for vulnerability assessment, comprising criteria regarding policy relevance, feasibility and easiness of communication. The case study Rotterdam focussed on flooding of residential and commercial buildings, as well as traffic nuisance on major roads. The case study Nijmegen involved pluvial flooding of buildings only, but it also included an extensive sensitivity analysis. The cases provide useful information for the evaluation of the suitability of the ATP-method. The findings of the case study have been included in an analysis of the Strengths, Weaknesses, Opportunities and Threats. The most important strengths of the method relate to its ability to indicate the urgency of climate change adaptation, its flexibility and communicability. The most important weaknesses relate to the need for impact assessments and their high uncertainty. Opportunities are available for increasing the feasibility of the method, for example regarding assessment of ATPs on the basis of expert judgement. In addition, the methods could be extended with an assessment of opportunities for combining adaptation measures with other measures. A threat to the ATP-method is that municipalities do not want to define their ATPs out of fear of creating enforceable norms. In addition, methods for impact and damage assessment need to be developed further.

In conclusion, the ATP-method is a suitable method for quantification of vulnerability of urban areas to climate change. It provides useful information for municipalities in addition to traditional impact and damage assessments and provides a way to assess the urgency of adaptation to pluvial flooding. If the method is further developed for groundwater flooding, drought and heat stress, it is possible to use the ATP method for objective comparison of vulnerabilities to different climate change related problems. Next to research into the application of the ATP method for groundwater flooding, drought and heat stress, it is necessary to perform additional research into easy ways of predicting future climate change impacts and damages under changed climatic conditions.

1 Introduction

Urban areas are affected by climate changes induced variations in amplitude, frequency and duration of natural hazards. As estimated by the association of Dutch insurers for instance, insurance claims due to extreme rainfall events will increase from 6% to 22% from 2010 to 2050 if no climate adaptation measures are taken [Ririassa and Hoen, 2010]. With the exception of heat waves, many of the identified climate change related effects in The Netherlands do not necessarily lead to high impacts of single events; pluvial floods do not lead to structural collapse, injuries and casualties but accumulated over time, the damages are substantial [Ten Veldhuis, 2010]. In some areas, this would also increase the probability of groundwater flooding. More frequent and longer periods of drought on the other hand are expected to increase damages to wooden foundation pillars, deterioration of urban vegetation and water quality problems [Van de Ven et al., 2010]. Finally, more frequent and longer heat waves lead to higher hospitalization and mortality [Daanen et al, 2010], as well as a decreased productivity. These impacts are only an illustration of some of the effects in urban areas associated to climate change. [Bosch Slabbers Landschaps-architecten, 2010; Planbureau voor de Leefomgeving, 2011]. Increased vulnerability to natural hazards is not only caused by climate change but also change due to socio-economic developments. Increasing urbanisation and growth of the population intensifies the possible effects of climate change over time.

To gain insight in the effects of climate change, a comprehensive and in-depth assessment is needed that covers both hazard, exposure and sensitivity of people and assets in urban areas. This is especially prudent for authorities and decision makers since they need to facilitate and implement possible climate adaptation measures. Increased vulnerability to climate change implies higher impacts and costs in relation to coping with, recovering from and adapting to climate change. Pro-active adaptation to climate change can help municipalities to reduce the costs of climate change significantly, especially in intensively used urban areas [Kabat et al., 2005].

Runhaar et al. (2012) observed, on the basis of an empirical research, that the sense of urgency for pro-active adaptation policies and measures felt by scientists cannot be found among many policymakers in Dutch municipalities. Examples of barriers to climate change adaptation in Dutch municipalities include: limited financial and human resources, lack of knowledge about potential impacts on local level, inflexibility of structural elements of neighbourhoods, a lack of insight into the costs and benefits of adaptation, institutional fragmentation and competition with other planning problems. (Runhaar et al., 2012, IPCC, 2007). Vulnerability assessments can provide municipalities with

the information that they need in order to be able to achieve genuine pro-active adaptation strategies (Runhaar et al., 2012).
The inspection of the Ministry of Spatial Planning considers the lack of vulnerability assessments as one of the reasons for limited attention to climate change adaptation (VROM-Inspectie, 2010). Most municipalities have a general idea about the regional climate outlooks and also have a general idea about the key risks to which the city is exposed. However, quantitative insight into vulnerability is lacking and future vulnerability often is not assessed. (Vrolijks et al., 2011, Ministerie van Infrastructuur en Milieu, 2011).
Many methods have been developed to assess climate change impacts and vulnerability: from qualitative guides for vulnerability assessment in general (e.g. UKCIP, 2010, Snover et al., 2007, Government of Australia, 2006, Future Cities, 2010) to sophisticated methods for specific hazards that involve specialized impact modelling and damage estimation.

This leads to the following main question which is the driver for this research topic:

To identify and pre-test a quantitative method which is manageable for municipalities to assess current and future vulnerabilities as a function of climate change.

This question can be subdivided into a number of sub questions:

Sub questions:

1. What is vulnerability and in what ways are urban areas vulnerable to pluvial floods, groundwater floods, heat and drought?
    a. What is vulnerability?
    b. What are the elements of vulnerability?
    c. In what way are urban areas vulnerable to pluvial floods, groundwater floods, heat and drought?

2. What are the criteria and requirements of municipalities regarding the assessment of their vulnerability to climate change?
    a. How do municipalities currently deal with the assessment of their vulnerability to climate change and how can quantification of vulnerability to climate change improve the way in which municipalities deal with climate change?
    b. What information about vulnerability to climate change is required by different stakeholders within and outside municipalities in which form, on which time scale and on which spatial scale?

3. What is the design space for the design of methods for quantification of vulnerability of municipalities to the themes pluvial floods, ground water floods, heat and drought?
    a. What methods for quantifying vulnerability to climate change in general and to the themes specifically are available already?
    b. What indicators can be formulated that represent vulnerability to each of the themes and how can these indicators be quantified?
        i. What data and methods are available as basis for quantification of vulnerability for each of the themes?
        ii. What are the limitations of the development of indicators regarding the availability of data and methods for measurement for each of the themes?
        iii. In what unit can the indicators and indices be expressed in such a way that vulnerability themes and elements of vulnerability can be combined in a meaningful way?
    c. What are designs of a general method for quantification of vulnerability that can be applied to all of the themes?
    d.
4. Which design choices in the method best match the requirements and criteria to the available design options?

5. What lessons can be drawn from application of the method in Rotterdam-Noord and Nijmegen?

6. What are the strengths and weaknesses, threats and opportunities of the designed method?

1.1 Methodology

This section describes the methodology of the research. For each of the research questions, it is described how the question will be answered and in which chapter the question is addressed.

1. *What is vulnerability and in what ways are urban areas vulnerable to pluvial floods, groundwater floods, heat and drought?* **Ch. 2**

Research question 1 is answered by a literature research. A large body of scientific literature about the (disagreement about the) definition of vulnerability and its elements is available [e.g. Birkmann, 2006; Brooks, 2003; Gallopin, 2006; Hufschmidt, 2011; Kazmierczak and Handley, 2011; Lindley, 2009; Marchand, 2009; Villagrán de León, 2006]. Analysing key publications on this topic made it possible to make a reasoned choice for one of the definitions. Using the chosen definition of vulnerability, this report describes in what ways Dutch urban areas are vulnerable to climate change.

2. *What are the criteria and requirements of municipalities regarding the assessment of their vulnerability to climate change?* **Ch. 3**

Since the method is intended for Dutch municipalities, seven interviews in different municipalities have been conducted to assess their wishes. The topics of these interviews were: the perception of municipalities towards their vulnerability to climate change, their actions to reduce vulnerability and the barriers that they are confronted with, current efforts to assess vulnerability to climate change, data availability and further requirements. In addition, a literature research has been conducted concerning barriers to climate change adaptation.

3. *What design options are there regarding the design of methods for quantification of vulnerability of municipalities to the themes pluvial floods, ground water floods, heat and drought?* **Ch. 4**

Since there are many methods available for the assessment of vulnerability, an analysis of the available methods has been made. The goal of this analysis was to identify promising methods, to identify possibilities to combine methods and to prevent designing a method that was available already. The answer to this research question is based on a literature research.

4. *Which design choices in the method best match the requirements and criteria to the available design space?* **Ch. 4**

As basis for the choice of method, first a pre-selection of two promising methods has been made. Then a score card is used to match the needs of municipalities with the most promising methods.

5. *What lessons can be drawn from application of the method in Rotterdam-Noord and Nijmegen?* **Ch. 5&6**

The chosen method is pre-tested on the basis of two different case studies in Rotterdam-Noord and Nijmegen. These case studies involved modelling, data collection and a field visit.

6. *What are the strengths and weaknesses, threats and opportunities of the designed method?* **Ch. 7**

The final research question of this research project has been answered on the basis of literature research, the outcomes of the case studies and in discussion with stakeholders of the case studies and experts in the field.

1.2 Structure of the report

Chapter 2 describes the definition of vulnerability that is applied in this research project and explains two alternative interpretations of vulnerability: outcome vulnerability and contextual vulnerability. Chapter 3 addresses adaptation strategies in Dutch municipalities and their need for vulnerability assessment. Chapter 4 reviews and describes the choice of a method for quantification of vulnerability of Dutch urban areas. Chapter 5 and 6 describe the case studies that have been performed in Rotterdam-Noord and Nijmegen. Chapter 7 includes an analysis of the strengths, weaknesses, opportunities and threats of the chosen method. The conclusions and recommendations have been included in chapter 8.

2 Defining vulnerability

Because of the large diversity of vulnerability definitions, apparently similar climate change vulnerability assessment methods can be based on very different basic ideas [Lindley, 2009]. Different studies within the same field of research as well as different fields of research use the same word for vulnerability, but mean something different and use the different words for the same concepts [Villagrán de León, 2006].This disagreement about the definition of vulnerability does not only cause confusion among scientists, but also among policy makers [Brooks et al., 2005; Brooks, 2003; O'Brien et al., 2007; Gallopin, 2006].

In order to prevent confusion about this definition of vulnerability in the context of this report, the following two sections explain which definition is chosen. Section 2.1 explains which vulnerability definition has been chosen and further clarifies some of its related concepts. Section 2.2 describes the important difference between outcome vulnerability and contextual vulnerability. Section 2.3 describes a number of characteristics of vulnerability and how they can be measured.

2.1 Chosen vulnerability definition

This section describes the definition of vulnerability that is used in this report and the terms that it contains. The definition that is chosen can be seen as an integrated definition of vulnerability. It is a definition that is often used in vulnerability studies and it enables multiple types of vulnerability assessment, which will be further explained in section 2.2.

"Vulnerability is the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity" [McCarthy et al., 2001, p.995]. This definition of vulnerability contains a number of terms that should be further clarified.

In this report, the *system* under consideration is an urban geographical area, e.g. a neighbourhood or a city. This demarcation is considered as the most suitable, since most of the responsibilities of municipalities are on spatial level rather than on the level of individuals, buildings or other elements within city areas.

Climate change refers to any change in climate over time, whether due to natural variability or as a result of human activity [McCarthy et al., 2001, p.984]. For municipalities it does not matter whether the changes of the climate are human-induced or natural. Adaptation to climate change and increased climate variability are equally important.

Hazards are defined as “climate or weather-related events which directly or indirectly have the capacity to harm people, places or things” [Samuels and Gouldby, 2009]. In this research project the following hazards are taken into account: extreme rainfall events, extreme periods of drought and heat waves.
The *exposure* is defined as “the nature and degree to which a system is exposed to significant climatic variations” [McCarthy et al., 2001, p.987]. Exposure factors include variables that make a neighbourhood more or less exposed to hazards or their related consequences. On municipal level it could be argued that the water-related hazards are geographically uniformly distributed, since rainfall and drought do not vary on such small local scale. Exposure to extreme temperatures differs per neighbourhood because of the urban heat island effect.
Sensitivity is defined as “the degree to which a system is affected, either adversely or beneficially, by climate related stimuli. This effect may be direct (e.g. a change in crop yield in response to a change in the mean, range or variability of temperatures) or indirect (e.g., damages caused by an increase in the frequency of coastal flooding due to sea level rise)” [McCarthy et al., 2001, p.993]. In the context of this report, the sensitivity of urban geographical areas is determined by the number and type of elements, such as people and objects, and their individual susceptibility to damage or impact.
Adaptive capacity is “the ability of a system to adjust to climate change (including climate variability and extremes), to moderate potential damages, to take advantage of opportunities, or to cope with the consequences” [McCarthy et al., 2001, p.982]. It is not easy to quantify adaptive capacity, since it depends on a lot of (social) factors that are difficult to quantify. In addition, it refers to short-term coping with extreme events, as well as long-term planning for gradually evolving climate change risks. This research project focuses on vulnerability of areas to climate change in the long term and primarily on the physical elements of it. In this context it can be stated that the availability of cheap, frequent and feasible adaptation opportunities makes the adaptive capacity of a geographical area high.

2.2 Outcome vulnerability and contextual vulnerability

Figure 1 shows two fundamentally different views on vulnerability: Outcome vulnerability and contextual vulnerability [Kelly and Adger, 2000, O'Brien et al., 2007]. This paragraph explains the differences between these two interpretations of vulnerability and why these differences are crucial for the type of vulnerability assessment.

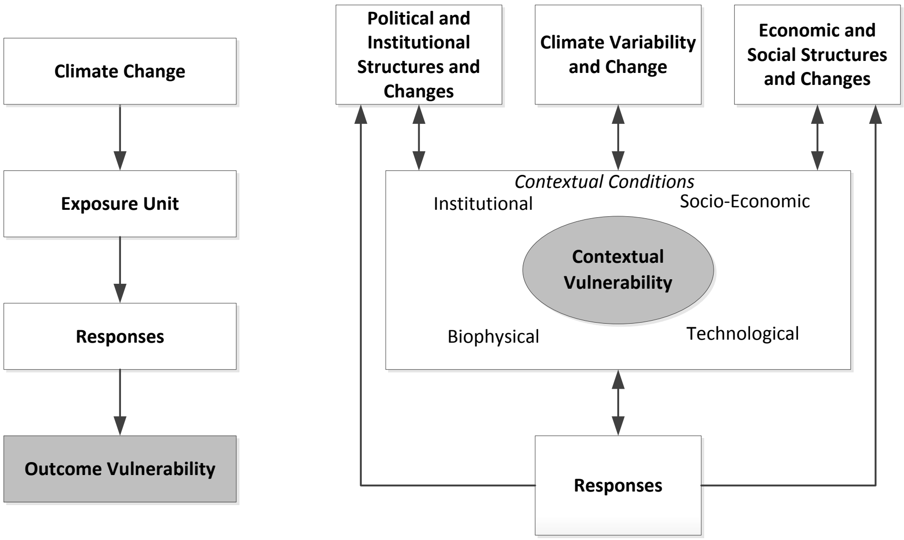


Figure 1: Two interpretations of vulnerability to climate change. Left: Outcome vulnerability, Right: contextual vulnerability (O'Brien et al., 2007, p.75)

Outcome vulnerability can be seen as the impacts after the process of adaptation has taken place [Kelly and Adger, 2000]. Assessment of outcome vulnerability can be classified as top-down. It starts with climate modelling, resulting in a number of scenarios. Then impact studies are performed and responses are identified. The remaining impacts are seen as outcome vulnerability, which can include economic as well as social dimensions (Brooks, 2003).
Contextual vulnerability does not consider vulnerability as an outcome of climate change, but as an overarching concept, covering exposure to hazards, inability to cope, consequences and the risk of slow recovery [Kelly and Adger, 2000]. Maxim and Spangenberg [2006, p.3] describe contextual vulnerability as: “the state of a system before the hazard acts”. Another example of a contextual vulnerability definition is: *"The ability or inability of individuals or social groupings to respond to, in the sense of cope with, recover from or adapt to, any external stress paced on their livelihoods and well-being."* [Kelly and Adger, 2000, p.328]

Figure 2 describes the relations between the elements that define the vulnerability to climate change. Contextual vulnerability is not independent of outcome vulnerability. Contextual vulnerability can be seen as a determinant of outcome-vulnerability (Brooks, 2003). There are large differences between methods for assessment of contextual vulnerability and outcome vulnerability.
Assessment of outcome vulnerability gives insight in the potential magnitude of climate change impacts at a certain moment in future and thus gives insight into the need for action (Eriksen and Kelly, 2007). Assessment of outcome vulnerability often leads to sectoral and mostly technical advices to decrease the amount of assets at risk or the susceptibility to damage, since these types of measures can be measured easily in terms of the “net impacts” (Eriksen and Kelly, 2007). Füssel (2007) argues that the outcome-approach is more suitable for raising awareness and identifying research priorities, but he also states that

it requires a large number of conditions including a long temporal focus, sufficient data and sufficient spatial detail.

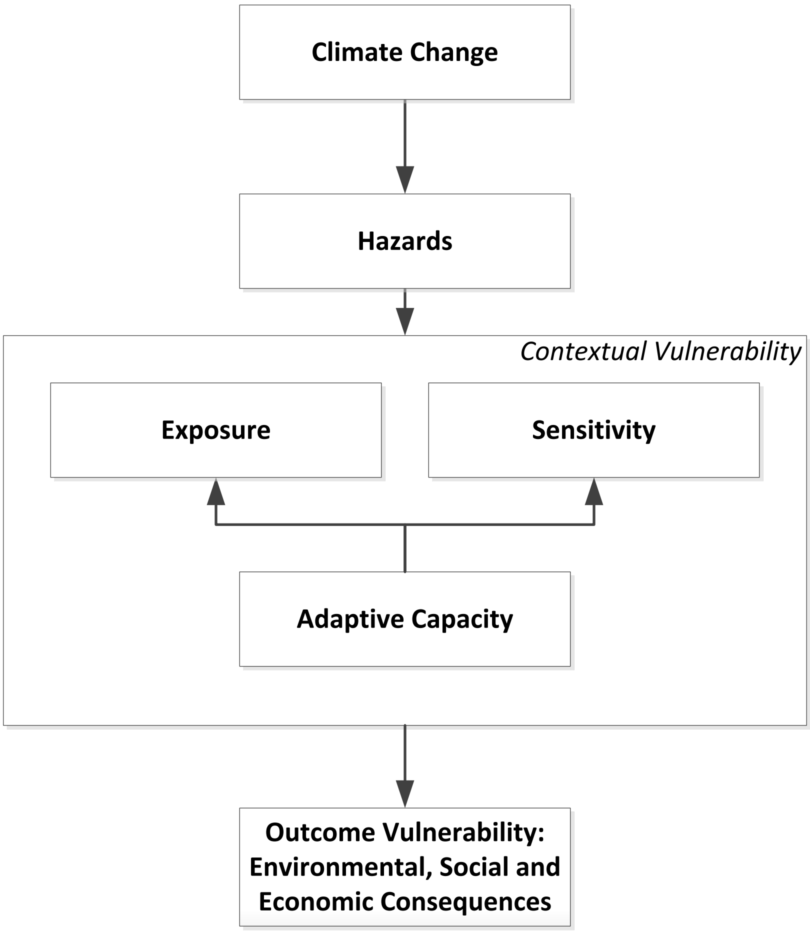


Figure 2: Relations between vulnerability concepts (Fünfgeld and McEvoy, 2011, p.41). Terms contextual vulnerability and outcome vulnerability are added by the author.

Assessment of contextual vulnerability focuses on the underlying causes and drivers of vulnerability [Eriksen and Kelly, 2007]. Vulnerability is on the one hand caused by external forces to which an asset is exposed and on the other hand by the limited capacity to respond (Chambers, 1989). This response can refer to coping with present stress, recovery from extreme events and proactive long-term adaptation to future conditions and events (Eriksen and Kelly, 2007). The outcomes of this type of analysis generate a wider range of policy recommendations [Eriksen and Kelly, 2007]. Improved understanding of contextual vulnerability can provide greater assistance to municipalities in their efforts to develop their adaptation policies in relation to climate change and all other relevant developments. Assessment of contextual vulnerability is mostly useful for identifying vulnerability hotspots if [Füssel, 2007]:

- data is scarce, since modelling or estimation of impacts is not necessary. It only involves mapping a number of variables of the current system.
- the time horizon is low, since present variables can only indicate vulnerability on the short term.

