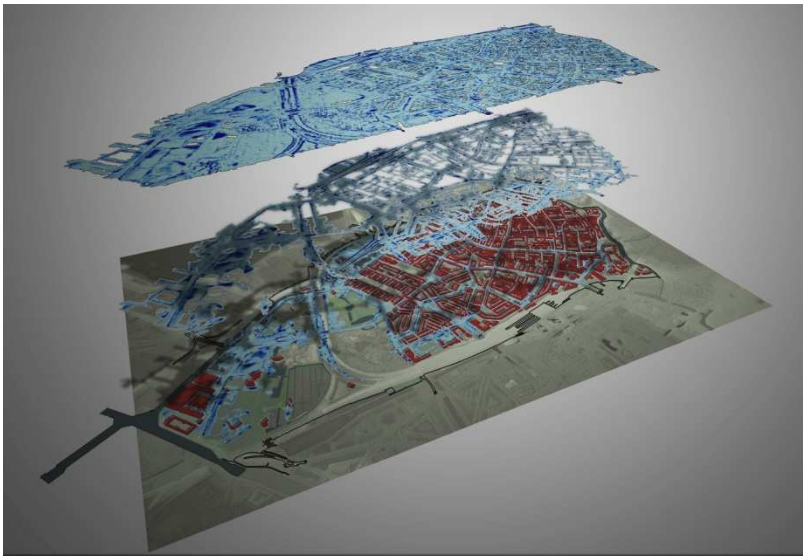
# Quantifying urban vulnerability to climate change

*Exploration of the suitability of the Adaptation Tipping Point Method for municipalities*



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# Preface

This master thesis report is the end result of my graduation project for the master programme Systems Engineering, Policy Analysis and Management at the faculty of Technology, Policy and Management at the Technical University Delft. The thesis is conducted at UNESCO-IHE and Deltares, within the context of Work Package 2.3 Sensitivity, Vulnerability and Impacts of the research programme Climate Proof Cities, which is part of the Knowledge for Climate Programme.

A large number of people contributed in direct and indirect way to the quality of this thesis:

First, I would like to thank Karin Stone and William Veerbeek, the external supervisors. They gave me the opportunity do this research about the important topic of climate change vulnerability in urban areas. William did not only support, inspire and supervise me and my work, he also did a great job with the application of the flood models, of which I could use the results in the application of the Adaptation Tipping Point method.

Second, I would like to thank the members of my graduation committee from TU Delft, professor Thissen, Bert Enserink and Ellen Jagtman. Throughout the project, they gave valuable and constructive feedback which strongly contributed to this thesis.

Third, I would like to thank Ton Verhoeven and Emile Willemse of municipality Nijmegen. They did not only facilitate the pre-testing of the ATP-method within Nijmegen, they also conducted field work in the city centre of Nijmegen to measure doorstep heights.

Fourth I would like to thank all the persons who I could interview. They gave me a good insight in how municipalities currently deal with vulnerability to climate change and the need for vulnerability assessment. Toine Vergroesen helped William and me by reflecting on the flood modelling in Rotterdam-Noord and sharing his model results in the same area. In addition, I would like to thank professor Daanen for coming to delft to have very enjoyable and informative meetings.

Fifth I would like to thank my colleagues at UNESCO-IHE, who gave me a nice working environment, help with the thesis and a lot of fun.

At last I would like to thank family and friends for the help with my thesis and the necessary distraction.

# 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 and vulnerability assessment help reducing the costs of the impacts of extreme weather events. At this moment, quantitative vulnerability assessment on municipal level is scarce. The objective of this thesis 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 thesis 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 with regard to the municipal need for vulnerability assessment, comprising criteria regarding policy relevance, feasibility and easiness of communication. Case study Rotterdam assessed flooding of residential and commercial buildings, as well as traffic nuisance on major roads. 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.