- the climate impacts have to be seen in relation to other developments. It can be difficult to include the effect of socio-economic developments in the modelling of impacts of climate change.
- climate uncertainty is high. Impact assessments have a limited value if the uncertainties in the outcomes of the analysis are high. In this case it might be more attractive to perform a contextual vulnerability assessment.
- resources for the assessment are small. Since no modelling is required, costs can be considerable lower than assessment of outcome vulnerability.

Assessment of both contextual vulnerability and outcome vulnerability can be in line with the chosen vulnerability definition. “The degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change” can be measured in terms of the residual impacts (i.e. climate change impacts after adaptation), which is in line with the definition of outcome vulnerability. Quantification of the exposure, sensitivity and adaptive capacity of a system can be seen as an assessment of contextual vulnerability. This definition gives the freedom to tailor the method to the needs of municipalities, since at this stage it is not yet clear what type of information is needed by municipalities.

2.3 Vulnerability indicators

No author has succeeded in developing one general measure for outcome vulnerability; Birkmann [2006] states that such a measure does not exist. Vulnerability depends on spatial scale, temporal scale, per actor and on many other factors, which make it impossible to develop one number that covers all aspects of the concept. This section addresses a number of general measures for elements of outcome vulnerability.

2.3.1 Mean annual impacts

The most direct way to quantify vulnerability on the basis of its impacts is to calculate the yearly averaged (net) impacts. In order to calculate the yearly averaged (net) impacts it is necessary to calculate the future impacts of climate change related events and the probability distribution of these impacts. In practise this often means that a distinct climate change scenario is chosen on which the future probability distribution is based. This often introduces the problem of how the current climate probability distribution will transform into that associated to the future scenario. By calculating the weighted average, the mean annual impacts are derived. Note that this means that information will be lost since the impact distribution (e.g. the differences between frequent and rare events) is absorbed into the single figure expressing the mean annual impact. Mean annual impacts are often made operational by using monetary terms, expressed as the expected mean annual damage.

2.3.2 Graduality of impacts

Expressing the proportionality of impacts as a function of stressor levels is important to identify threshold effects (i.e. sudden increase of impact levels by only a limited increase of the stressor level). For instance, flood damages can increase dramatically after the flood level exceeds the critical height of the doorsteps, resulting in inundation of houses and subsequent damages.

De Bruijn [2005] addresses this issue with an additional indicator. Graduality is a measure for discontinuities in the damages in relation to increasing stress levels. De Bruin applies this metric to a river system where the relative increase of discharge in percentages and the corresponding relative increase of damage are compared. The indicator has a value of 1 if the damage function is linear and 0 if the impact function is a step-function.

As long as there is a function available that specifies the amount of impact for each level of a climate change related stressor, graduality can be calculated. However, as stand-alone indicator it does not provide a lot of information. De Bruijn [2005) uses graduality as one of the three indicators for flood resilience. The other who indicators are annual mean damages/casualties and an index for recovery rate.

2.3.3 Spatial distribution

Another aspect that is not represented in the mean annual impacts, as well as in the graduality of impacts, is the spatial distribution of impacts. The type of measures and thus the adaptive capacity of an area regarding climate change, depends on the spatial distributions. If impacts are concentrated in a very small known area, it is easy to prioritise locations of measures and take technical measures to reduce the vulnerability. When impacts occur on such locations there will be more public pressure to reduce its vulnerability. This can for example be seen in locations with regular groundwater flooding of buildings. If impacts are spread over a large region, it is more difficult to take technical measures. Consequently there should be paid more attention to non-structural measures or decentralised technical measures. Vulnerability to heat stress could for example be seen as widely distributed, although some hotspots can be identified as well. The impacts of pluvial flooding are located on limited areas. Especially for very extreme events or if no proper models are made, it is impossible to predict where exactly the rainfall intensities are maximal and where the impacts will be the highest.

Table 1: impact of spatial distribution on vulnerability

Concentrated		**Widely spread**
Known locations	**Unknown locations**	
Focus on centralised technical measures	Focus on non-structural measures and decentralised technical measures	Focus on non-structural measures and decentralised technical measures
Strong incentive to take measures (after extreme event occurred)	Strong incentive to take measures (after extreme event occurred)	Weak incentive to take measures
Centralised responsibilities, large role for municipality	In principle distributed responsibilities, larger role for the affected stakeholders. If damages/impacts are very high, municipalities take measures.	Distributed responsibilities, larger role for the affected stakeholders
Groundwater flooding, drought, pluvial flooding	Pluvial flooding	Pluvial flooding, heat stress

2.3.4 Proportional vulnerability, vulnerability gap and vulnerability severity

Adger [2006] argues that a general measure of vulnerability should not only take into account the number of elements that are exposed to hazards or the elements that do not have adaptive capacity, but it also should take into account the severity of the vulnerability. The measure should address the well-being of a population in general, instead of focusing on material cases only. In addition, it should also take into account the risk of being vulnerable, instead of only focusing on who or what is currently vulnerable and the distribution of the vulnerability within vulnerable populations. Adger [2005] bases his general measures for vulnerability on a general measure for poverty (Foster et al., 1984):

$$V_\alpha = \frac{1}{n}\left[\sum_{i=1}^{q}(W_0 - w_i / W_0)^\alpha\right]$$

Where, Vα is the vulnerability indicator, Wi is the well-being of individual i, W0 is the threshold level of well-being representing danger or vulnerability, n is the total number of individuals, q is the number of people above the vulnerability threshold, α is the sensitivity parameter. Individuals are ordered from bottom to top (W1 is more vulnerable than W2) Well-being can be interpreted in a broad way, it does not limit itself to human well-being. Individuals can be people, communities, neighbourhoods etc.

Adger then proposes the following more specific vulnerability measures. The symbols in the formulae have the same meaning as those in the formula of Foster et al. (1984)

Table 2: A class of vulnerability measures and their intuitive interpretation (Adger, 2006, p.279)

Measure		Explanation
Proportional vulnerability	$V_0 = \frac{q}{n}$	This is a 'headcount' indicator. Proportion of relevant population that is classified as vulnerable.
Vulnerability gap	$V_1 = \frac{1}{n}\left[\sum_{i=1}^{q}(W_0 - w_i / W_0)\right]$	The summed distance of the well-being of an individual from the vulnerability threshold of well-being. Vulnerability can be reduced by limiting the number of vulnerable individuals or by reducing the scale of their vulnerability.
Vulnerability severity	$V_2 = \frac{1}{n}\left[\sum_{i=1}^{q}(W_0 - w_i / W_0)^2\right]$	The severity of vulnerability is measured by weighting the distribution of the vulnerability gap within the vulnerable population. The greater the vulnerability is skewed towards the most vulnerable, the greater is the severity

These measures of vulnerability can be seen as classes of vulnerability indicators. Which class is chosen depends on the goal of the vulnerability assessment and the type of measures that need to be taken (Adger, 2006). V0 only considers whether an individual is vulnerable. V1 and V2 also consider the deviation from the vulnerability threshold. The higher α is set, the more weight is put on the individuals that show large deviations from the vulnerability threshold W0. Please note that this measure does not consider the dynamic nature of vulnerability. However, it is possible to define vulnerability as composite vector of exposure and adaptive capacity (Adger, 2006).

The formulae for proportional vulnerability, vulnerability gap and vulnerability severity provide the possibility to include the severity of the impact in a measure of vulnerability. Further it is possible to define the welfare function on the basis of an index, allowing for a comprehensive measure of vulnerability.

2.3.5 (Adaptation) Tipping points

The adaptation tipping point (ATP) method, focuses on the temporal dimension. It does not so much indicate a specific vulnerability dimension but addresses the interaction between current norms or goals and the moment when these are exceeded by trend changes in the vulnerability drivers. For instance, current norms for pluvial flooding might be formalized as: "no flooding of streets may occur for rainfall with return periods of 2 years or higher". Since climate change in this case might change the probability distribution, some areas that now offer higher protection standards (e.g. 5-year rainfall events) might reach this 2-year norm at some point in the coming future. This point is referred to as the tipping point. Within The Netherlands, Jeuken and te Linden [2011] first applied this method to gain insight in the longevity of current flood protection standards in the Dutch delta area to a changing climate. Yet, the method is basically suitable to be applied for practically any domain and problem as long as agreement exists about the norm or goal (i.e. the exeedance threshold), the trend changes in the stressor levels (e.g. changing rainfall distribtions caused by climate dhange) and the metrics to measure the impact. This also introduces a more fundamental aspect of the ATP method: it basically acts as a post-assessment analysis since it requires some other vulnerability assessment method (e.g. annual damages) to calculate the tipping points.

2.3.6 Observations

As described, the broad concept of vulnerability is operationalized using various methods and metrics that all focussing on specific aspects of the term. Since vulnerability encompasses various spatial and temporal scales, systems, events as well as a range of post-analysis methods, no all-encompassing method can be defined that provides both the depth and breadth required for a comprehensive vulnerability analysis for urban areas to natural hazards. Furthermore, the data requirements and complexities of the presented concepts differ substantially, making them not always applicable to all domains, problems and expert levels. The application of vulnerability metric therefore requires careful consideration of the aims, the available data and resources and ultimately the level of expressiveness required to serve its purpose.

2.4 Conclusions

Operationalizing the concept of vulnerability is a non-trivial task. It requires a deep understanding of the aims, system, metrics and subsequent requirements needed to perform a vulnerability assessment. While various methods are available, most of these focus on a specific aspect of vulnerability. Hotspot and cluster mapping indicate the spatial distribution of vulnerability but only focus on single events. Mean annual impacts offer comparable figures but do not express the distribution of impacts over a range of probabilities. Graduality offers insight in threshold effects but do not provide absolute figures about the expected impacts. Tipping points focus merely on the temporal scale in relation to norms or goals without indicating the amplitude of the problem. Furthermore, not all methods are easily interpreted or useful in practise. The requirements of experts might significantly differ from policy makers or the general public. It is therefore essential to perform a comprehensive study on the requirements for any vulnerability assessment especially since many metric are resource and data intensive.

While this chapter provides an overview of a selected set of metrics for vulnerability assessment, the methods themselves are not operationalized in the context of natural hazards or climate change. Transforming these methods to operational tools requires substantial context and domain specific modelling techniques ranging from hazard modelling (e.g. climate modelling), exposure modelling (e.g. hydraulic modelling of storm water drainage networks) and sensitivity modelling (e.g. flood depth –damage relations of specific building types). In the context of natural hazards and climate change, the Dutch urban areas suffer only from a subset of impacts. A detailed description of these impacts is available from Stone et al [2011], where 4 major climate related hazards are covered: pluvial flooding, groundwater flooding, drought and heat stress.

3 Municipalities and need for vulnerability assessment

This chapter describes how municipalities cope with the assessment of their vulnerability to natural hazards and how they formulate their adaptation policies. This review is a vital part in choosing and applying a vulnerability assessment method that is suitable for application in a policy making environment. Apart from the sources that are mentioned throughout the chapter, interviews have been conducted in Arnhem, Nijmegen, Rotterdam, Amsterdam Nieuw-West, Amsterdam Watergraafsmeer and Den Haag with various policy advisors and experts in the field of climate adaptation, urban water management and heat stress. Appendix 2 contains the names and positions of all interviewees.

3.1 General goals and responsibilities of municipalities

Municipalities have the task to integrally manage their areas. They represent the general management on local level. In general, the goals of most municipalities include: high safety, high welfare, good business environment, high quality of living, good public health and a good environment. There are no general regulations that force municipalities to achieve a certain amount of climate change adaptation [Planbureau voor de Leefomgeving, 2011], which means that municipalities have a certain amount of freedom to determine to what extent they invest in adaptation strategies and what requirements they pose on (re)development of urban areas. Municipalities are not the only organisations that are responsible for management of vulnerability to climate change. Other important stakeholders are parcel owners, housing corporations, water boards and project developers. For heat stress and its operational management, the Municipal Health Services (GGD) have a significant role. Many of the municipal responsibilities are theme-specific. These are included after this section in the theme-specific sections.

3.2 Pluvial flooding

The interviews indicate that pluvial flooding is the theme that is considered as "the most important" by municipalities, in comparison with groundwater flooding, drought and heat stress. Since pluvial flooding is the theme that will be addressed in the case studies, this theme will be addressed in more detail than the other themes.

3.2.1 Responsibilities

Municipalities have a large responsibility regarding the vulnerability to pluvial flooding. Traditionally, municipalities are responsible for the urban drainage system and thus the prevention of pluvial flooding. However, recently, new regulations ("zorgplicht hemelwater") have been adopted that specify that parcel owners are only allowed to discharge their excessive rainwater into public areas if it is not reasonable to store it on their own parcel (Ministerie van Infrastructuur en Milieu, 2012). Municipalities can decide in which situations it is reasonable to expect that the owner of a parcel can process the storm water himself (Waterschap Amstel Gooi en Vecht, 2009a). Despite the large role of parcel owners in storing water on their parcels, municipalities often take the responsibility to take measures if pluvial flooding has occurred (Bergsma et al., 2009). However, under conditions of increased pluvial flooding it can be expected that the responsibilities of parcel owners will increase (Bergsma et al., 2009).

3.2.2 Measures

Virtually all municipalities need to implement measures to make sure that the amount of pluvial flooding remains acceptable. 92% of the municipalities actually take measures to prevent pluvial flooding in urban areas [Ministerie van Infrastructuur en Milieu, 2011], taking future increase in pluvial flooding into account. Table 3 shows the type of measures that Dutch municipalities take, based on a large survey [Oosterom, 2011]. Most municipalities take measures to increase the discharge capacity of the urban drainage system, by enlarging the current system or by disconnection of areas from the sewerage systems. Half of the municipalities take measures on surface level, for example to guide flood water to suitable places. One fifth of the municipalities take measures to increase the amount of open water.

Table 3: Percentages of municipalities that take measures to prevent pluvial flooding (Oosterom, 2011, p.100).

Measure	% municipalities
Enlarge current system	64
Extra rainfall sewerages and disconnection	89
Measures on surface level	51
Extra surface water	38
Other measures	21

There are different views on which strategy should be followed for dealing with increased extreme rainfall events. On the one hand there are people who indicate that next to enlargement of sewerage system capacity, (decentralised) measures should be taken in the public space, such as creation of extra storage on surface level, infiltration facilities and green roofs. On the other hand, there are people (for example a number of sewerage specialists) who indicate that the most important thing is that the sewerage capacity is always sufficiently high.

Decentralised spatial measures require cooperation of many stakeholders. In addition, they do not always perform as expected. The effect of infiltration facilities can decrease over time, for example. On the other hand, measures regarding the sewerage system are the sole responsibility of the municipality and its functioning is better known. The type of measures that can be taken also depends on the building density. In highly urbanised areas, there is little room for spatial measures.

Many spatial measures, such as creation of green areas and increasing the amount of open water have multiple positive effects on the urban environment, for example regarding the attractiveness of the area, recreation and reduction of the urban heat island effect. Measures that are primarily taken because of these other reasons contribute to a reduction of vulnerability to pluvial flooding (Runhaar et al., 2012 and interviews).

From this subsection it can be concluded that it is important that the vulnerability assessment regarding pluvial flooding should be able to indicate the effect of current and future measures. It is important that not only the capacity of the sewerage is taken into account, but the capacity of the entire urban drainage system. Further it is important to consider the fact that not only an excessive extent of vulnerability to pluvial flooding is a driver for adaptation measures, but also vulnerability to other themes and the spatial quality and attractiveness of the areas.

3.2.3 Norms

Pluvial flooding cannot be prevented completely. A majority of the people in the Netherlands accept water on the streets as long as the impacts are limited and no damage occurs [Oosterom, 2011]. This subsection addresses the norms for pluvial flooding in the Netherlands.

Apart from the norms that have been established in the National Covenant on water [Dutch: Nationaal Bestuursakkoord Water, NBW], there are no official quantitative norms for water on the streets on national level [Nlingenieurs Sewer Systems Workgroup, 2009). The Nationaal Bestuursakkoord Water (Stumpe, 2011) states that the surface water system should be able to cope with rainfall events with return periods of 100 years or less [Stichting RIONED, 2006]. For rainfall events that occur with a higher frequency, municipalities can decide what level of protection they provide [Waterschap Amstel Gooi en Vecht, 2009a]. RIONED suggests the use of a rainfall event with a return period of two years for the assessment of the performance of the minor drainage system [Stichting RIONED, 2006]. Table 4 shows the norms that are commonly used within The Netherlands for pluvial flooding.

Table 4: Norms for pluvial flooding (copied from Stichting RIONED, 2006)

	Sewerage in flat areas	**Sewerage in sloping areas**
Design rainfall	Design rainfall, T=2 year, Runoff model for flat area	Design rainfall, T=2 year, Run-off model for sloping area
Norms	Max a short period of water on the street, check consequences of more extreme rainfall events.	Max a short period of water on the street, check consequences of more extreme rainfall events.
functioning in normal circumstances	Storage in sewerage system and discharge capacity towards overflows	Extreme rainfall events, (less) storage in sewerage system and (more) discharge towards overflows
Functioning in extreme circumstances	Use of storage on the streets	Discharge of water through the streets, storage on local depressions (often limited capacity)

Table 5 shows a rather qualitative classification of impacts of pluvial flooding that has been developed by RIONED, the Dutch association of sewerage and urban water management. Acceptance of these impact categories is dependent on the statistical frequency of the event. For events that occur very rarely, it is accepted that some damage occurs. Regular inconvenience, however, is accepted only as long as it does not occur too often.

Table 5: Difference between inconvenience and nuisance (Stichting RIONED, 2006)

Type of pluvial flooding	**Description**
Inconvenience	Limited quantities of water on the street. Duration: 15-30 min This level of inconvenience can occur if the design rainfall event occurs and is therefore accepted.
Serious inconvenience	Large quantities of water on the street, Duration: 30-120 min This amount of inconvenience can occur if the rainfall event is more extreme than the once-in-2-year event. No direct damage is caused.
Nuisance	Very large quantities of water on the streets, water in buildings with material damage and possibly also serious hindrance of the economy and/or traffic. Duration: 120 min and more If rainfall is extremely heavy, damage can occur, or long lasting traffic delays.

From this subsection it can be concluded that norms for pluvial flooding are not established on national level, except for the norms that have been established in the National Covenant Water. Consequently, municipalities are allowed to establish their own quantified norms for rainfall events that occur more frequently than once in a hundred years. At this moment there is no formally established quantified norm that can be used uniformly in all municipalities to classify an area as vulnerable or invulnerable.

3.2.4 Modelling and data

Apart from assessment of the NBW-norms, vulnerability assessment regarding pluvial flooding is in general limited to the question whether the sewer system has sufficient capacity on the basis of 1D-sewerage models [Ten Veldhuis, 2010]. These calculations are often based on a design rainfall event with a return period of 2 years (Bui 8). 2D-calculations that actually simulate the overland flow in case of exceedance are often not performed. This is to some extent due to the rather cumbersome calibration procedure of these models that depend on empirical data. Often this data is not available since flood depths due to pluvial flooding are generally not measured.

The consequence of this approach is that the impacts of actual exceedance (e.g. flooded basements) are not modelled and assessed. Yet, rainfall events with return periods between 2 and 100 years often lead to consequences that cannot be ignored [van Luijtelaar et al., 2006]. If municipalities want to extend their sewerage strategies with spatial measures to decrease effects of pluvial flooding, it would be highly recommended to use 2D overland flow models as well. This is acknowledged by municipalities. A shift from the use of 1D sewer models towards GIS-based surface analysis and coupled 1D-2D models is currently taking place [van Dijk et al., 2012].

3.3 Groundwater flooding

Groundwater flooding and nuisance can occur in all Dutch municipalities. Especially areas around city centres are vulnerable, since they are built in drainage-dependent areas [Van de Ven et al., 2010]. If no measures are taken, groundwater flooding will increase under the influence of climate change.

Measures to prevent groundwater flooding and the nuisance that is caused by it, comprise measures to affect the groundwater levels and a reduction of the sensitivity of buildings and other objects. It is for example possible to drain an area with the use of horizontal and vertical drainage or ditches, but it is also possible to prevent the groundwater from entering the living areas of houses. If the groundwater is too high in gardens, the gardens could be elevated. Which measure is most suitable and effective depends on the situation [van de Winckel, 2005].

Groundwater problems can be a large problem in urban areas, for example in a number of neighbourhoods in Den Haag and Nijmegen. The interviews showed that the topic can be politically sensitive on these places.

For groundwater floods, municipalities have the duty to take measures in the public space to prevent or reduce structural adverse effects of high groundwater levels in relation to the functions that are assigned to parcels [Waterschap Amstel Gooi en Vecht, 2009b]. Municipalities should specify in what they consider as “structural” adverse effects of groundwater levels in their (obligatory) sewerage plan. The groundwater duty is not a hard obligation, however [Royal Haskoning, 2011]. The municipality is only obliged to take measures when they are appropriate and if they do not fall within the responsibilities of water boards and provinces [Waterschap Amstel Gooi en Vecht, 2009b]. Municipalities have a coordinating role in the joint process for solving structural groundwater problems and serve as first contact for inhabitants [Waterschap Amstel Gooi en Vecht, 2009b].

The extent of (pro-active) monitoring and modelling of groundwater levels and fluctuations differs per municipality and on the extent to which problems exist (ten Bras et al., 2006).

3.4 Drought

The general impression from the interviews is that drought does not get a high place on the political agenda, with the exception of the areas in which damage is caused to wooden foundation pillars. This is a politically sensitive subject, since residents try to make municipalities bear the (substantial) costs for repairs in court (NOS, 2011). Another important issue is land subsidence, which causes damage to buildings and underground infrastructures. Costs for this can be considerable as well (Stone et al., 2011).

Damage to wooden foundation pillars due to low groundwater levels is an important topic in some municipalities. Van de Ven [2010] estimated that approximately one third of the historical buildings in the Netherlands are vulnerable to drought. The issue of financial liability has been taken to court [Waterforum Online, 2011). Municipalities do not have specific policies for this problem. The issue of the impact of land subsidence is not quantified yet and the effect of drought on parks and trees is also largely unknown [Van de Ven et al., 2010]. Water quality issues are important as well, but the water boards are responsible for most of the water bodies.

3.5 Heat stress

Municipalities do not have general adaptation policies for heat stress. Driessen et al. [2011) state that municipalities take no responsibility at all for adaptation to extreme heat events and leave adaptation to inhabitants. However, Döpp et al. [2011) states that municipalities focus on problem formulation and no-regret measures, such as subsidies for green roofs and awareness raising. Apart from the National Heat Plan [Ministerie van Volksgezondheid, 2007], which focuses on operational actions to reduce heat-related health problems, the national government does not provide any guidance or incentives for municipalities to reduce heat stress [Van de Ven et al., 2010].

Municipalities are mostly interested in health effects and thermal comfort [Stone et al., 2011). Municipalities do not have general adaptation policies on heat stress, but some of the municipalities already take no-regret measures and use communicative and economic instruments for increased adaptation to heat stress [Döpp, 2011]. Measures to increase the spatial quality of an area are partially justified by using reduction of the urban heat island effect as additional argument for the project [Runhaar et al., 2012]. The ministry of Human Health issued a National Heat Plan in which recommendation for actions during heat waves are made that can be used by stakeholders on local level [Ministerie van Volksgezondheid, 2007]. Further guidance or incentives are not provided [Van de Ven et al., 2010].

3.6 Need for vulnerability assessment in municipalities

There are many reasons why knowledge about vulnerability to climate change is useful and why vulnerability assessment is useful for municipalities. During the interviews, the following questions were raised by the interviewees.

3.6.1 Sense of urgency/lack of awareness

In general, it seems that many municipalities do not see the need for pro-active adaptation strategies (based on interviews and Runhaar et al., 2012). During the interviews, the following reasons became apparent: unawareness, a conscious decision to prevent overinvestment in unnecessary adaptation measures, the idea that climate change will evolve gradually and that measures can be taken if the consequences are more certain, uncertainty about the potential magnitude of climate change on local level and an interest in short-term politics only. Assessment of outcome vulnerability can address this issue.

Municipal organisations are composed of different departments. The awareness of climate change vulnerability can differ per department. For example, the department that is responsible for the management of the sewerage can be very aware of the possible consequences of climate change, while more general departments, such as urban planning, might choose other priorities. Vulnerability to climate change is not their only concern and they should be able to make a well informed comparison between all of their interests. A method for outcome vulnerability can help with this comparison, since it indicates the size of future impacts. Methods for contextual vulnerability can help with identifying adaptation options and the most important points of attention for the design of urban areas.

3.6.2 Difficulties with allocation of resources

Since the current impacts of extreme weather events do not seem to be unacceptably high and future impacts are uncertain, it is difficult for municipalities to determine how much money they should be spending on pro-active adaptation measures to decrease the vulnerability of their areas to climate change. Municipalities have to balance the risk of overinvesting in adaptation measures and strategies with the risk of unacceptable consequences. It would help municipalities if they have more insight into the possible range of magnitudes of impacts and damages. This would also help them to choose a reasonable amount of investment in adaptation strategies. Assessment of outcome vulnerability can address this issue.

3.6.3 Difficulties with engaging stakeholders

From the previous analyses it has become clear that local climate change adaptation is not the sole responsibility of municipalities. Because of this, it is important that awareness is raised among other stakeholders and that it is shown to these stakeholders what they can do. Municipalities can enforce certain adaptation measures in new areas, but in many cases it has to be done on a voluntary basis. Vulnerability assessment can help municipalities with engaging stakeholders

Politicians are sensitive to public opinions. Events with severe impacts lead to an increase of public pressure on the municipal organisation. On the one hand, there is no external incentive for municipalities from inhabitants and other stakeholders as long as no large impacts occur, whereas, on the other hand, if they should occur, people will wonder why no action was taken before. The extreme heat during the Nijmegen Four Days Marches in 2006 can be seen as an event that to some extent changed the view of the general public on heat stress. It is however not likely that such external autonomous events will occur in the context of pluvial flooding and groundwater nuisance. Pluvial flooding is so local that it does not have major news value and groundwater flooding is a gradual process rather than a calamity. This makes communication of the sense of urgency very important.

3.6.4 Lack of knowledge about benefits of adaptation measures

Important opportunities for physical adaptation measures occur during urban (re)development projects. In these kind of projects, many stakeholders with different requirements and interests are involved. It is, however, not yet possible to force project developers and housing corporations to implement adaptation measures [Runhaar et al., 2012]. An extra complicating factor is the increase in power of large project developers, due to their increased land ownership [Driessen et al., 2011]. This development makes profitability of land development increasingly important, which makes inclusion of adaptation measures more difficult, since it is difficult to convince the project developers of the benefits of these measures. When it comes to projects with external stakeholders it is often difficult to make a good business case for adaptation measures.

Another barrier is the existence of split incentives, because of which the stakeholders who need to pay for the adaptation measures are not able to reap the benefits from them [Driessen et al., 2011]. At this moment it is not clear yet whether the value of properties that are less vulnerable to climate change is higher than the value of more vulnerable properties [Driessen et al., 2011]. Project developers thus are not stimulated to include adaptation measures.

3.6.5 Lack of adaptation due to low amount of urban restructuring on large scale

All municipalities try to maximise benefits by combining measures and investment plans with other measures and plans [Ministerie van Infrastructuur en Milieu, 2011]. The low amount of developments in existing areas is considered as a barrier for adaptation [Runhaar et al., 2012]. The interviews also showed this. Restructuring is often taking place on a small scale, which makes it difficult to combine it with adaptation measures. This makes it for municipalities to make sure that opportunities which arise are recognised and valorised whenever they occur. This makes it necessary to provide insight in causes and drivers of vulnerability and insight into what factors are important to manage.

3.6.6 Lack of monitoring of vulnerability

Pro-active adaptation strategies require some extent of monitoring. Adaptation is a continuous process rather than a one-off project. Some municipalities state that they want to be ”climate proof” in a certain year, e.g. in Rotterdam [Rotterdam Climate Proof, 2010]. This might raise the idea that from this moment in time, the job is complete. In practice the definition that is used involves “ensuring that the systems comply with the norms and making sure that they will remain compliant under a changing climate”, according to one of the interviewees. This requires having insight in the consequence of climate change on the performance on the objectives of the municipality regarding climate change vulnerability, and thus assessment of outcome vulnerability.

Vulnerability assessment can also be achieved through monitoring of current characteristics of areas and progress of adaptation projects. If a coherent set of indicators is used that are able to indicate vulnerability, the method could be seen as a method for contextual vulnerability.

Although vulnerability assessment methods can help with the monitoring of adaptation policies and the vulnerability of urban areas to climate change, it is necessary to include them in a broader management framework in order to ensure that they are used effectively and regularly.

3.6.7 Lack of identification of vulnerable people, objects and areas

It is useful for municipalities to see in which of their areas the vulnerability to specific themes and of specific objects is high. It would for example be useful to know in which areas the risk of heat-related mortality is high or where future problems with regard to pluvial and groundwater flooding are likely to occur in future. Although this knowledge might be implicitly available within the municipal organisation or among external experts, it would be useful to make this knowledge more explicit in order to make it available for non-experts as well. In principle, assessment of contextual vulnerability would be most suitable for addressing this topic [Füssel, 2007].

3.6.8 Further criteria

This section describes a number of criteria that result from the interviews with municipalities. Three main categories of criteria have been identified: Policy relevance, feasibility and communication.

The method should ideally address many of the problems that municipalities have regarding the management of the vulnerability to climate change of their areas, which have been described by Stone et al (2011). The criteria that relate to the policy relevance are directly linked to these problems.

Since the method needs to be applied for and/or by municipalities it needs to be feasible. Although many criteria affect the feasibility of the method, three factors are considered to be the most important:

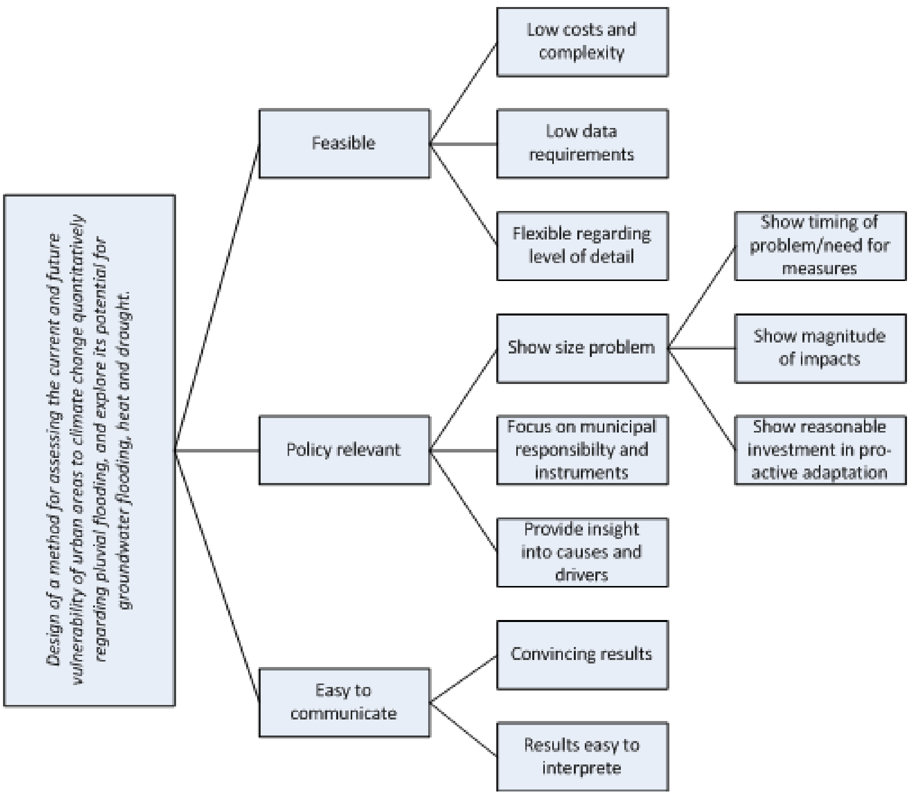
- Low data requirements: Data retrieval can be difficult, time consuming and expensive. Although quantitative assessment requires data, the methods should make optimal use of existing data.

- Flexibility regarding level of detail: Not all areas are equally vulnerable to climate change. Because of this, it would be ideal to spend most of resources in the most vulnerable places. In one area it could be sufficient to do a preliminary qualitative vulnerability assessment, while in other areas it could be necessary to develop and use a comprehensive model.

- Low costs and low complexity: Apart from being feasible, the method should allow relatively easy interpretable results that are suitable for communication with all stakeholders, within and outside the municipality. This means that both the outcomes and the steps that lead to the outcomes should be understandable for non-technical people. Related to this criterion, the results of the method should be convincing. This is especially important, since the sense of urgency to take measures and to take vulnerability to climate change into account in the design of urban areas and its elements is not high.

At last, the method should focus on the responsibilities of municipalities. The criteria have been included in Figure 5.

Figure 5: Design criteria



3.7 Conclusions

This chapter describes the way in which municipalities currently cope with climate change. Dutch municipalities are responsible for the general management of their areas. Although responsibilities for climate change adaptation are shared with other stakeholders, such as inhabitants, water boards and housing corporations, municipalities are a key stakeholder in the field of climate change adaptation for all the hazards that are part of this research project.

Research by Oosterom et al. [2011] showed that more than 90% of the Dutch municipalities take measures to prepare for more extreme rainfall events. However, in the context of groundwater flooding, drought and heat stress, less pro-active adaptation takes place. The conducted interviews led to the conclusion that a major barrier to climate change adaptation is that it is not clear how large and likely the consequences of climate change will be. In addition, the interviews made clear that it can be difficult to convince urban planners and external stakeholders, such as project developers, of the need for no- and low-regret adaptation measures.

Current quantitative assessment of vulnerability to climate change in many municipalities is limited to the question whether the sewerage system is able to deal with a rainfall event with a return period of once in 2 years. A better assessment of vulnerability to pluvial flooding, as well as assessment of vulnerability to the other themes is difficult, due to a lack of methods, a lack of data and the high costs of data retrieval.

Municipalities have a rather qualitative view on their vulnerability to climate change. During the interviews it became clear that municipalities would like to better know whether they should see climate change as a major problem and how much they should do to prevent negative consequences. Further analysis showed that many of the major barriers to climate change adaptation indeed relate to the inability to objectify the extent of vulnerability of an area and the amount of adaptation that would be justified.

Finally, due to the different roles and responsibilities of experts, operational management and policy makers, the breadth and depth of knowledge differs substantially. While the municipal urban drainage department might be comfortable with quantitative data resulting from specialized hydraulic models, long term integrated climate adaptation policies and the experts that formulate these require more strategic long term data that can be integrated into other domains, strategies, policies and measures. Furthermore, there is a clear distinction between indicating current vulnerabilities and future ones. The former might require immediate measures while the later fits often better within a strategic concept that includes structural as well as non-structural measures. This makes the choice of a general vulnerability assessment method that meets the requirements of all municipal departments highly improbable.

4 Choosing vulnerability assessment methods

The number of methods that can be used for vulnerability assessment is very large. A broad overview of many tools can be found on: weadapt.org [WeADAPT, 2012). Through this vast landscape of assessment methods it is important to remember some basic aims of the method in the context of this project:

1. The method should be applicable to different natural hazards (e.g. drought, flooding, heat stress);

2. The method should specifically address climate change;

3. The method should be fit for handling the complexity, differentiation and different spatial scales of urban areas.

These aims create a set of requirements and constrains. The desire to apply the method for different domains (i.e. types of natural hazards) excludes assessment types that specifically focus on single hazards and seems to point at some sort of meta-assessment able to distil high-level vulnerability components. Furthermore, it seems to suggest that the vulnerabilities from different domains should become comparable (e.g. through some multi-criteria evaluation). An intuitive candidate for such an approach would be to use mean annual damages; all impacts are translated into monetary terms and therefore become comparable. An alternative approach would be the use of indices since these are non-dimensional and can therefore be easily compared to each other. Other qualitative methods focusing on the spatial distribution (e.g. hotspot analysis) also seem candidates although the lack of quantification might make their choice less likely.

The second aim specifically introduces the temporal dimension to the vulnerability assessment. Since climate change encompasses trend changes with a medium to long horizon the method should focus on the subsequent changes in vulnerability rather than on determining the vulnerability for a specific event. Furthermore, this issue addresses relative changes (e.g. compared to the current conditions) rather than absolute values. The introduction of climate change also points in the direction of scenarios; since the rate and changes of climate changes are unknown, the introduction of (multiple) scenarios in the methodology is a requirement. Future vulnerabilities might change depending on the applied (or agreed on) scenario.

Finally, the aim to focus especially on urban areas introduces a challenge in complexity. Urban systems consist of many interacting components that all exhibit different sensitivities and levels of exposure to different natural hazards. Impacts are tangible and intangible as well as direct and indirect. Furthermore, due to the concentration of assets and people, the method needs to be expressive enough to accommodate urban differentiation; typical regional vulnerability assessment methods treating large areas as uniform units are suboptimal when used in an urban setting. On the other hand, urban areas cover different scale levels varying from individual buildings to complete districts.

4.1 Additional criteria

The focus of the project is to provide a vulnerability assessment method that is particularly aimed at municipalities to gain information about the urgency and severity of natural hazards and climate change. While the different municipal departments are to some extent prepared and equipped to cope with some of the identified natural hazard, the interviews and literature study identified a lack of integrated tools that provide both a broad overview of local vulnerabilities, a prioritization of sensitive areas to climate change (i.e. urgency) and a flexible methodology in which existing models, knowledge and measures can be introduced. This creates an alternative set of requirements:

- *Strategic and integrated*. The method should first of all be able to be used in an integrated and strategic context. Municipalities need not only to gain insight into the immediate problems caused by natural hazards, but also be able to mainstream possible strategies and solutions into existing policies and developments (e.g. urban redevelopment plan). This means that apart from urgent local problems that require an immediate fix by specialized departments, the assessment should be able to deal with medium and long term prospects and issues covering different spatial extents and domains.

- *Focus on urgencies*. While the current protections standards are relatively adequate to cope with at least frequent weather events, the uncertainty about changes in future vulnerabilities prevents many municipalities to develop a comprehensive and coherent climate adaptation strategy. Furthermore, municipalities are uncertain about the spatial distribution of the expected impacts; which areas will suffer from climate change mostly and at when do the expected changes become problematic? Especially in a policy context in which pro-active adaptation is required, good insight in the spatial distribution of 'problem areas' is a necessity.

- *Integration and flexibility*. Apart from developing an adequate assessment method, a main requirement of the proposed method is that it will be adopted and used by municipalities. This means that complex, data and resource intensive methods that require extensive training and investments are less likely candidates. Furthermore, many municipalities (partially) monitor current problems, run and maintain models and tools and acquire and maintain extensive knowledge about their regions. Apart from the fact that it would be inefficient not to integrate those resources into a vulnerability assessment method, it would also raise serious questions about the legitimacy and adoption of the proposed method. This means that existing tools, knowledge and practises should provide a basis for the proposed methodology.

From all the investigated vulnerability assessment methods and metrics, the adaptation tipping point seems the most likely candidate. The method acts as a meta-method, building outcomes on existing data, specifically addresses the temporal dimension, future scenarios (both climate change related as well as other), can host multiple problems and domains and finally is relatively easy to comprehend and maintain. Furthermore, it requires local knowledge and discussion on goals (and/or norms) without becoming overly focussed on specific (technical) issues.

4.2 Adaptation Tipping Point-method

The Adaptation Tipping Point (ATP) method is based on the development of ATPs and an assessment of the robustness of a strategy in relation to these ATPs and climate change. The underlying idea of the method is to calculate under what circumstances a strategy will no longer meet its objectives. Roughly said, the method can be applied for two purposes: indicating the urgency of problems, and comparing and evaluating adaptation measures and strategies [Jeuken and te Linden, 2011]. The method does in principle not predict the future but it explores multiple possible future scenarios in a sensitivity analysis, based on physical modelling, and then converts them into the time until the current strategy does not satisfy anymore.