# Table of contents

# 1. Introduction

Urban areas are affected by climate change in a number of ways. An increase of the frequency and severity of extreme rainfall events causes increased vulnerability to pluvial floods. The association of Dutch insurers calculated that the insurance claims due to extreme rainfall events will increase with 6%-22% from 2010 to 2050 if no adaptation measures are taken (Ririassa and Hoen, 2010). Pluvial floods do not lead to structural collapse, injuries and casualties. However, if all relatively small damages are cumulated over time, the damage is similar to the damages due to a reasonably big fluvial flooding (Ten Veldhuis, 2010). More frequent and longer periods of drought cause damage to wooden foundation pillars, deterioration of urban vegetation and water quality problems (Van de Ven et al., 2010). A higher average rainfall increases the problems with groundwater floods. Finally, more frequent and longer heat waves lead to higher hospitalization and mortality, as well as a decreased productivity. Daanen et al. (2010) calculated that the current annual number of 36 premature deaths in Rotterdam could be doubled by 2050. These impacts are only a selection of the consequences of climate change. (Bosch Slabbers Landschapsarchitecten, 2010, Planbureau voor de Leefomgeving, 2011).

Increased vulnerability to climate change is not only caused by the changing climate itself. Socio-economic developments also contribute to increased vulnerability to climate change. Increasing urbanisation and growth of the population intensifies the possible effects if climate change over time (Planbureau voor de Leefomgeving, 2011).

Section 1.1 further elaborates on the motivation for this research. Section 1.2 describes research goal and research questions that are addressed in this thesis. Section 1.3 explains how the research questions are answered and section 1.4 finally presents the structure of the remainder of the thesis.

## 1.1 Motivation for research

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). This requires good insight into the causes and consequences of increased vulnerability, however.

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. The question is, which is the best method to help municipalities with the quantitative assessment of their vulnerability to climate change.

## 1.2 Research goal and research questions

The problem analysis in section 1.1 leads to the formulation of the following research objective and main research question:

**Research objective:**

> 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.

**Main research question:**

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

**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?

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?

## 1.3 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&3 |

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 (see 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 thesis describes in what ways Dutch urban areas are vulnerable to climate change.

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| 2. *What are the criteria and requirements of municipalities regarding the assessment of their vulnerability to climate change?* | Ch. 4 |

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. 5 |

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. 5 |

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.

| | |
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| 5. *What lessons can be drawn from application of the method in Rotterdam-Noord and Nijmegen?* | Ch. 6&7 |

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. 8 |

The final research question of this thesis has been answered on the basis of literature research, the outcomes of the case studies and in discussion with stakeholders of the case studies, researchers at TU Delft and UNESCO-IHE.

## 1.4 Structure of the report

Chapter two describes the definition of vulnerability that is applied in this thesis and explains two alternative interpretations of vulnerability: outcome vulnerability and contextual vulnerability. Chapter three describes in what ways urban areas are vulnerable to pluvial flooding, groundwater flooding, drought and heat stress. Chapter four addresses adaptation strategies in Dutch municipalities and their need for vulnerability assessment. Chapter five describes two promising methods for vulnerability assessment for contextual vulnerability and outcome vulnerability and explains the choice of a method for quantification of vulnerability of Dutch urban areas. Chapter six and seven describe the case studies that have been performed in Rotterdam-Noord and Nijmegen. Chapter 8 includes an analysis of the strengths, weaknesses, opportunities and threats of the chosen method. The conclusions and recommendations have been included in chapter nine and a reflection on the project has been included in chapter ten.

# 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 thesis, 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 thesis 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 thesis, 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 thesis 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 thesis, 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 thesis 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.