4.2.1 Introduction

An Adaptation Tipping Point (ATP) is defined as: “the point where the magnitude of climate change is such that the current management strategy will no longer meet the objectives” (Kwadijk et al., 2010, p.730). The term of Adaptation Tipping Point sometimes causes confusion. In climate change research, the term “tipping point” refers to a situation in which a system is changed into a new state, which might be irreversible. A tipping point often refers to “situations of no return” [Russil and Nyssa, 2009]. An adaptation tipping point is less drastic. An ATP can be reached because of physical, social, economic or ecological reasons and it does not necessarily mean that a point of no return has been reached. It only means that the current management strategy needs to be revised in order to make sure that it complies with its objectives. For example, in the field of pluvial flooding it could mean that the sewer needs to be expanded or that other facilities for storm water retention, infiltration or discharge need to be developed. The outcome of the analysis comprises the timings of ATPs on the basis of different climate scenarios and calculated measures [Jeuken and te Linden, 2011].

4.2.2 Steps of the ATP-method

This subsection explains the steps of the ATP-method. The steps of the ATP-method are as follows [Jeuken and te Linden, 2011, p.9]:

1. Define scope
2. Identify indicators and threshold values
3. Determine ATPs
4. Translate ATPs to time

In the original steps of the ATP-method, a final step is included in which the effect of measures on the timing of ATPs is calculated. This step is beyond the scope of the project, since this project addresses vulnerability assessment only.

1. Define scope

Vulnerability assessment requires resources in terms of finances, time and knowledge. Because of this, it is important first to perform a preliminary (qualitative) assessment of the largest and most important climate change related risks. The ATP-method is flexible regarding the geographical scope and the level of detail of analyses. It is for example possible to determine the ATP for one area on the basis of existing studies in combination with rules of thumb, while it is possible to determine the ATP for other areas with complex and comprehensive modelling methods. Similarly, it is possible to compare ATPs of neighbourhoods with ATPs on (sub)municipal level. After defining the scope of the analysis it is possible to choose appropriate indicators, which is part of the next step.

2. Identify indicators and threshold values

ATPs consist of an indicator and a threshold value. Indicators can be seen as "variables which are an operational representation of an attribute, such as a quality and/or a characteristic of a system" [Gallopin, 2006, p.14]. In this project, indicators thus operationally represent vulnerability of urban areas to climate change.

All indicators that include predictions of future impact of climate change - related events can be used as basis for the ATPs. It is important that the indicators can be communicated and understood easily [Jeuken and te Linden, 2011]. One of the main features of the ATP-method is that normative aspects of evaluation of vulnerability can be left to decision makers and other stakeholders. This advantage would be absent if the indicator cannot explain itself.

Examples of possible indicators are numbers of affected objects and yearly monetary damage. Inspiration can be drawn from the indicators that are mentioned in section 2.3. The simplest indicators can be directly extracted from the applied modelling results, such as number of flooded manholes, number of flooded houses, total flooded area etc. In order to be able to use the same threshold values for different urban areas, the use of percentages, rather than absolute numbers, is necessary.

Once the (vulnerability) indicators have been chosen, it is necessary to define the threshold values. The threshold values comprise the quantitative limits that determine whether an ATP is reached and thus whether an area is considered as vulnerable or not. Vulnerability thresholds can be based on physical, legal, economic, social, moral or other grounds. Establishment of the threshold value is typically done by or in consultation with stakeholders.

Examples of indicators and threshold values are shown below:

- Number of neighbourhoods in which the temperature rises above 37 ^{o}C for three consecutive days is less than 2
- Estimated average amount of additional deaths in neighbourhoods due to climate change in comparison to 1990 is less than 1.
- During a rainfall event with a return period of 2 years, no houses get flooded.
- The total expected value of damage due to pluvial flooding during a rainfall event with a return period of 50 years is less than €50.000.
- The maximum areal percentage of each neighbourhood in the city that has a drainage depth of less than 0,7 meters is less than 20%.

Establishment of realistic vulnerability thresholds is important. If the vulnerability threshold is too strict, there will be a risk of overadaptation, potentially leading to unnecessary investment in adaptation measures. If the threshold is too loose, a situation might occur in which the vulnerability to a certain hazard is unacceptable, or opportunities for mainstreaming and win/win measures are missed.

3. Calculate ATPs

In this step it is calculated under which circumstances the ATP is reached and when this moment will occur under different climate scenarios. In this project, the headroom is defined as the maximum climate change factor at which the vulnerability threshold is exceeded. The climate change factor is defined as an uplift of the current driving forces of climate change consequences, such as rainfall volume, temperature and number of tropical days. An example regarding extreme rainfall events is that the climate change factor is determined by the relative increase in 1-hour rainfall volumes of a rainfall event with a return period of 2 years. Calculation of the headroom involves a sensitivity analysis on the basis of modelling, expert judgment or estimations based on previous climate change impact studies. By incrementally increasing the climate change factor it is assessed at which climate change factor the area first exceeds the threshold value.

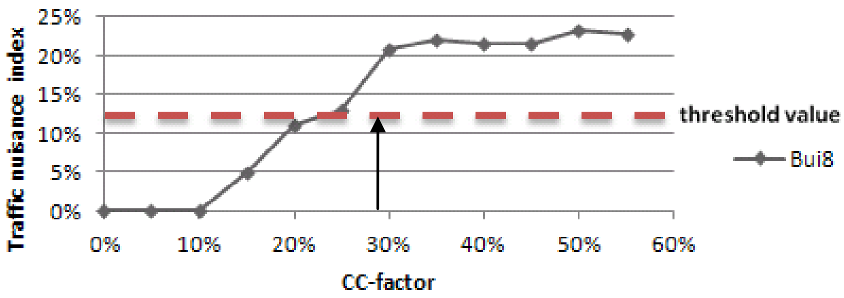


Figure 6: Illustration of the calculation of an ATP

Figure 6 shows a graph that explains the calculation of the ATP. The vulnerability threshold is composed of the vulnerability indicator, the traffic nuisance index and a threshold value of 12% under an extreme rainfall event (bui 8) with a return period of 2 years. First it is calculated whether the neighbourhood complies with this vulnerability threshold in the current situation (climate change factor is 0%). Then it is calculated for all climate change factors what the percentage of blocked road segments is and for each scenario it is calculated whether the vulnerability threshold is exceeded. The diamond symbols indicate each calculated scenario. Then it is assessed when the vulnerability threshold, which is represented by the dashed horizontal line, is exceeded. It can be seen that the vulnerability threshold for traffic nuisance exceeded at a climate change factor of approximately 23%. This is the headroom of the area for increased rainfall with regard to traffic nuisance. In the next step of the ATP-method , this value will be converted into a period of time.

4. Translate ATPs into time

On the basis of the calculated headroom in combination with climate change scenarios, it is possible to calculate the timing of the ATP. The timing of the ATP is calculated through linear inter- and extrapolation of the current and future rainfall volumes on the basis of the KNMI climate scenarios. The impact that has the shortest timing of the ATP can be considered as the most urgent. It is not only possible to compare different geographical units regarding one hazard, but it is also possible to compare vulnerability to different hazards in the same area. Additional weighting of hazards is not necessary, since this is implicitly done by determining the vulnerability thresholds in step 2.

Figure 7 shows a possible way of presenting the end results of an ATP analysis. The values that are shown in this figure are fictive. It can be seen that in neighbourhood 1, the ATP for the minor sewerage capacity and heat-related mortality is not reached before 2100, which means that the area is robust to the effects of climate change. It can be seen that the ATP with regard to flooded buildings will be exceeded in the year 2095 under the KNMI W scenario and in 2087 under the KNMI W scenario. On the level of sub municipality 1 it can be seen that the ATP the urban heat island effect is already exceeded in the current situation.

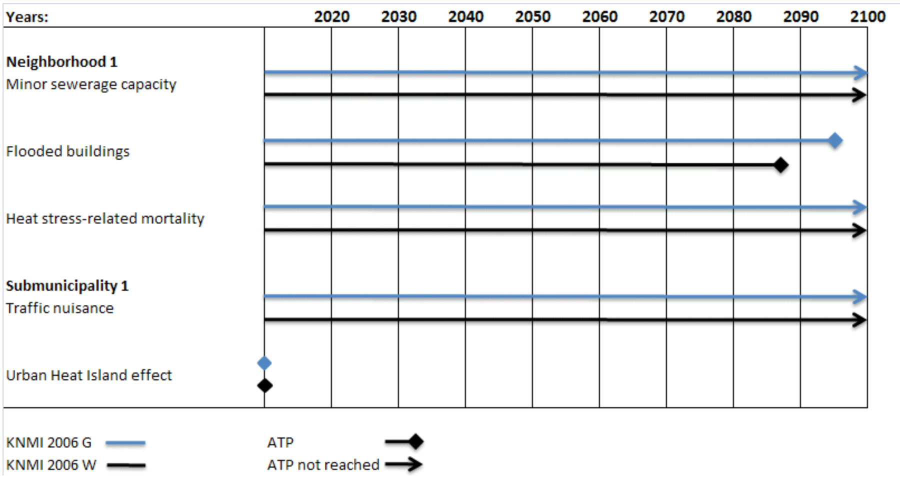


Figure 7: Illustrative example of end result of the ATP method

4.2.3 Earlier applications

The first application of the ATP-method in the Netherlands was in 2008, in a study called "Klimaatbestendigheid Nederland Waterland" [Kwadijk et al., 2008a, Kwadijk et al., 2010, Kwadijk et al., 2008b]. The study was applied to the national flood protection system (coastal and riverine) as well as to the water supply in the south-west of The Netherlands. Results from the ATP analysis have been used as input for different policy documents, such as the National Water Masterplan [Ministerie van Verkeer en Waterstaat et al., 2009] and an important advice about future adaptation options in The Netherlands [Deltacommissie, 2008]. The method was also applied by Passchier et al. [2010], Hoogvliet et al. [2010], Franssen et al. (2011) and Asselman et al. [2008].

Two applications on neighbourhood level have been performed. Nasruddin [2010) applied the method in Wielwijk, a neighbourhood in Dordrecht. He assessed the robustness of the minor and the major urban drainage system for climate change and calculated the effect of measures on the timing of ATPs. Another application of the ATP-method was performed in Stadshavens (“city harbours”) Rotterdam [Gemeentewerken Rotterdam and Deltares, 2008, Asselman et al., 2008]. This analysis focused on the identification of the effects of sea level rise on flood risk and their timing, identification of potential measures and insight into the flexibility and robustness of different strategies. The analysis was based completely on workshops with experts. These two examples show that application of this method can be based on both modelling and participatory approaches.

4.2.4 Relation of the ATP-method with vulnerability

The Adaptation Tipping Point method is a method for assessment of outcome vulnerability. In fact, the method extends on a water system analysis or an analysis of heat impacts and presents the outcomes of these analyses in terms of the timing of ATPs [Jeuken and te Linden, 2011]. Outcome vulnerability can be described as the impacts of climate change minus potential adaption [Kelly and Adger, 2000]. An Adaptation Tipping Point comprises an indicator and a threshold value [Jeuken and te Linden, 2011]. The indicator represents the vulnerability of an area. Considering limitations to impact and damage modelling, it is not feasible to model outcome vulnerability completely. It is possible to calculate the effect of adaptation of measures on the timing of ATPs. Since an Adaptation Tipping Point is based on the moment when the current strategy is not acceptable anymore it could be assumed that the potential adaptation is not relevant, since the focus of the analysis is to determine when adaptation measures should be taken. Potential adaptation is not relevant in this respect. The method is, however, suitable for assessing the effect of adaptation measures on the moment when measures are necessary to prevent unacceptably vulnerable situations.

5 Case 1: Rotterdam-Noord

The first case study in this research project has been conducted in Rotterdam-Noord. This case study serves as a proof of concept, rather than as a substantive vulnerability assessment.

5.1 Introduction

Rotterdam-Noord consists of the neighbourhoods Liskwartier, Oude Noorden, Agniesebuurt, Provenierswijk, Blijdorp, Blijdorpsepolder and Bergpolder. All of these neighbourhoods were constructed at the end of the 19th century and the beginning of the 20th century. Figure 8 contains a map of the area. Most of the neighbourhoods in Rotterdam-Noord are residential areas, which are shown in Table 6. The neighbourhood Blijdorpse Polder is mainly an area of industry and recreation.

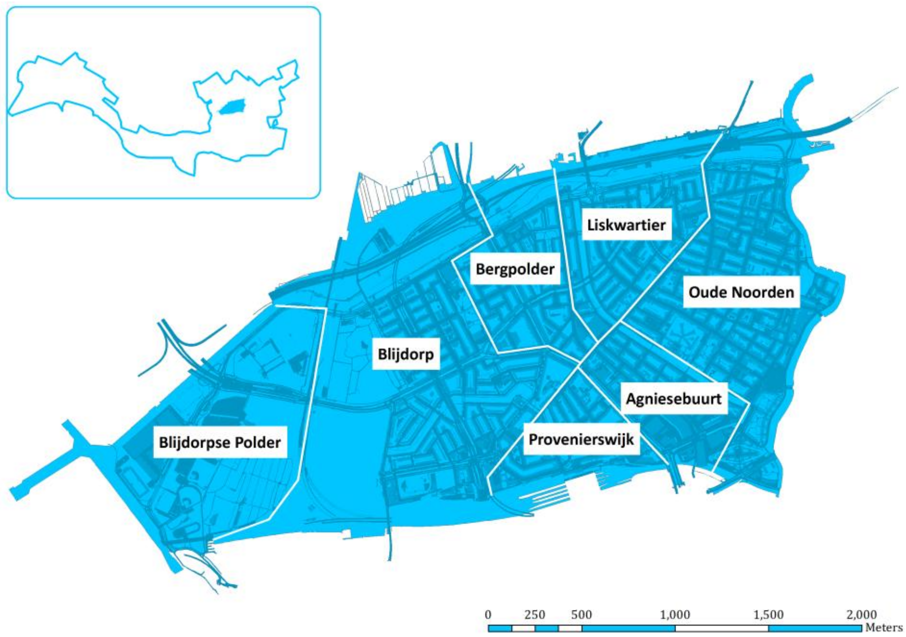


Figure 8: Overview of Rotterdam-Noord

Table 6: Total number of buildings in each neighbourhood. Source: Gemeente Rotterdam

Neighbourhood	Residential	Commercial	Public	Vacant	Total
Agniesebuurt	544	64	3	4	615
Bergpolder	1225	98	3	19	1345
Blijdorp	1449	63	12	9	1533
Blijdorpse Polder	18	5	1		24
Liskwartier	1260	53	4	9	1326
Oude Noorden	2075	425	9	45	2554
Provenierswijk	664	41	6	1	712

The area has a (traditional) combined sewerage system (Nelen & Schuurmans, 2009). It has a low amount of open water and green areas and a high amount of paved areas (Vergroesen, unpublished). These factors theoretically add to the vulnerability to pluvial flooding. However, complaints from inhabitants and other actors in the area are rare. A number of known places where pluvial flooding due to extreme rainfall events takes place are mentioned in the sub-municipal water plan (Nelen & Schuurmans, 2009). Figure 9 shows those locations. In reality, most of the occasions of pluvial flooding occur in relation to blocked manholes (Nelen & Schuurmans, 2009).

Figure 9: Map with flooding locations as mentioned in the sub-municipal water plan of Rotterdam-Noord (Nelen & Schuurmans, 2009)

5.2 Application of method

This subsection briefly explains all the steps of the method and gives a short account of the results of each step.

5.2.1 Step 1: Define scope

No complete vulnerability assessment has been conducted, but models indicate that Rotterdam-Noord is vulnerable to pluvial flooding (Nelen & Schuurmans, 2009, Vergroesen, unpublished). This assessment performed in this study focused on pluvial flooding in relation to flooded residential and commercial buildings as well as on the road system that runs through the area. The data that have been used in this case study mainly come from sources that are available on national scale, such as the Digital Elevation Model AHN, base map information as provided by the GKBN, standard administration of addresses and contours of buildings, as included in BAG and Google Streetview. This makes it possible to perform the analysis in other areas with more or less the same sources of data. The modelling of overland flow of storm water has been performed using TUFLOW (2011) in combination with AQUAVEO (2012). Further analysis has been performed with standard software packages like ArcGIS and Microsoft Excel.

Note that the flood modelling should is by no means representative for the actual conditions. Since this study is focussing on the choice of a vulnerability assessment method, only limited resources were spent on the development and application of the flood models. One of the main limitations is that the storm water drainage network has not been represented as a 1D pipe flow model. Instead, all paved surfaces have been assigned with the capacity to absorb the design rainfall event 'BUI 8' which corresponds to the 2-year return period. The consequence of this simplification is that the storm water drainage network behaves like a uniform infiltration unit which does not reflect real conditions.

Step 2: Formulate indicator and threshold values

On the basis of the vulnerability indicator and a threshold value it is assessed whether the urban geographic areas are considered as vulnerable.

Since this report considers vulnerability on geographic scale, rather than on the scale of individual assets, the indicators should indicate the vulnerability neighbourhood level. The indicator needs to be simple, in order to facilitate easy stakeholder involvement and it needs to address outcome vulnerability, i.e. consequences of hazards. In this respect, simple indicators on geographic scale are the number or percentage of assets that are (potentially) harmed and/or the extent to which they are potentially harmed. In this respect it is possible to refer to the concepts of vulnerability such as defined by Adger (2006), which define vulnerability on the basis of the relative amount of assets that is harmed, with or without taking the size of the harm into account. The concept of proportional vulnerability (Adger, 2006) has been chosen as basis of the vulnerability indicators for flooded residential and commercial buildings. In this approach, only the relative amount of flooded buildings is calculated. It takes into account whether a building is flooded, but not the flood height itself. Table 7 shows the vulnerability indicators and threshold values. The indicators are based on the percentage of buildings that flood under different standard rainfall events. Appendix 3 describes these rainfall events in detail.

Taking the percentage of flooded buildings as a basis for the vulnerability of neighbourhoods makes it possible to formulate the same threshold values for different neighbourhoods, which makes it possible to compare the neighbourhoods objectively. The threshold values are dependent on the return periods of the standard rainfall events. Bui 8, which has a return period of 2 years, occurs relatively often, so in this case any damage should be very small. Bui100, a rainfall event that statistically occurs once in 100 years, is so extreme that some extent of damage could be accepted. After conducting the analyses it became clear that, with plausible threshold values, the case study area did not reach any ATP in relation to the flooding of buildings. This is why very strict vulnerability thresholds for the flooding of buildings have been chosen. In a realistic case, looser vulnerability thresholds would have been formulated.

For traffic nuisance of roads, an indicator has been developed that takes into account the size of the nuisance, based on the water depth and the importance of road segments. The index has a value of 100% if all roads are blocked and of 0% if no nuisance takes place at all. Only major roads have been taken into account in the analysis. Appendix 4 contains the calculations regarding the vulnerability of roads.

The vulnerability indicators and threshold values have not been discussed with the stakeholders. In reality this would be highly recommended. One of the main advantages of the method is that the ambition level of municipality regarding the vulnerability indicators and threshold values, can be set easily by decision- and policy makers, instead of by modellers and experts.

Table 7: Chosen vulnerability indicators and threshold values in Rotterdam

Rainfall event	Return period	Threshold
Bui 8 (T=1/2 year)	2 years	Percentage of flooded houses in neighbourhood < 0,1% Percentage of flooded commercial buildings < 0,1 % Traffic nuisance index = 10%
Bui 50 (T=1/50 year)	50 years	Percentage of flooded houses in neighbourhood < 0,5% Percentage of flooded commercial buildings < 0,5% Traffic nuisance index = 30%
Bui 100(T=1/100 year)	100 years	Percentage of flooded houses in neighbourhood < 1% Percentage of flooded commercial buildings < 1% Traffic nuisance index = 35%

Step 3: Calculate ATPs and express them in time

The result of step three is the calculation of the condition under which the ATPs are reached, i.e. the climate change factor at which the threshold values of the vulnerability indicators are reached and its conversion into time. This requires a calculation of the vulnerability indicators for a range climate change factor. The minimum value at which the ATP is reached is called the headroom.

The applied overland flow model uses a 5 by 5 meter grid, derived and interpolated from the Digital Elevation Model AHN (Actueel Hoogtebestand Nederland). Rainfall events are assumed to be spatially uniform while hydrologic losses, compensating for the capacity of the storm water drainage network, were set at 20 mm/hour for paved surfaces (mainly roads).

In order to determine whether and to what extent a building is flooded, the doorstep height has been subtracted from the flood depth. The doorstep height has been manually investigated with the use of Google Streetview. Only shops where the modelled water level was higher than 5 cm and houses where the modelled water level was higher than 10 cm were taken into account. A field trip confirmed that this assumption was reasonable. By combining all flood scenarios and the doorstep heights it has been assessed which buildings are flooded in each scenario in order to calculate the percentage of flooded buildings.

Figure 10 shows buildings that flood in any of the calculated scenarios, covering all rainfall events and climate change factors. It can be seen that the number of flooded buildings is low. Further it can be seen that in the majority of the cases it is one building that floods, rather than a group of adjacent buildings. Flooded buildings can be found in Oude Noorden, Bergpolder, Liskwartier and Provenierswijk.

Figure 10: Map with all buildings that flood in any of the modelled scenarios

Table 8 shows the results of the analysis regarding flooding of commercial and residential buildings. ATPs regarding bui 8 are reached at a climate change factor of 15% in many neighbourhoods. ATPs regarding other rainfall events are only reached in Liskwartier and in relation to commercial buildings only. The other ATPs are not reached within the range of calculated scenarios, which means that the headroom is larger than 55%

Table 8: Climate change factors at which ATP for flooding of commercial and residential buildings are reached

	Commercial buildings			**Residential buildings**		
Neighbourhood	**Bui 8 (T=1/2 Y)**	**Bui 50 (T = 1/50 Y)**	**Bui 100 (T = 1/100 Y)**	**Bui 8 (T=1/2 Y)**	**Bui 50 (T = 1/50 Y)**	**Bui 100 (T = 1/100 Y)**
Agniesebuurt	≥55%	> 55%	> 55%	> 55%	> 55%	> 55%
Bergpolder	15%	> 55%	> 55%	> 55%	> 55%	> 55%
Blijdorp	> 55%	> 55%	> 55%	> 55%	> 55%	> 55%
Liskwartier	> 55%	30%	30%	15%	> 55%	> 55%
Oude Noorden	15%	> 55%	> 55%	15%	> 55%	> 55%
Provenierswijk	> 55%	> 55%	> 55%	15%	> 55%	> 55%

The calculations of traffic nuisance entailed an intersection of the outcomes of the 2D overland flow model with the road segments of major roads within the area. The maximum water level on a particular road segment has been considered as the flood level of the road. The road has been considered to be blocked if the water level exceeds 10 centimetres. If the flood level is between 5 and 10 centimetres it is assumed that there is significant traffic nuisance. The traffic nuisance index considers the road nuisance as half as important as blocked roads. On the basis of the values of the traffic nuisance index, it has been calculated at which moment the ATPs are reached. Table 9 shows headroom of Rotterdam-Noord with regard to traffic nuisance.

Table 9: Headrooms regarding traffic nuisance

	Bui 8 (T=1/2 Y)	Bui 50 (T = 1/50 Y)	Bui 100 (T = 1/100 Y)
Rotterdam-Noord	15%	10%	15%

Step 4: Calculate timing of ATP

The timing of ATPs has been calculated on the basis of current one-hour rainfall volumes and projected one-hour rainfall volumes, which are supplied by the KNMI (Klein Tank and Lenderink, 2009). Appendix 3 describes the procedure that is followed.

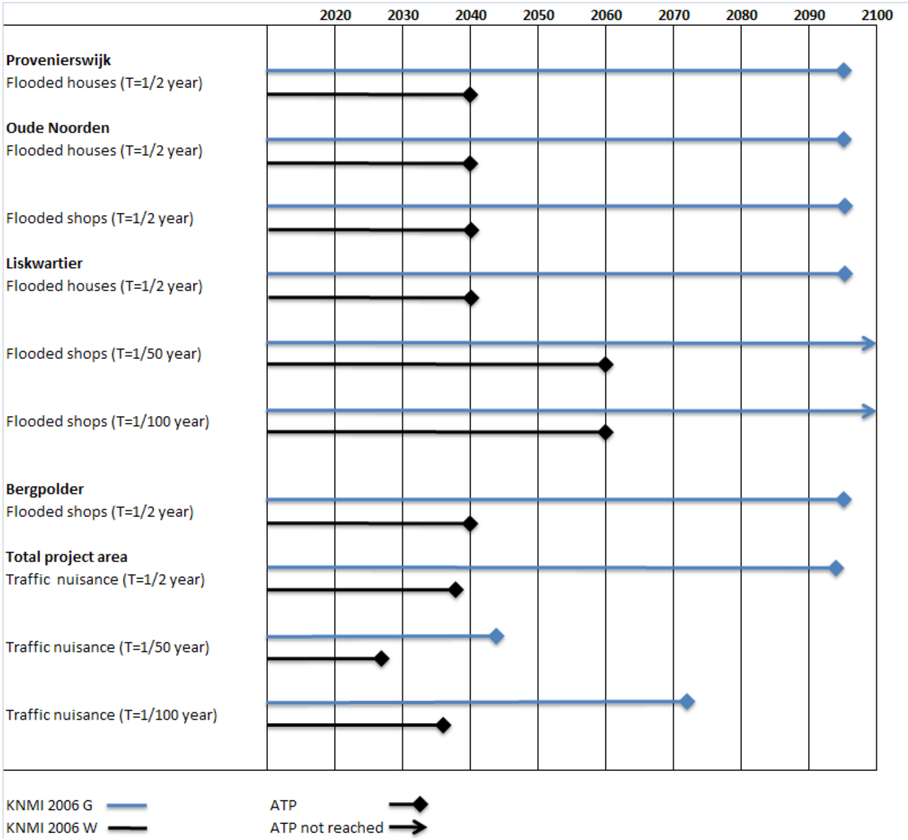
Figure 11 shows the results of the calculations of the timing of ATPs with regard to buildings and traffic nuisance. Only the ATPs that are reached within the range of calculated scenarios are included. The length of the bars indicates the amount of headroom in terms of time. The diamond symbol indicates the ATP. For example, the top lines indicate that the ATP regarding flooded residential buildings in Provenierwijk is exceeded in 2095 under the KNMI G scenario and in 2040 under the KNMI W climate change scenario. The blue lines represent timings of ATPs under the moderate climate change scenario (G) of the KNMI and the black lines represent timings of ATPs under the warm climate change scenario (W) of the KNMI. When the ATP is beyond the range of calculated scenarios the diamond symbol is replaced by an arrow symbol.

It can be seen that the first ATPs that are reached relate to bui 8 with a return period of 2 years. In 2040 the ATP is reached for flooding of residential buildings in Provenierswijk, Oude Noorden and Liskwartier and for flooding of commercial buildings in Oude Noorden en Bergpolder, under KNMI Climate Scenario W. Under the KNMI G climate change scenario these ATPs would be reached in 2095. Liskwartier is the only neighbourhood in which the shops are vulnerable to flooding for bui 50 and bui 100. These ATPs are both reached in 2060 under the KNMI W scenario. Under the G climate change scenario the ATPs are not reached before 2100.

The results of the ATPs regarding traffic nuisance show a larger urgency. These thresholds have been set on a more plausible level and they are all reached before 2100. Especially the more extreme rainfall events lead to urgent ATPs. The results indicate that the ATP for traffic nuisance under bui 50, which occurs once in 50 years statistically, could be reached in 2027 already under the KNMI W scenario and bui 100 could lead to an ATP in 2036. Under the more moderate KNMI G scenario, the results indicate that the first ATP is reached in 2044 under bui 50.

Further reflection on the case study is addressed in the next section.

Figure 11: Calculated ATPs. Not shown are the ATPs that were not reached within the range of calculated scenarios..



5.3 Discussion

The produced outcomes are generally uniform. For the G scenario, most of the calculated ATPs related to the inundation of houses or commercial objects are not reached or are located close to the year 2100. For the W scenario this period is substantially shorter; most ATPs are located around 2040. The ATPs related to traffic nuisance are especially for infrequent rainfall events located in the near future.

The main question for municipal decision and policymakers is what this information actually communicates in terms of strategies or measures. The overall conclusion of these outcomes would be is that no urgent measures are required to adapt to the expected increasing rainfall. Furthermore, there is no single neighbourhood that reaches the ATP prior to most others which means that no urgent measures are needed to extent the ATP to a future point in time. Since the vulnerability is almost uniformly spread over the different neighbourhoods, it seems prudent to start developing an adaptation strategy at a more fundamental level. Since the ATPs are located far into the future, many individual assets within the area will reach either the end of their lifecycle or undergo major refurbishment. A gradual implementation of an adjusted standard (e.g. a minimum doorstep height) could upgrade the protection standard of the area to a level that can withstand the expected rainfall increase for a generation. This conclusion changes somewhat for the W scenario since the ATPs are reached within the next 30 years. This would mean that a more active adaptation strategy is required.

For the traffic nuisance, the identified ATPs suggest prompt action. Yet, the question remains if the traffic network should be able to withstand a rainfall event with a 50 year return period. Especially since the impact mainly consists of traffic interruption that lasts only for a limited period, no interventions might be necessary.

Since the focus of this case study is to show whether the ATP-method is suitable for application on municipal level as vulnerability assessment, the calculations of the ATPs are not the end point of the ATP analysis. For a better understanding of the relation between the ATPs and vulnerability, further evaluation of the results is necessary.

5.4 Lessons learnt from case study Rotterdam-Noord

The main research question that is answered through this case study is whether the ATP-method could successfully be applied in Rotterdam-Noord and whether it could provide policy relevant information for the municipality of Rotterdam.

5.4.1 Policy relevance

In the case study it became clear that the ATP-method provided useful information about the timing of different ATPs. It is also easy to compare the timings of ATPs for different themes. In case Rotterdam-Noord, pluvial flooding of residential and commercial buildings under more and less extreme rainfall events is compared, as well as traffic nuisance due to pluvial flooding. The graph that is included in Figure 11 makes it possible to easily compare all ATPs with each other and all areas, which enabled Rotterdam to prioritize adaptation strategies and further research to climate change vulnerability in a better way. This advantage would be further amplified if ATPs to more climate change impacts would be included in the analysis.

The impact modelling that is necessary for calculating the headroom of neighbourhoods can provide important information by itself. It can be used for prioritising measures without conversion of the results to headrooms. However, impact models often have a strong geographic focus and a lack of focus on time. The ATP-analysis is of great help in making clear the timing of impacts and assessing the acceptability of impacts over time.

5.4.2 Feasibility

Another question raised in the course of this case study is whether the application of the ATP is practicable in terms of required financial and personal resources. In this case study, a new model study has been performed to calculate the ATPs. Many model runs had to be completed in order to finally calculate the ATPs. If existing models would have been used, the time required to do the analysis would have been considerably smaller.

5.4.3 Easiness of communication

The graph that is presented at the end of the analysis (Figure 11) seems to be a bit complicated to understand for people who are not accustomed to it. Because of this, it is important to explain it thoroughly.

Superficially seen, ATPs are very easy to understand, since they just indicate when a strategy does not comply with the objectives anymore. The timing of ATPs might even suggest a more certain and convincing impression of the vulnerability of an area to a certain impact than it can offer. Deeper interpretation of ATPs is however more troublesome. Not only do the indicators not include all information that is needed for proper decision making, which has been explained in subsection 5.4.1, they are also surrounded by a large amount of uncertainty. The method only provides additional information to decision makers.

6 Case 2: Nijmegen

The second case study was performed in Nijmegen. This case study only involves pluvial flooding of buildings.

6.1 Introduction

Nijmegen is situated in the East of the country along the river Waal. The city has approximately 165.000 inhabitants (Gemeente Nijmegen, 2012). The water plan of the municipality of Nijmegen has as main objective: " to collaborate with the water partners for a sustainable water chain, with as a goal a healthy and resilient water system as well as an attractive living environment against minimal costs" (Gemeente Nijmegen, 2010). In the city's structure vision 2010 (Gemeente Nijmegen, 2009) it is stated that the city has the ambition to be climate sensitive in 2030. This ambition involves integrating water in a general climate policy and complete alignment with other sectors, such as urban planning, economy and recreation, as well as valorising opportunities within urban projects such as cold-heat-storage (Van Koppen et al., 2009). However, this ambition is not formally established by the Council (Verhoeven, 2011).

Pluvial flooding mostly takes place in the east of the city. A rainfall event in 2009 led to a water stream on a road on sloping terrain, crossing two traffic squares. During this rainfall event, the fire brigade received 50 notifications of water nuisance, mainly in the city center (De Gelderlander, 2009). According to the comments by readers of an (online) newspaper article, a supermarket had to be closed for 45 minutes. It is also claimed that a number of cars broke down because of water in the engine.

6.2 Application of ATP-method

This section briefly describes the application of the ATP-method in Nijmegen. Appendix 4 contains a more extensive description of the case study. The discussion of the results and the reflection on the case study are included in further sections of this chapter.

Step 1: Define scope

The geographic scope of the analysis is shown in Figure 15. The analysis covers the neighbourhoods Stadscentrum, Benedenstad and Biezen completely and a number of neighbourhoods partially. The ATP-analysis entails ATPs on the scale of the complete project area, but separate ATPs have been calculated for the neighbourhoods Stadscentrum, Benedenstad and Biezen as well. The analysis only covers flooding of buildings.

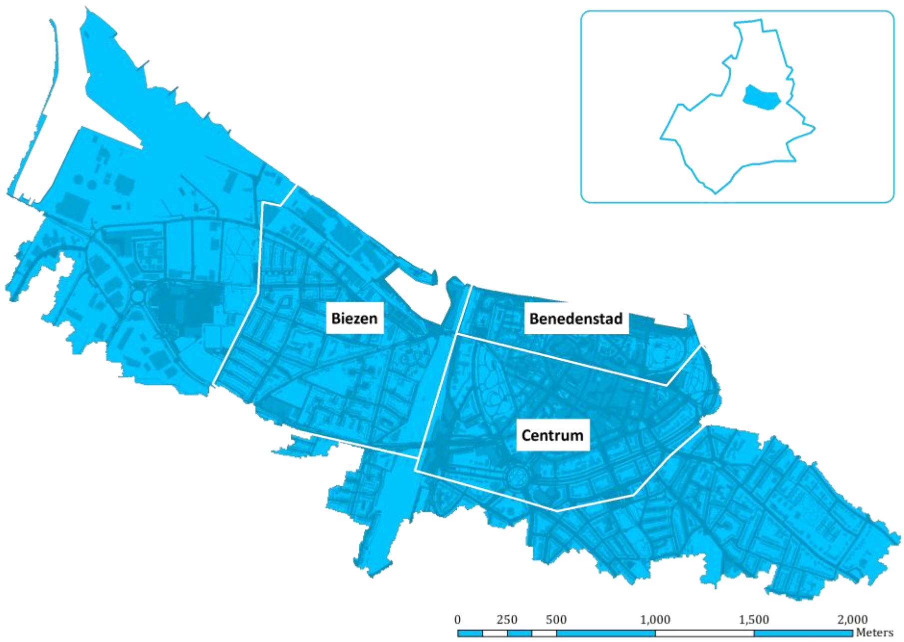


Figure 15: Geographical extent of the case study. Blue area represents geographical scale of the flood model.

Step 2: Determine indicators and threshold values

Fout! Verwijzingsbron niet gevonden. shows the selected threshold values for Nijmegen. In this case, no separate categories of buildings are applied. The choice for the threshold values is based on the personal views of the author. They have not been chosen in collaboration with the municipality of Nijmegen. It can be seen that the thresholds differ from those of Rotterdam-Noord, which makes it difficult to compare the ATPs and their timing between the two cities.

Table 10: Selected indicators and threshold values

Indicator	Threshold
Maximum percentage of buildings that flood once in two years	1%
Maximum percentage of buildings that flood once in 50 years	2,5%
Maximum percentage of buildings that flood once in 100 years	5%

Step 3 and 4: Calculate ATPs and their timings

In general, the same steps have been taken in order to calculate the ATPs as in Rotterdam. An important difference with the case of Rotterdam is that all doorstep heights (except for the ones that have been manually assessed by Nijmegen) are assumed to be 10 cm. A sensitivity analysis has performed to assess how the results change when other assumptions are made. Figure 16 shows all buildings that have been manually assessed. These locations are situated in a shopping district and can be considered as high risk, due to the flat street profile. These locations have been selected in collaboration with the municipality of Nijmegen. The manually assessed doorstep heights are excluded from the sensitivity analysis.

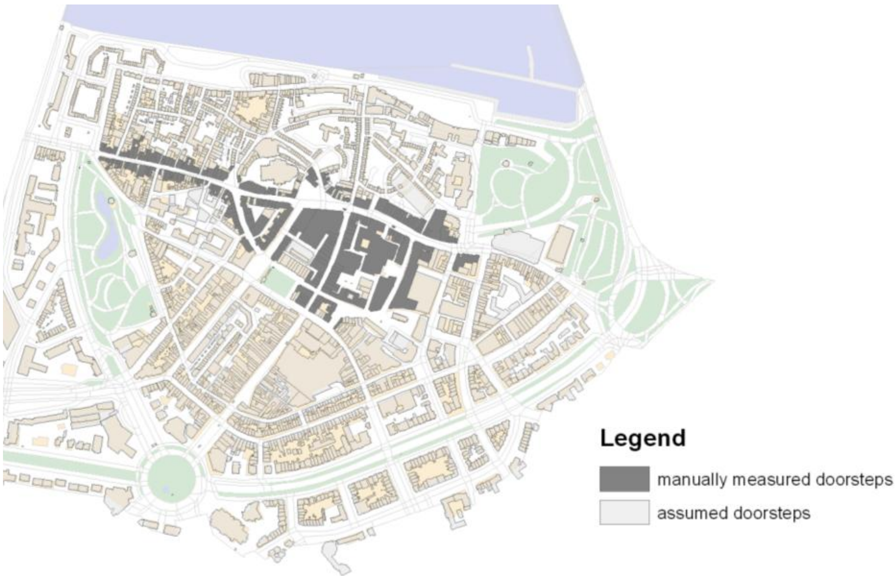


Figure 16: Manually investigated doorsteps in Nijmegen Stadscentrum and Benedenstad

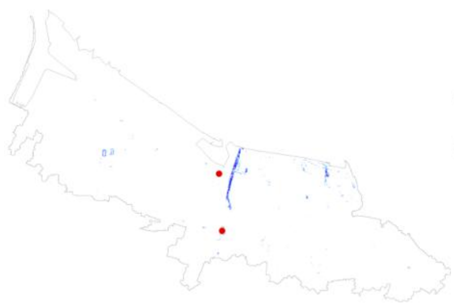
Figure 17 shows the location of flooded buildings in Nijmegen Stadscentum and Benedenstad. The modelling indicates that the number of flooded buildings is very low under the standard rainfall event that occurs once in two years statistically. The locations of buildings that flood in the current situation with climate change factor 0% are different from the situation in which the rainfall volume is increased by 50%. This could point to possible inaccuracies in the modelling. In the more extreme rainfall events, more buildings flood. It can be seen that there are three main locations where groups of buildings are flooded:

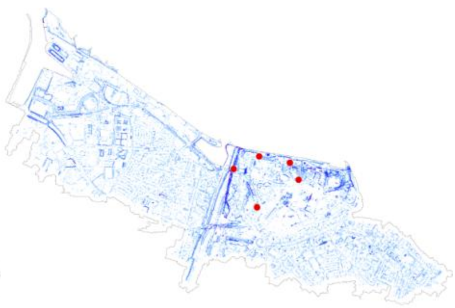
- an area surrounded by the Bottelstraat, Kloosterstraat, Obervantenstraat and the Oude Haven
- The Lange Hezelstraat and its prolongation the Stikke Hezelstraat
- Broersstraat

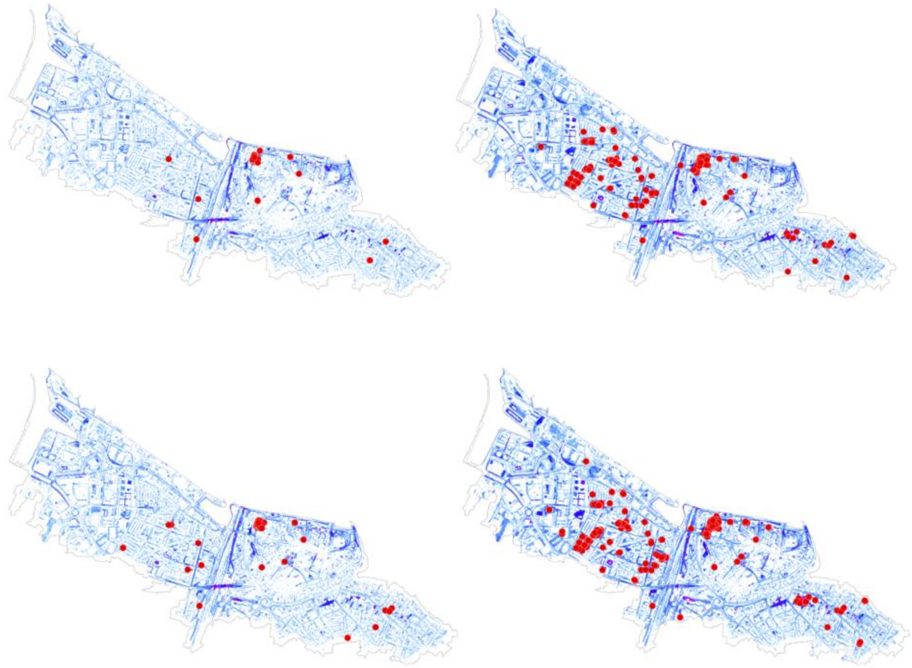
The first location is mainly flooded because of high flood water levels, that exceed 10 cm. The latter two areas are mainly flooded since they have low doorsteps. These areas are part of the area in which doorsteps have been manually investigated by the municipality of Nijmegen. Since these streets are part of the shopping district in the city centre of Nijmegen, they have lower doorsteps than buildings in other areas.