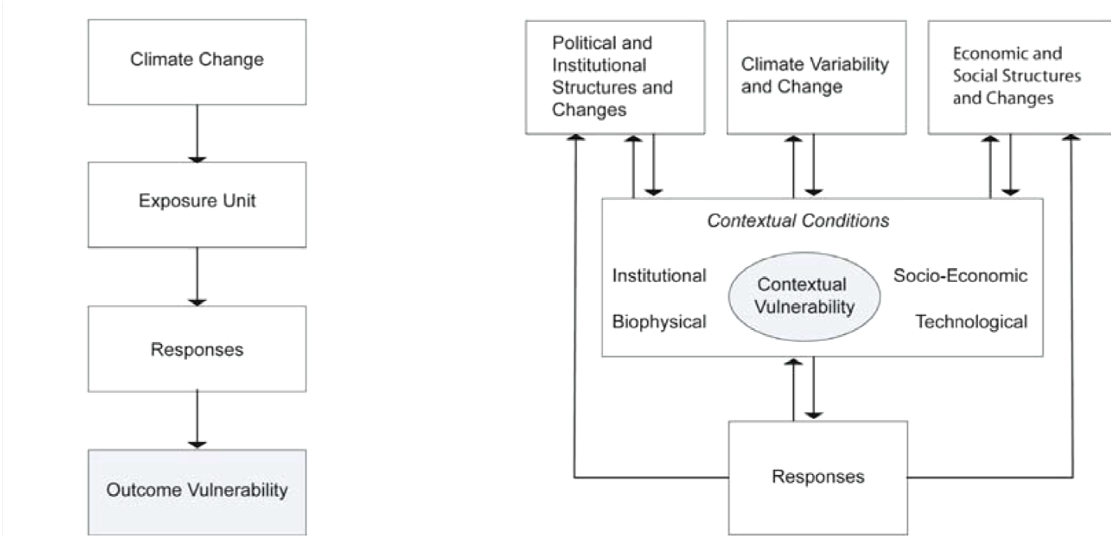


**Figure 1 Two interpretations of vulnerability to climate change. Left: Outcome vulnerability, Right: contextual vulnerability (O'Brien et al., 2007, p.75)**

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)*

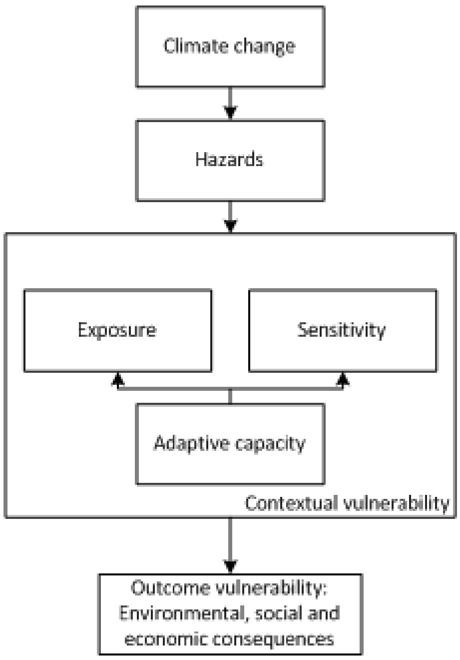


**Figure 2 Relations between vulnerability concepts (Fünfgeld and McEvoy, 2011, p.41). Terms contextual vulnerability and outcome vulnerability are added by the author.**

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.

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 pro-active 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. Indices (non-dimensional indicators that can be seen as relative measures of vulnerability) are not included, since they will be addressed in section 0.

### 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. By multiplying the impacts with the probabilities it can be calculated what the magnitude of the problem is that municipalities face. As long as impact models or estimates of future impacts are available, it is possible to calculate the mean annual impacts.