It is interesting to see that the number of isolated flooded buildings is relatively low. A possible explanation is that there is a certain amount of relief in the area. Another reason might be found in the assumptions regarding the doorstep heights. Except for the area in which the doorsteps have been investigated manually, the doorstep heights are considered to be 10 cm in the reference scenario. The sensitivity analysis showed that the spatial distribution of flooded buildings increases strongly if lower doorstep heights are assumed. This will be further explained in section 6.3.

Figure 17: Flooded buildings (in red) for the design rainfall bui 8 (top), bui 50y (middle) and bui 100y (bottom) for the current conditions (left) and 50% climate change (right)







The results of the ATP-analysis are shown in **Fout! Verwijzingsbron niet gevonden.**. The lengths of the bars indicate the amount of headroom that is available in the urban area to deal with overland flow (i.e. the relative increase in rainfall volume and intensity that can be dealt with in an acceptable way). Please note that the different rainfall events (bui 8, 50 and 100) are assessed on the basis of different threshold values. The diamonds indicate that an ATP is reached and the arrows indicate that the ATPs are beyond the range of calculated scenarios. It can be seen that a number of ATPs are not reached. In Benedenstad, the current situation leads to an exceeding of the ATPs for the rainfall events that occur once in fifty and a hundred years. Other ATPs are not reached before 2070, even under the KNMI W climate scenario, which is the most extreme climate scenario for which 1-hour rainfall volumes are available.

On the basis of the ATP analysis it can been concluded that Benedenstad is the most vulnerable neighbourhood within the project area, since both for bui 50 and bui 100, which statistically occur once in 50 and 100 years, the ATP is reached already in the current situation.

Figure 18: Timings of ATPs in total project area and in the neighbourhoods Benedenstad, Stadscentrum and Biezen.

6.3 Discussion

The ATP-analysis showed that (parts of) the project area have already reached an ATP and that a part of the area will reach an ATP before 2100. None of the areas will reach an ATP before 2100 that relates to bui 8, which occurs once in two years. The more extreme rainfall events, bui 50 and bui 100 cause more problems. The neighbourhood Benedenstad already exceeds the ATPs that relate these rainfall events in the current modelled situation. This means that if the current standard extreme rainfall events with return periods of 50 and 100 years occur, more than respectively 2,5% and 5% of the buildings get flooded. Within the neighbourhood Biezen the first ATP will be reached in 2085 under the KNMI W scenario and in the neighbourhood Stadscentrum, the first ATP will be reached in 2070.

The results of the ATP analysis showed that the threshold values for bui 50 and bui 100 have already been exceeded. This outcomes suggest that instead only of focussing on a (moderate) adaptation strategy, local measures might need to be taken to extent the ATP of Benedenstad. While Benedenstad is well capable of coping with rainfall events with 2 year return periods, the area is relatively vulnerable to those with return periods of 50 years and higher. Other areas are relatively safeguarded against frequent as well as infrequent events.

The following recommendations to the municipality of Nijmegen can be made on the basis of the ATP-analysis:

- The neighbourhood Benedenstad is the most vulnerable to pluvial flooding of buildings. In fact, the neighbourhood already reaches the (fictive) ATP in the current situation. Measures to reduce the amount of pluvial flooding or to decrease the sensitivity of buildings in this neighbourhood should be prioritised.

- The analysis shows that a small number of isolated buildings are flooded when a doorstep of 10 cm is assumed. On these locations measures at building/parcel level might be recommended. There are three locations where a group of buildings floods in a number of extreme scenarios. On these locations it might be better to take measures on street level. Since the analysis did not look at the specific location of doors, manual on-site investigation of locations is however required to assess features of the locations that have not been taken into account. More research is required into the distribution of doorstep heights in order to get more reliable estimations of the number of flooded buildings. In this respect it is most important that the low doorstep heights are assessed. The sensitivity analysis showed that the amount of buildings and the spatial distribution of the buildings that flood under bui8 increase strongly if the doorstep height is less than 10 cm. It is recommended that all new buildings are built with a minimum doorstep of 10 cm.

6.4 Lessons learnt from case study Nijmegen

This section describes the lessons that have been learnt from application of the ATP-method in Nijmegen.

6.4.1 Policy relevance

A number of reasons became apparent why the vulnerability indicators did not fully capture all relevant characteristics of vulnerabilty:

- Case Nijmegen clearly shows that ATPs for entire areas could be reached because of flooding of small parts of the areas. An ill-designed shopping district with low doorsteps could cause an ATP for a complete neighbourhood to be reached. This can be seen as a negative aspect of the ATP analysis. These kinds of details are not represented in the ATP. It is therefore questionable whether it is reasonable to apply the same threshold value to different urban areas.

- An important difference with case Rotterdam-Noord was the spatial distribution of the flooded buildings. In Rotterdam, only a number of buildings that were far from each other were prone to flooding. In Nijmegen it could be seen that there clearly were a number of locations that were more prone to flooding than others (under an assumed doorstep height of 10 cm). This observation is, however, not reflected in the vulnerability indicator, which is based only on the percentage of flooded buildings in the area of analysis.

- In addition, the analysis showed that area borders can have a significant effect on the results of the analysis. Buildings on one side of a street belong to Stadscentrum, while buildings on the other side of the same street belong to Benedenstad.

- The slopes of the impact curves varied. A steep curve implies a higher sensitivity to climate change, since the extent of the impacts after an ATP are reached, increase faster at the same rate of climate change.

6.4.2 Feasibility

An important difference with Rotterdam was that the results of the 2D overland flow modelling seemed to be more plausible for the extreme rainfall events with a return period of 50 and 100 years. A possible explanation is that the Nijmegen case study is much more sloped than the relatively flat case study area in Rotterdam. Since actual pluvial flooding is rare in Nijmegen, it is not possible to verify the results with empirical evidence.

6.4.3 Easiness of communication

Another aspect that was shown in this case study is that the certainty which the headrooms and timings of the ATPs imply, is misleading. It has been shown that the uncertainty with regard to the timing of ATPs regarding assumptions of doorstep heights is very large, causing completely different timings of ATPs and completely different policy recommendations. This uncertainty would not have been removed if only the flooding of buildings would have been modelled without the ATP-analysis, but the value of the headrooms, whether in terms of time or the climate factor, give the illusion that the results are more reliable than, in fact, they are.

7 Discussion of suitability ATP-method

After conducting the case studies it is possible to discuss and reflect on the application of the ATP-method on municipal scale for assessing vulnerability to climate change.

7.1 Strengths

The method proves to be very flexible in terms of implementing various climate change induced impacts. The timing of ATPs is an indicator that can be used conveniently to compare vulnerability of different urban areas and vulnerability to different types of extreme events. It does not matter in what terms these impacts are measured or what type of vulnerability indicator is used. One ATP can be based on monetary values while other ATPs are based on the number or percentage of casualties. It is also possible to use more integrated indicators of vulnerability, including coefficients for adaptive capacity. In short, the ATP method can be used for integrating different hazard modalities, ranges, areas and scenarios. Furthermore, it can be used in combination with other vulnerability assessment models, thus application does not require municipalities to implement a completely new set of models or tools; the ATP acts in this case as an integrative instrument.

On the basis of this indicator it is possible to compare vulnerability to extreme rainfall events with the vulnerability to prolonged periods of drought and heat waves. This would have been more difficult if all impacts had to be expressed in monetary terms or if a non-dimensional indicator would have to be used. Timing of ATPs prevent the need for indirect valuation of intangible impacts, such as mortality or ecological damage, and the need for applying weights. By specifying the conditions under which the vulnerability to a certain extreme event is unacceptable, stakeholders can easily be involved in the vulnerability assessment and they can discuss for themselves what the vulnerability indicators and vulnerability thresholds should be.

One of the most important strengths of the ATP method is its focus on the temporary dimension of vulnerability. In practise, policy and decision makers are more interested in the consistency and longevity of their policies than in the actual details of specific measures, which are operationalized by specialist departments. The ATP method improves the insight if a policy target be achieved and to what future point in time the proposed strategy is efficient. Note that in this research no adaptation strategies are included, but from the methodology it might be clear how alternative ATPs would be calculated when specific strategies or measures are taken. The focus on the temporal dimension also means that the implementation time of a specific measure can be taken into account and set against the expected changes resulting from climate change. This provides another means to not only decide on the type of measures themselves, but also on the period on which they become effective.

A final, more practical advantage of using the ATP method is that the calculations of the ATPs do not have to be repeated when new climate change scenarios become available, which will certainly occur within the time frame of the analysis.

7.2 Weaknesses

Despite the strengths of the method, it also has a number of significant weaknesses.

First of all, the method implies a large amount of certainty and objectivity that it cannot deliver. This was also shown in the case studies. Although one number represents the vulnerability of a certain area to a certain extreme event, it is not shown to what extent this number would change under different assumptions. This implies that the modellers need to make clear to decision makers that the timings of ATPs are indicative, rather than absolute.

In this report, vulnerability indicators are based on the level of neighbourhoods, for example, the percentage of flooded buildings. The timing of the ATP does not show to what extent the threshold value is exceeded, it does not show which buildings are flooded and how important these buildings are and the indicator is based on a rather arbitrary geographical neighbourhood border. An ATP could be reached because of flooding of various separate buildings spread throughout a neighbourhood, but also because of a number of ill-designed buildings on a small area. It is questionable whether this indicator thus reflects sufficiently the need for adaptation measures.

This relates to one of the most difficult aspects of using the ATP method: the definition of the thresholds. Since the thresholds define to a large extent when the tipping points are reached, a significant amount of effort should be put on the definition of what are acceptable vulnerability levels or norms. This should be part of a large discussion among stakeholders. Furthermore, the thresholds should be operational; methodologies and data should be available to model and/or measure the vulnerability metric. In practise this requires a carefully orchestrated process in which stakeholders and experts agree on meaningful, feasible and sustainable thresholds. While this process has already been followed for domains operationalized in a normative system (e.g. pluvial flooding), for other domains (e.g. heat stress) this might be a cumbersome operation. Furthermore, the question arises if the defined thresholds should be uniform for all neighbourhoods or municipalities.

Another weakness is that the formulation of thresholds could lead to unwanted normation. It is possible that municipalities are afraid that this normation could become legally enforceable. This could be a reason for them to produce either ill-defined or loose thresholds for which the ATPs will not be reached in the near future. This would mean that adaptation measures could be taken too late. These kinds of considerations can have a significant impact on the outcomes of the analysis. On the other hand, it is possible to find an urgent ATP if one searches for it. There is no hierarchy in the ATPs so any ATP could in principle express that an urban area vulnerable.

In conclusion one can say that the need for a definition of thresholds is one of the main weaknesses, since they can become object of manipulation or interests from those who define them. On the other hand one could argue that any goal, metric or norm is subject to the same criticism.

7.3 Opportunities

The ATP-method as applied in this research project can be improved to make the method more feasible for application outside of the scientific arena:

ATPs can be determined on the basis of expert judgement. This is for example done in Rotterdam Stadshavens for the theme of water safety (Asselman et al., 2008). This would prevent the need for applying modelling. In addition it is easier to take into account specific characteristics of the areas, that are not included in impact models and non-physical elements of vulnerability. A disadvantage is the subjectivity of the experts.

The calculations of ATPs can be a first step towards identification of Adaptation Pathways (Haasnoot et al., 2012). These show possible sequences of adaptation strategies under increasing climate change. At a certain stage it might not be attractive anymore to upgrade the capacity of the sewerage system and it would be more attractive to invest in measures on damage reduction. Whether this is the case should be further investigated. Most likely, adaptation pathways are quite similar for Dutch municipalities.

Another option to make the ATP-method more feasible is to perform the analysis in a very comprehensive way for different standard neighbourhoods with an extensive sensitivity analysis. In this way it might be possible to extrapolate the results of these standard neighbourhoods to other neighbourhoods.

Further it would be interesting to develop a general framework for vulnerability indicators and threshold values. In this way, different municipalities can be compared as well. Proper comparison of different municipalities would however also requires standardisation of modelling techniques and crucial assumptions.

7.4 Threats

There are a number of threats to the application of the ATP-method within Dutch municipalities:

Municipalities are not prepared to define the vulnerability indicators and threshold values out of fear for being held responsible for achieving them. This might lead to claims from inhabitants if they are harmed by extreme events.

Researchers will not pay enough attention to finding ways to improve the feasibility of the method. The only way to make sure that extensive research continues to be done in this respect is to take up this issue in the research agendas of, for example, the Knowledge for Climate programme. It is also possible that steps are taken in this respect by individual municipalities.

7.5 Summary

The results of the SWOT analysis have been included in Table 11.

Table 11: SWOT analysis of ATP-method

Strengths Flexible method Results are easy to explain Clear indication of urgency of climate change vulnerability. Bottom-up approach: municipalities and stakeholders need to indicate the acceptable outcome vulnerability to hazards. Comparison of vulnerability between themes can be done without relative weighting and indirect valuation. Modelling does not have to be repeated when new climate scenarios are made available	**Weaknesses** Misleading sense of objectivity and certainty The acceptance of vulnerability levels can be easily adapted to changing political preferences. The method is susceptible to opportunistic behaviour Vulnerability indicators do not capture all factors relevant to decision making.
Opportunities Assessing opportunities for combining measures with other urban projects by applying the ATP-Adaptation Mainstreaming Opportunities method. Options are available to use expert judgment if modelling would be too	**Threats** Municipalities and/or other stakeholders need to explicitly define situations that are considered as vulnerable or invulnerable. Are municipalities prepared to do that? Impact models will not be improved and made more accessible for munici-

complicated. Impact studies on typical areas can be used as basis for assessment of specific neighbourhoods. General framework for vulnerability indicators and threshold values for all Dutch municipalities.	palities

8 Conclusions and recommendations

The research objective of this project was developing and pre-testing a method for assessing the current and future vulnerability of urban areas to climate change quantitatively regarding pluvial flooding, groundwater flooding, heat and drought. This objective has been achieved by answering the following main research question:

How can vulnerability to pluvial floods, groundwater floods, heat and drought in urban areas in Dutch municipalities be quantified?

Since multiple definitions of vulnerability exist it is important to specify it explicitly. In this report vulnerability is defined as “the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity” (McCarthy et al., 2001, p.995). This definition allows measurement of vulnerability in terms of its outcomes (impacts after adaptation) or in terms of the (contextual) factors that determine the vulnerability “before the hazard acts”.

The following section addresses the vulnerability of Dutch urban areas to climate change, municipal strategies for adaptation and municipal vulnerability assessment, the choice of the method, the description of the suitability of the method. Finally it makes a number of recommendations for further research.

8.1 Vulnerability of Dutch urban areas to climate change

This research project addresses pluvial floods, groundwater floods, heat and drought, which can be seen as extreme events that will occur more often and can become more severe because of climate change. Chapter 3 introduced the vulnerability of Dutch urban areas to these extreme events. The following conclusions have been drawn in terms of the requirements for the method:

- The different themes affect different assets. For example, pluvial flooding mainly affects buildings and traffic, while heat stress mainly affects persons.

- Vulnerability to the different themes is determined by the objects at risk themselves, but similarly by their environment. Vulnerability differs over place and time, both in terms of the time of the day and the duration of the extreme event. Human behaviour and socio-economic developments also have a large effect on the vulnerability of urban areas. Although some of the contextual factors of vulnerability show similarities, such as the amount of green areas and the amount of open water, there are many differences in the factors that determine the vulnerability of urban areas to the different themes.

- The different extreme events have economic, social and ecological impacts, as well as impacts on public health. Similarly to the factors for contextual vulnerability, these impacts do not have a natural common quantity.

8.2 Municipalities, vulnerability and adaptation.

Municipalities are the main stakeholders within the field of local climate change adaptation. They have a general responsibility for the management of urban areas. A number of other stakeholders have responsibilities as well, such as water boards, housing corporations and parcel owners.

Current vulnerability assessment methods

- The vulnerability of the areas to pluvial flooding is assessed on the basis of sewer modelling, in combination with an uplift to account for future climate change. More advanced modelling is only applied on ad-hoc basis if problems have arisen.

- For the other themes (groundwater flooding, drought and heat stress) no structural pro-active vulnerability assessments take place. If, however, problems arise, municipalities assess the causes of the problems.

- In general, registration of pluvial flooding, groundwater flooding and drought is limited to the complaints that municipalities receive from inhabitants. The call registers are, however, difficult to use as basis for an assessment of historical vulnerability, since the records are not complete and causes of calls are not always clearly specified.

Current adaptation strategies

Since vulnerability of urban areas is largely not assessed proactively, adaptation policies have to be based on limited knowledge about the range of possible climate change impacts. Municipalities use the following adaptation strategies:

- Almost all municipalities take pro-active measures to prepare for more extreme rainfall events, such as enlargement of sewers and open water.

- Measures to reduce problems regarding groundwater floodings and drought are mainly reactive.

- Some measures, such as the creation of open water and green areas, are often taken with other motives. Reducing vulnerability to pluvial flooding and heat stress is often used as an additional argument for the project.

During the interviews, municipalities indicated that it sometimes is difficult to convince municipal urban planners, who need to consider many more interests than climate change only, and other stakeholders of the need for adaptation measures and the extra costs that they bring along. This makes it particularly important for municipalities to acquire more knowledge about the potential impacts of the climate change-related extreme weather events, in order to better justify the need for adaptation measures.

Type of information relevant to different stakeholders

In order to make the method usable it needs to match the need for information of different stakeholders:

- Decision makers are mainly interested in the results of the analysis: How large and urgent is the problem? When and where should measures be taken?

- Urban planners and water specialists want to understand the method to be able to assess what recommendations they should make to the decision makers.

- Urban planners need to be able to weigh the interests regarding climate change vulnerability with other interests.

- External stakeholders that are involved in urban projects need to know to what extent they could be affected by climate change, mainly in terms of finances.

8.3 Choice of method

The analyses of the needs of municipalities showed that many of the problems that they have regarding their vulnerability to climate change, relate to the assessment of the urgency of the problem. This makes assessment of outcome vulnerability most suitable. Methods for assessment of outcome vulnerability are diverse. A distinction can be made between cause-based methods and effect-based methods. Since effect-based method are more suitable for local application and for involvement of decision makers and it is able to take into account local circumstances. Because of this, effect-based methods are preferred over cause-based methods. The Adaptation Tipping Point (ATP) – method has been selected, among Adaptation Pathways and Exploratory Modelling, as most promising method for assessment of vulnerability to climate change on municipal scale since (1) it results in an indicator for outcome vulnerability, (2) it is the most feasible method of the methods for assessment of outcome vulnerability that have been evaluated and (3) it leads to results that are relatively easy to communicate. Therefore, the ATP-method has been selected for pre-testing in the two case studies in Nijmegen and Rotterdam-Noord.

8.4 Case studies

Two case studies have been performed during this project: Rotterdam-Noord and Nijmegen. The focus of the case studies was to explore the suitability of the ATP approach to vulnerability assessment on local scale. However, some conclusions have been drawn about the vulnerability of the case study areas. The lessons that have been learnt about the application of the ATP-method in the case study are included in section 8.5.

Case study Rotterdam-Noord involved modelling of flooding of commercial and residential buildings as well as traffic nuisance due to pluvial flooding. It is important to stress that the applied modelling only involved overland flow of water. The capacity of the sewerage system and flooding from open water have not been taken into account. It has been concluded that:

- Rotterdam-Noord relatively well protected against the impacts of pluvial flooding. The few locations where buildings flood are spread over larger areas. It is shown that under realistic threshold values, no ATP is reached before 2100.

- Traffic on the major roads in Rotterdam-Noord is more vulnerable to pluvial flooding. The first ATP is reached in 2025. The amount of traffic nuisance might, however, be overestimated. Under less extreme rainfall scenarios, mostly east-west connections are prone to nuisance. In the more extreme scenarios, north-south connections also get flooded.

If the results of the analysis are considered as sufficiently reliable, the following recommendations would be made:

- Focus on no-regret adaptation measures and on policy measures to make sure that the vulnerability of buildings does not increase in future.
- Validate the results of the traffic nuisance under the current rainfall event with return period of 2 years in the current situation with past experiences and check whether there are specific details in the design that prevent or reduce pluvial flooding.

In Nijmegen only flooding of buildings has been assessed. The analysis clearly showed that the neighbourhood Benedenstad was the most vulnerable, since one of the ATPs was reached already in the current situation. In the other neighbourhoods, the first ATPs were exceeded after 2070. Most of the buildings that flood are situated on three locations. Because of this it could be interesting to take measures on street level, rather than on building level.

A sensitivity analysis showed that the results are highly sensitive to a decrease in the assumed doorstep heights. Not only has the amount of flooded buildings increased strongly, also the geographical spread of the buildings. Two conclusions can be drawn on the basis of these observations:

- It is essential for good vulnerability assessment to pluvial flooding of buildings that doorstep heights are measured.
- Municipalities should focus on doorstep heights to decrease vulnerability of buildings to pluvial flooding.

For more extensive conclusions about the case studies themselves, readers are referred to paragraphs 6.4 and 7.4.

8.5 Strengths and weaknesses of ATP- method

In order to evaluate assessment of vulnerability to climate change on the basis of timing of adaptation tipping points, an analysis has been made of its strengths, weaknesses, opportunities and threats. The analysis has been shown in Figure 29. The most important strengths of the method relate to its flexibility and its ability to give insight into the urgency of climate change vulnerability. In addition, it is relatively easy to involve decision makers in the analysis. Its main weaknesses relate to the feasibility of the application of impact models to calculate the ATPs. In addition, the ATPs give a rather simplified insight into vulnerability. Characteristics of vulnerability, such as spatial spread and graduality, are not represented in the analysis and should be assessed separately. Major opportunities arise when the method is applied with the use of expert judgment. In addition, the analysis can be a first step to perform an analysis of adaptation pathways and it can be used for the assessment of opportunities for combining adaptation measures with other physical measures. A weakness is that the method and its underlying impact models, will not be made more

8.6 Recommendations for further research

This section contains a number of recommendations for further research. The specific recommendations for the municipalities of Rotterdam and Nijmegen are not repeated here. The outcomes of the SWOT analysis provide important input for the recommendations of this project. The most important barrier to application of the ATP-method is the feasibility, so this is the topic to which more research is crucial. There are different options to make the application of the method more accessible:

Identifying best ways to efficiently model impacts of climate change and developing standard procedures for the ATP-method could not only help realizing a uniform application, but it can also help municipalities to scope the analysis in a shorter period of time.

Expert judgment can be used as an alternative to physical modelling. Especially for the groundwater- and heat-related themes, this could be a first step to applying the ATP-method before physical models are developed and/or used.

Approximation of ATPs on the basis of standard neighbourhoods is another option that could be used to prevent that municipalities have to apply physical modelling themselves. These standard neighbourhoods should be investigated thoroughly and extensive sensitivity analyses should be performed in order to find the most important factors that determine the timing of the ATP.

More research could be done to formulate best practices regarding the formulation of vulnerability indicators and threshold values. It is most likely that the same type of indicators can be used within different municipalities. This would make it easier to perform the ATP analysis. In addition, it could be assessed which range of threshold values would be reasonable, in order to give municipalities an idea of reasonable and generally feasible threshold values.

In addition, more research is required to the way in which other aspects of vulnerability than the size of the impacts can be taken into account. For example, the percentage of flooded buildings within a neighbourhood does not indicate the spatial distribution or the graduality of impacts. These characteristics are however relevant to decision makers.

In the context of this project, a number of interviews has been conducted. These interviews had an exploratory character. It is recommended to further investigate what municipalities really need to improve their management of climate change vulnerability. The selection of municipalities should include small and large municipalities as well as frontrunners and followers regarding climate adaptation efforts. In addition, it would be recommended to further investigate how municipalities use the ATP-method and its results. For example, it would be useful to investigate how the method can be implemented in a decision making framework for adaptation and policy making.

At last, this research only pre-tested the ATP-method with regard to pluvial flooding. Pre-tests for groundwater flooding, drought and heat stress are necessary to better assess the general applicability of the ATP-method in the context of Dutch urban areas.

The sensitivity analysis that has been performed in Nijmegen showed that the results and the amount of flooded buildings strongly depended on the assumptions regarding the doorstep height. From this observation it can be concluded that it is crucial for municipalities to ensure that the doorstep heights are sufficiently high. It would be highly recommended to include minimum requirements for doorstep heights in building regulations.

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10 Appendix 1: Applied vulnerability assessment methods in The Netherlands

A lot of methods for vulnerability assessment have developed and applied in the past. Analysis of the currently applied tools is necessary to make sure that the method that is designed in this project doesn't exist already. Additionally there might be methods that could be extended to serve the goals of the design criteria. This section only covers methods that can (potentially) be used for quantitative assessment of vulnerability to pluvial flooding, groundwater flooding, drought and heat stress.

Within The Netherlands a number of methods for quantitative assessment of vulnerability are available. The website "Practical Guide Space for Climate (Praktijkboek Ruimte voor Klimaat) describes Dutch case studies, best practices and instruments for climate proof spatial design. The methods that are described below are relevant for the quantitative assessment of (elements of) vulnerability to climate change.

Klimaatkaart (Climate Map)

The klimaatkaart (climate map), which is developed by Bosch Slabbers Landschapsarchitecten (2010) consists of a map of a city, based on "climatopes": areas with similar micro(climate) conditions (temperature, heat radiation, air moisture and wind circulation as well as ground and water features). Further, the map is composed of various additional layers including population density, locations with experienced pluvial flooding and so on. The maps thus provide an intuitive graphical overview of the current vulnerability of locations to climate change. The map can be considered as a method for assessment of contextual vulnerability to climate change in the form of a map.

GRaBS

GRaBS (Green and Blue Space Adaptation for Urban Areas and Eco Towns) is an international research programme in which a tool has been developed in which all stakeholders (decision makers, professionals and general public) can overlay different maps and perform a qualitative vulnerability assessment (Kazmierczak and Handley, 2011, Kingston and Cavan, 2011). The tool can be seen as a basis for the development of a vulnerability profile or index. It only considers current vulnerability. Contextual indices are included for, among others, pluvial flooding and heat stress. The method is applied in Amsterdam Nieuw-West as well as in other European cities. Application of the tool in Amsterdam was however not satisfactory due to the small size of the area and problems with data supply.

Ruimtelijke Klimaatscan (Spatial Climate Scan)

The Ruimtelijke Klimaatscan (De Groot et al., 2009) is a quasi-quantified GIS-based method for assessing climate robustness of land use functions on provincial scale. It can be seen as a composite indicator for robustness of land use. The method combines an assessment of climate effects and a sensitivity analysis per land use function and presents it with colours and symbols on a map. A major drawback of the method is that it can't be seen whether an area is vulnerable due to a high probability of a hazard or because of a high sensitivity. Application of the method on urban scale might be difficult, because of the large density of land use functions and a higher required level of detail.

Duurzaamheid op Locatie (Sustainability on Location)

Duurzaamheid op Locatie (DPL) is a tool for assessment of the sustainability of neighbourhoods (IVAM, 2011). The related Klimaattool (climate tool) is added later. The method is based on the comparison of neighbourhoods with reference neighbourhoods, that comply with legal requirements, but are not further improved by additional adaptation measures. All dimensions of sustainability are given a rank on the scale of 1 to 10. The method addresses amongst others pluvial flooding, drought and high temperatures. It is applied in 30 municipalities and 8 districts (IVAM, 2011). It is interesting that the method is applied on neighbourhood level, which is the focus of this project as well. Application of the method can be done very quickly and the information that is gained is policy-relevant: a comparison of a different neighbourhoods.

Adaptation Tipping Point – Adaptation Mainstreaming Opportunities method

The Adaptation Tipping Point – Adaptation Mainstreaming Opportunities method (ATP-AMO) can be considered as an extension of the Adaptation Tipping Point Method. It add a bottom-up assessment of opportunities for mainstreaming adaptation options with urban redevelopment projects. It assesses when the last moment for combining measures with other physical urban development projects before an adaptation tipping point is reached.

Adaptatiewiel (Adaptive Capacity Wheel)

The "Adaptatiewiel" (adaptative capacity wheel) is a guide for evaluating the adaptive capacity of a institutions, for example organizations, laws or formal and informal agreements (Gupta et al., 2011). In fact it is an extensive vector-valued indicator that could be used in any index for vulnerability. However, it does not provide information about how the indicating variables can be aggregated. It is stated that the tool is primarily effective for "starting the discussion".

11 Appendix 2: List of Interviewees

Date	Respondent	Organisation
10-10-2011	Lissy Nijhuis, Jos Streng	Gemeente Rotterdam
16-12-2011	Ton Verhoeven	Gemeente Nijmegen
3-1-2012	Hans van Ammers	Gemeente Arnhem
4-1-2012	Marco van Bijnen	Gemeente Utrecht
12-1-2012	Anja Boon, Astrid Vermeulen, Nathalie Rasing	Deelgemeente Amsterdam Nieuw-West
18-1-2012	Peter van Wensveen, Arthur Hagen, Kees Hufen	Gemeente Den Haag
19-1-2012	Paulien Hartog en Maarten Claassen	Waternet
2-3-2012	Toine Vergroesen	Deltares
6-3-2012	Ton Verhoeven, Emile Willemse, Robert van Wijk and Antal Zuurman	Gemeente Nijmegen

12 Appendix 3: Standard rainfall events and climate change factors

This appendix describes the rainfall events that have been used for the modelling in this project and explains the climate change factor. In the 2D overland flow modelling, scenarios have been run for all of the standard rainfall events and for multiple climate change factors.

Figure 1 and Table 1 describe the rainfall intensities of the rainfall events that were used in this project. It can be seen that Bui 8 is quite moderate with gradually increasing rainfall intensities, while Bui 50 and Bui 100 have a strong peak in rainfall intensity, which indicates a lot of rainfall in a very short time. The total rainfall volumes of bui 50 and bui 100 are quite similar, while bui 8 contains less than half of both.

Table 1: Design Storm characteristics

	Bui 8	Bui 50	Bui 100
Total rainfall volume (mm)	19.9	42.95	45.3
Return period (years)	2	50	100

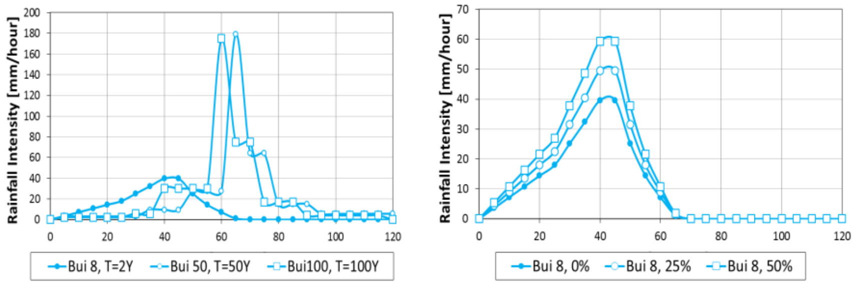

Figure 1: Applied design Storms (left) and the Influence of the climate change factor on Bui 8 (right)

The climate change factor is the ratio between current and future rainfall volumes (Gersonius, 2012). Because a higher volume of rain falls in the same time, the intensity of the rainfall event increases as well. As an example, Figure 1 illustrates the effect of a number of climate change factors on bui 8.

13 Appendix 4: Flood modelling

The developed inundation maps are based on numerical 2D overland flow models using TUFLOW. From the outcomes, the maximum inundation depths are calculated and used for further analysis. As already mentioned in the report, the applied model does not include a 1D representation of the storm water drainage network. Instead, the infiltration rates provided by the network are modeled as hydrological losses on impervious surfaces. Additional infiltration rates for different surface types are derived from literature. This also holds for the roughness values that influence the flood propagation. These values were applied on the vector base land use maps which in turn were provided by the case study partners. The applied rainfall events are conceptualized as spatially uniform; on every location in the case study areas the precipitation intensity evolves equally over time. The applied digital elevation (dem) and derived digital terrain models (dtm) were based on the AHN1 digital elevation model (Rotterdam) and LIDAR data (Nijmegen). For Rotterdam, the dtm was scaled up to a 5m resolution while for the Nijmegen case study area a 3m resolution DTM was used. For both cases, gaps in the dem's were filled using an inverse weighted interpolation. At a later stage, calculations for Rotterdam were performed using a 3m dtm based on the AHN2 dem. This was mainly done to investigate the influence of artifacts and peculiarities in the outcomes. The calculations involved 6 design rainfall events or the Rotterdam case study: Bui 8, Bui 9, Bui 10, Bui 25, Bui50 and Bui 100 and 3 design rainfall events for the Nijmegen case study: Bui 8, Bui 50 and Bui 100. For both instances, 3 climate change factors were applied: 5%, 25% and 50%. This lead to a total of 24 simulations for the Rotterdam case study and 12 for the Nijmegen case study. A typical result for the Rotterdam case study is depicted in figure 1.

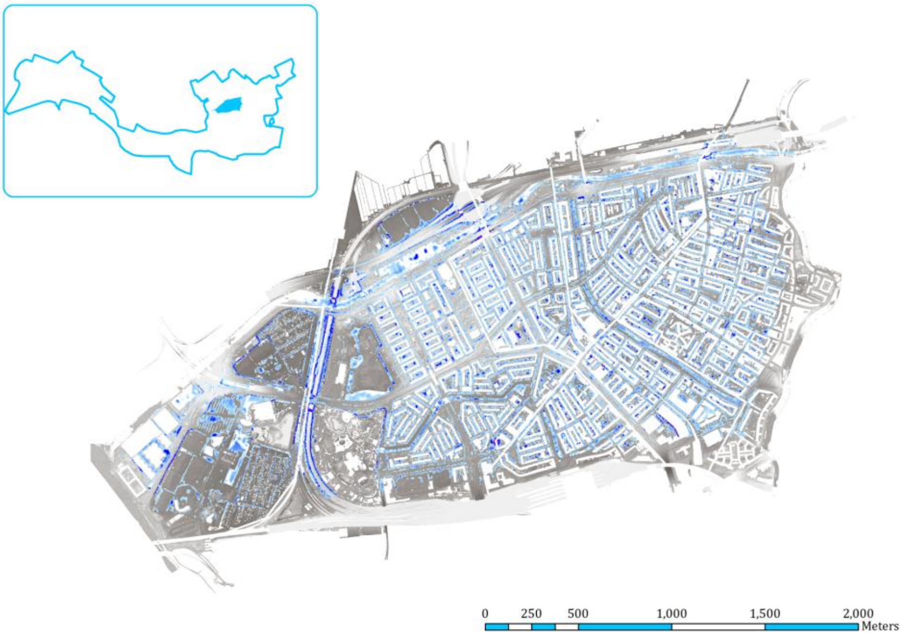

Figure 1: Inundation map for Bui 10 with a climate change factor of 10%

One of the major difficulties in assessing the inundation of houses is illustrated in figure 2 and 3. Especially for the Rotterdam case, many of the courtyards in the closed building blocks are inundated. As depicted in figure 2, many of these courtyards are located at a lower elevation level which makes them behave as sinks; i.e. local depressions where the floodwater accumulates. Yet ground floor level, the adjacent housing blocks are mostly located at or above the street level at the outer perimeter of the block. While it is unknown of the sub ground floor levels of these buildings are in fact waterproof, not every house is equipped with a functional basement that could potentially suffer damages from inundations. The question now becomes which inundation level should be taken as the actual figure to assess if individual units are indeed inundated or not.

Figure 2: Detail of the digital elevation model used for the Rotterdam case study. Darker green areas represent lower elevation levels.

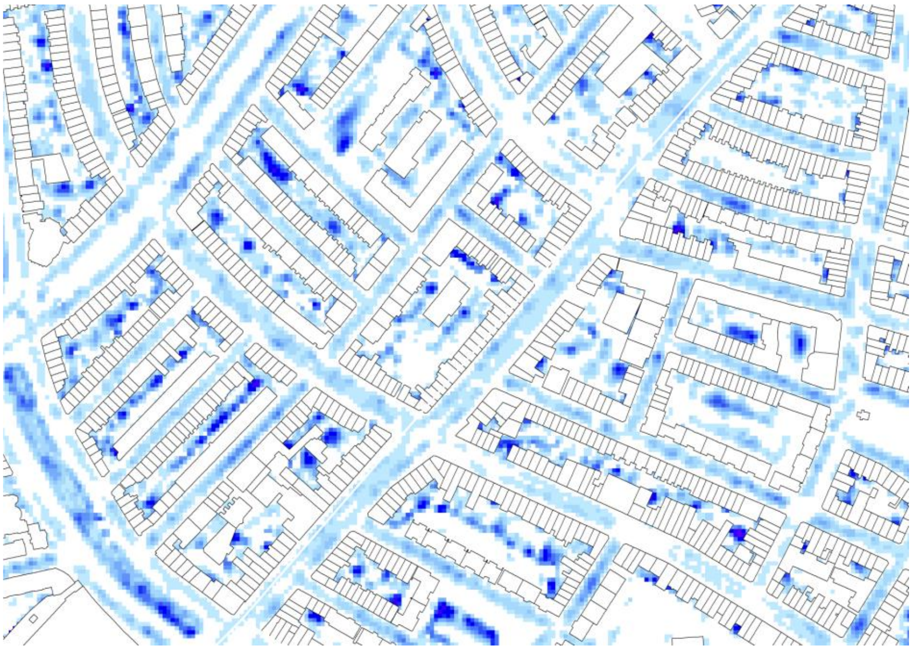

Figure 3: Detail of the inundation map from figure 1, showing higher inundation levels in the courtyards of the closed building blocks.

For the bulk of the analysis presented in the report, including the determination of the adaptation tipping points, it was decided that the minimum flood depths in cells adjacent to the building units were taken as the actual flood levels. Yet, this might result in an underestimation of the actual flood levels. Another factor that influences the outcomes is the applied resolution of the dtm. Curbes and other obstacles that direct the pathway of flood water could disappear during the up scaling of elevation data.

To gain insight in the sensitivity of the outcomes, analysis has for the Rotterdam case study has been performed using the minimal, mean and maximum inundation depth in the cells adjacent to the building units. Furthermore, the simulations have been performed using a 3m resolution dtm instead of the 5m dtm used for the ATP analysis. Some representative outcomes, for a 100 year rainfall event, are presented in table 1

Table 1: Inundated houses using the minimum, mean and maximum inundation depth of adjacent flooded cells, for a 100y rainfall event

	# houses where d > 10cm		
	Minimum d	Mean d	Maximum d
Agniesebuurt	0	11	90
Bergpolder	0	5	46
Blijdorp	0	5	51
Blijdorpse Polder	0	0	1
Liskwartier	0	3	124
Oude Noorden	0	15	224
Provenierswijk	0	2	77

Table 2: Inundated commercial functions using the minimum, mean and maximum inundation depth of adjacent flooded cells, for a 100y rainfall event.

	# commercial units where d > 5cm		
	Minimum d	Mean d	Maximum d
Oude Noorden	0	10	33
Provenierswijk	0	11	47
Agniesebuurt	0	7	21
Bergpolder	0	0	3
Blijdorp	0	6	31
Blijdorpse Polder	0	58	166
Liskwartier	0	5	17

The first observation that can be made from table 1 and 2 is that when taking the minimum depth as the reference value for flooding, neither housing nor commercial functions are flooded above the applied thresholds of 10 and 5cm respectively. This outcome differs from the results presented for the 5m dtm in the main report where limited inundation above the threshold was observed. This means that the produced flood pathways were significantly different due to curbs and other obstacles that disappeared in the much coarser 5m dtm. Another more striking observation is that the outcomes for the minimum, mean and maximum inundation depth of adjacent cells differs dramatically. While some of the outcomes for the maximum flood depth can be attributed to the lower elevations of the courtyards, the differences with the minimum or mean flood depths are too large to create reliable results. An on-site survey should be made to examine which of the 3 methods creates results that reflect the actual conditions.

14 Appendix 5: Observations Case Study Rotterdam

14.1.1 Flooding of commercial and residential buildings

The ATP analysis showed that Rotterdam-Noord is not very vulnerable to pluvial flooding of buildings. The total number of flooded houses is so low that none of the ATP would have been reached with realistic threshold values. Since very strict thresholds for buildings have been chosen, the outcomes of the analysis do not directly comprise a realistic assessment of the urgency of pluvial flooding of buildings. This subsection elaborates further on the results of the assessment of flooded buildings.

In many neighbourhoods it is shown that the ATPs relating to rainfall event with a return period of two years will be reached the soonest. This result however is highly uncertain. Figure 1 shows the results of the intersections of the flood models for Bui 8 with the contours of the buildings. It was expected that the percentage of buildings that would flood in each neighbourhood, would increase if the climate change factor increased. The results, however, show that the percentages of flooded buildings at climate change factor 15% are higher than the percentages at higher climate change factors. For example, it is shown in Figure 1 that the threshold value for flooding of residential buildings in Liskwartier is exceeded at a climate change factor of 15%. But at higher climate change factors (>35%) it drops below the threshold value. One of the main reasons for this phenomenon is the combination of flat areas and limited inundation depths that cause instable states within the model runs. This causes inaccuracies. In practise, the higher the return periods and the subsequent flooding, the more accurate the outcomes become.

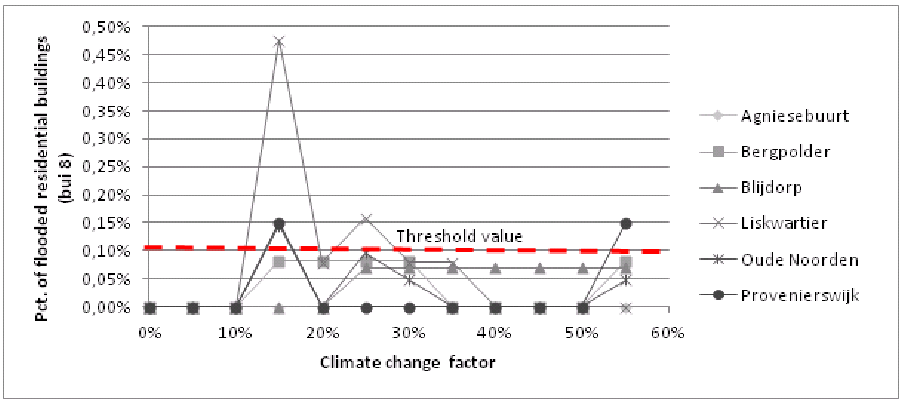

Figure 1: Percentage of flooded residential buildings in different neighbourhoods under bui 8

Figure 13 shows maps with the locations of flooded residential and commercial buildings. A number of observations can be made:

The location of the flooded buildings can be found in the eastern half of the sub municipality. Blijdorpse Polder only includes a small number of buildings, which could explain the low amount of flooded buildings. In bergpolder, however, which contains more buildings, no flooding of buildings takes place.

The locations of the flooded buildings under bui 8 and climate change factor 15% are different from the locations of flooded buildings under other standard rainfall events. This could be explained by the large difference in characteristics between bui 8 versus bui 50 and bui 100. The latter rainfall events are very similar. However, the locations of the flooded buildings are different as well, although it is difficult to draw conclusions with such small amount of flooded buildings.

The modelling indicates that pluvial flooding of buildings takes place on a very small scale. There are no areas that consist of multiple buildings within Rotterdam-Noord that face pluvial flooding under the calculated scenarios. It is one building that floods rather than a group of buildings in a street. This has implications for the type of adaptation measures that could be taken. This might be typical for other flat areas as well. These will be further addressed in the next subsection.

Figure 2: Locations of flooded residential and commercial buildings within Rotterdam-Noord for all rainfall events

In this case study, no sensitivity analysis has been performed. In order to improve the quality of the analysis and to investigate the robustness of the conclusions, it is highly recommended that a sensitivity analysis is performed. It could for example be researched how sensitive the results are for different assumptions regarding the assignment of flood levels to buildings, doorstep heights, and threshold values.

14.1.2 Traffic nuisance

The threshold values of the indicators for traffic nuisance under the different standard rainfall events are exceeded quite soon under the KNMI W scenario. Under the W scenario, the first ATP will be reached in 2025 and under the KNMI G scenario the first ATP will be reached in 2045. This implies that the urgency of taking measures regarding traffic nuisance is higher than the urgency of taking measures regarding the flooding of buildings.

As in the case of the assessment of flooded houses on the basis of the outcomes of the 2D overland flow modelling, the results of the analysis of traffic nuisance should be assessed with a number of considerations in mind:

The analysis disregards specific contextual factors that contribute to road nuisance. Under all rainfall scenarios with climate change factor 50%, the Gordelweg floods. It is, however, not taken into account that there is a canal along this road, which reduces its vulnerability. Possibly the road is designed in such a way that the water runs directly into the open water. The adaptive capacity with regard to this road is also high, since simple measures could be taken to direct the water to the canal.

The analysis was based on the amount of flooded road segments. These road segments vary in size. A crossing has a small surface, while a normal road segment has a large surface. One flood height is assigned to each road segment, which is based on the maximum water levels within that road segment. This is justified by the idea that the traffic nuisance on a road segment is based on the part of the road segment where the flood level is the highest. This means that the analysis is sensitive to outliers. It also means that the chance that a large road segment gets a high flood level is higher than the chance of this happening at a small crossing. Flood levels thus might be overestimated.

When assessing traffic nuisance it is not only the flood height and the number of blocked driving directions that are important, but also the amount of blocked cars, the amount of by-roads, and the duration of the flooding. These factors have not been taken into account explicitly.

Figure 3 shows the road segments with traffic nuisance. It should be noted that each road segment has one flood level (the maximum water level within the corresponding road segment). If the water level on a small part of a large road segment is high, the surface of the red area on the maps is large. Crossings are considered as one road segment. It is not easy to see to what extent crossings are blocked, while they are considered to be of greater importance than normal road segments.

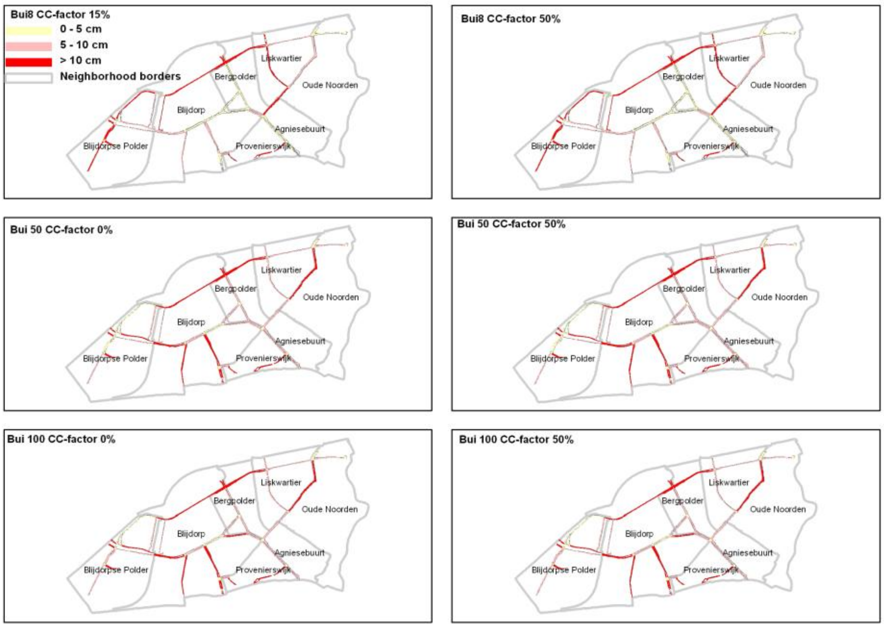

Figure 3: Traffic nuisance under all scenarios at climate change factor 0% (current situation) and 50%. Under bui 8 no flooding takes place, so for this rainfall event, climate change factor 15% has been included.

The following observations have been made:

Under bui 8, it is mostly east-west connections that are blocked, while under bui 50 and bui 100, the more extreme rainfall events, north-south connections are also blocked.
Bui 8 leads to different blocked roads than bui 50 and 100. For example, a number of roads get blocked in the east of the project area, which do not flood under bui 50 and bui 100. The differences between bui 50 and bui 100 are smaller. Again these differences can be explained by the large similarity between bui 50 and bui 100 and the large difference between these two rainfall events with bui 8.
The modelled number of roads that get blocked or cause nuisance under bui 8 with climate change factor 15% seems to be higher than expected. This observation is similar to the observations in relation to flooded buildings.

14.2 Conclusions and recommendations

The focus of this case study was not primarily to show the vulnerability of Rotterdam-Noord, but to show the potential of the application of the ATP-method for assessment of the vulnerability of Rotterdam-Noord. Still it is worthwhile to look at the conclusions that can be drawn on the basis of the case study for the municipality of Rotterdam in order evaluate the application of the ATP-method

It has been explained that the threshold values of the indicators for the vulnerability of buildings have been set on an unrealistically strict level, which had as effect that flooding of one or several buildings within one neighbourhood led to reaching the ATP. In addition it has been explained that the results of the 2D overland flow modelling were not in line with the expectations. The policy relevance of the case study, therefore, is limited. The following conclusions can be drawn regarding the policy dimension of the case study, if the results of the impact modelling are considered to be realistic and if more realistic threshold values are used to assess ATPs:

- The ATP-analysis showed that all neighbourhoods are almost invulnerable to pluvial flooding with regard to pluvial flooding of buildings, if vulnerability is defined on the basis of the percentage of residential and commercial buildings that flood on the basis of standard rainfall events with return periods of two, fifty and a hundred years.

- For the short term measures are not required. Neither does vulnerability in the long term require costly measures. Under the KNMI climate scenario W (the most extreme scenario that has been included) the range of calculated scenarios extends to 2100. So, multiple opportunities for combining spatial measures will arise before the first realistic ATP will be reached. In the meantime, municipalities can focus on no-regret measures and policy measures to create incentives to decrease vulnerability to pluvial flooding of buildings.

- The low amount of buildings that flood in combination with the large spatial distribution makes it less attractive to invest in technical measures on area level. The spatial size of these measures needs to be large and therefore they will probably be expensive. Measures on building level seem to be effective as well. These are mostly within the responsibility of the owners of buildings rather than of the municipality.

- Roads seem to be more vulnerable to pluvial flooding in terms of traffic nuisance. Under the KNMI W climate change scenario the first threshold will be exceeded in 2025. There are reasons, however, to assume that the amount of traffic nuisance is overestimated, since traffic nuisance on road segments is based on the maximum flood depths, and the modelled amount of roads that floods in the current once-in-two-years rainfall events seems to be higher than it is in reality. This should however be checked with empirical data.

- Specific design characteristics of roads and rainfall discharge facilities are not taken into account, so onsite assessment of vulnerable roads should be performed in order to see if measures are required.

A sensitivity analysis should be performed to test the assumptions regarding the doorstep heights (stair-step heights), threshold values and assumptions in the flood modelling, in order to get a better idea of the robustness of the conclusions.

15 Appendix 6: Observations Case Study Nijmegen

15.1.1 Flooding of commercial and residential buildings

This section first discusses the timings of ATPs under different rainfall events and their validity. After that, the results of the sensitivity analysis regarding the doorstep heights are presented and interpreted.

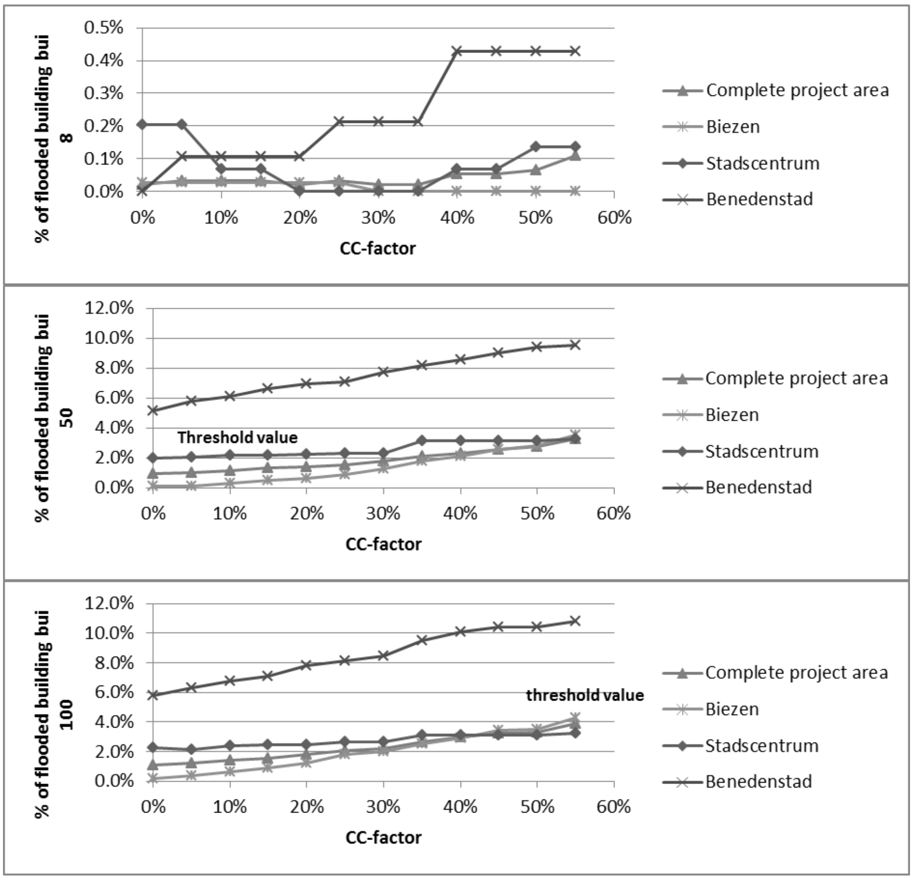

Figure 1: Percentage of flooded buildings under different rainfall events in the compete project area and in the neighbourhoods

Figure 1 shows the percentages of flooded buildings and the threshold values in all areas and for all standard rainfall events. It can be seen that none of the thresholds are reached under bui 8 and that the percentages of flooded buildings are less than half of the threshold value of 1%. It can also be seen that the number of flooded buildings does not always increase if the climate change factors increase. This effect could also be seen in Rotterdam. A possible explanation is that the water levels are too low for the type of modelling that is applied. In spite of the unexpected outcomes for bui 8, the results for bui 50 and bui 100 look more plausible.

The differences between the results under bui 100 are to a large extent similar to those under bui 50. This result could be expected since the rainfall events are very similar. Since the threshold value for bui 50 is set on 2,5% and the threshold value for bui 100 on 5%, the threshold value for bui 50 is exceeded in all areas within the range of calculated scenarios.

Another interesting remark that can be made on the basis of the figures is that the slope of the curves differs. It seems, for example, that the number of flooded buildings increases at a higher rate with increasing rainfall volumes and intensities in Biezen than in Stadscentrum. This implies that the vulnerability of Biezen is higher, but this is not reflected in the timing of the ATP.

Since not all doorsteps have been investigated manually, a rather rough assumption is made that all other doorsteps are 10 cm. This is an assumption that could potentially have a large effect on the number of flooded buildings. The sensitivity analysis that was applied confirmed this. The results of the sensitivity analysis are shown in Table 1. The headrooms define how much extra rainfall volume can be handled by the areas until the threshold value is exceeded.

When the doorstep height is assumed to be 3 cm, there are large differences in terms of the headroom. In the most extreme case the headroom of 55% is reduced to 0%, which represents a change in timing of the ATP of about 100 years under the KNMI W scenario and about 200-300 years under the KNMI G scenario, depending on the rainfall event. In all neighbourhoods, at least one of the ATPs is exceeded in the present situation (climate change factor 0%) if a doorstep of 3 cm is assumed. The high sensitivity of the neighbourhoods for lowering doorstep heights can be explained by the relatively large area with flood depths between 3 and 10 cm, which explains the high sensitivity of the area to a lowering of the doorstep height in this range.

If the doorstep height is increased to 15 cm, the differences are smaller. This is caused by the lower amount of locations where the water levels are between 10 and 15 cm.

There seems to be no correlation of the sensitivity of the different neighbourhoods for changing doorstep heights. The sensitivity for doorstep heights under the different standard rainfall events seems to be random.

Another observation is that if the doorstep height is assumed to be 3 cm, the buildings that flood are spread over the entire area. Because of this, the (policy) recommendations to Nijmegen change under the different assumed doorstep heights. On clear vulnerability hotspots it can be recommended to take physical measures to reduce the vulnerability, while widely spread vulnerabilities can more profitably be addressed by non-structural measures and policy measures.

Table 1: Sensitivity analysis - headrooms at different doorstep levels. The doorstep level of 10 cm is assumed in the reference scenario.

Area	**Rainfall event**	**Doorstep height (cm)**		
		3	**10**	**15**
complete project area	Bui 8	35%	55%	55%
	Bui 50	0%	45%	55%
	Bui 100	0%	55%	55%
Benedenstad	Bui 8	5%	55%	55%
	Bui 50	0%	0%	0%
	Bui 100	0%	0%	0%
Biezen	Bui 8	45%	55%	55%
	Bui 50	0%	45%	55%
	Bui 100	0%	55%	55%
Stadscentrum	Bui 8	45%	55%	55%
	Bui 50	0%	35%	35%
	Bui 100	15%	55%	55%

The high sensitivity on the one hand implies that good assessment of doorstep heights, especially if doorsteps are low, is crucial for assessment of the number of flooded buildings due to pluvial flooding. On the other hand, it implies that the doorstep height is a variable that municipalities could use to manage the vulnerability of buildings to pluvial flooding.

To develop the scientific and applied knowledge required for

Climate-proofing the Netherlands and to create a sustainable

Knowledge infrastructure for managing climate change

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