### 2.3.2 Graduality of impacts

The indicator of mean annual impact does not fully represent all dimensions of vulnerability. The indicator does not make any difference to events that happen with high frequency, but low impact and events that happen rarely, but have high impacts. These different type of hazards have different dynamics and require other types of adaptation policies, so the mean annual damages do not include all policy relevant dimensions of vulnerability. De Bruijn (2005) addresses this problem with an additional indicator. Graduality is a measure for discontinuities in the damages in relation to increasing flood depths. It compares the relative increase of discharge in percentages and the corresponding relative increase of damage. 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):

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

**$V_\alpha$ is the vulnerability indicator, $W_i$ is the well-being of individual i, $W_0$ 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 ($W_1$ is more vulnerable than $W_2$) 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 | $V_1 = \frac{1}{n}\left[\sum_{i=1}^{q}\left(W_0 - \frac{w_i}{W_0}\right)^1\right]$ | 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). $V_0$ only considers whether an individual is vulnerable. $V_1$ and $V_2$ also consider the deviation from the vulnerability threshold. The higher $\alpha$ is set, the more weight is put on the individuals that show large deviations from the vulnerability threshold $W_0$. 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.

# 3. Vulnerability to climate change

This chapter describes in what ways Dutch urban areas are vulnerable to pluvial flooding, groundwater flooding, drought and heat stress. For each of the themes it will first be explained what the effect of climate change is on the related hazards, such as extreme rainfall events and prolonged periods of drought and heat. Then it is described which are the most important impacts that relate to these extreme events. After that it is described which are the most important contextual factors for the vulnerability to the theme. Finally it is described what types of methods and data are available for modelling. Pluvial flooding is described in a more detailed way than the other themes, because this is the theme that will be addressed in the case studies.

## 3.1 Vulnerability to pluvial flooding

This section describes the effects of climate change on pluvial flooding in Dutch urban areas. Pluvial flooding is flooding that is caused by extreme rainfall events.

### 3.1.1 Effect of climate change on extreme rainfall events

The KNMI (the Royal Dutch Meteorological Institute) developed a set of climate change scenarios for The Netherlands in 2006 (van den Hurk et al., 2006). These climate change scenarios provide limited information about aspects of rainfall characteristics that are relevant for the occurrence of pluvial flooding. These characteristics have been further addressed in an extension to the KNMI climate change scenarios (Klein Tank and Lenderink, 2009). Table 3 describes the current rainfall extremes (measured in mm) and the projected rainfall extremes around 2050 for different return periods and climate scenarios. The increase in one-hour rainfall volumes is calculated only for the KNMI G and KNMI W (warm) scenarios. It can be seen that the projected increases in 1-hour rainfall volumes in 2050 amount to 7%-25%.

**Table 3 Expected precipitation for a 1, 10 and 100 year event under different climate scenarios for the year 2050 (Klein Tank and Lenderink, 2009, p.25).**

| | **1 hour** | | | | |
|---|---|---|---|---|---|
| **Return period** | **Current** | **G** | **G+** | **W** | **W+** |
| 1 year | 14 | 15 | - | 17 | - |
| 10 years | 27 | 30 | - | 33 | - |
| 100 years | 43 | 48 | - | 53 | - |

### 3.1.2 Impacts in relation to pluvial flooding

Figure 3 shows the results of a survey about pluvial flooding among Dutch municipalities (Oosterom, 2011). Here it can be seen that approximately 60% of the municipalities have problems with pluvial flooding on some locations in the form of wastewater on the streets and water in buildings. In almost half of the municipalities quiet streets get blocked. In 10% of the municipalities there are many places where wastewater ends up on streets. A small 10% of the municipalities have many locations where water enters buildings or where quiet roads are blocked. Blockage of busy roads in many places only happens in a few municipalities. Another observation from Figure 3 is that in most municipalities the problems regarding pluvial flooding are solved within one hour. Only few municipalities have problems that take more than six hours. From the figure it can therefore be concluded that many municipalities have problems regarding pluvial flooding, although these problems mostly occur on only a limited number of locations and the duration of the problems is mostly shorter than 5 hours. As a result, most municipalities do not consider the current amount of pluvial flooding as a very pressing problem.

This can also be seen in the interviews that have been conducted in the context of this thesis. Arnhem, Nijmegen, Rotterdam, Amsterdam Nieuw-West, Amsterdam Watergraafsmeer and Den Haag have not experienced a lot of pluvial flooding lately, unless on a number of known locations.

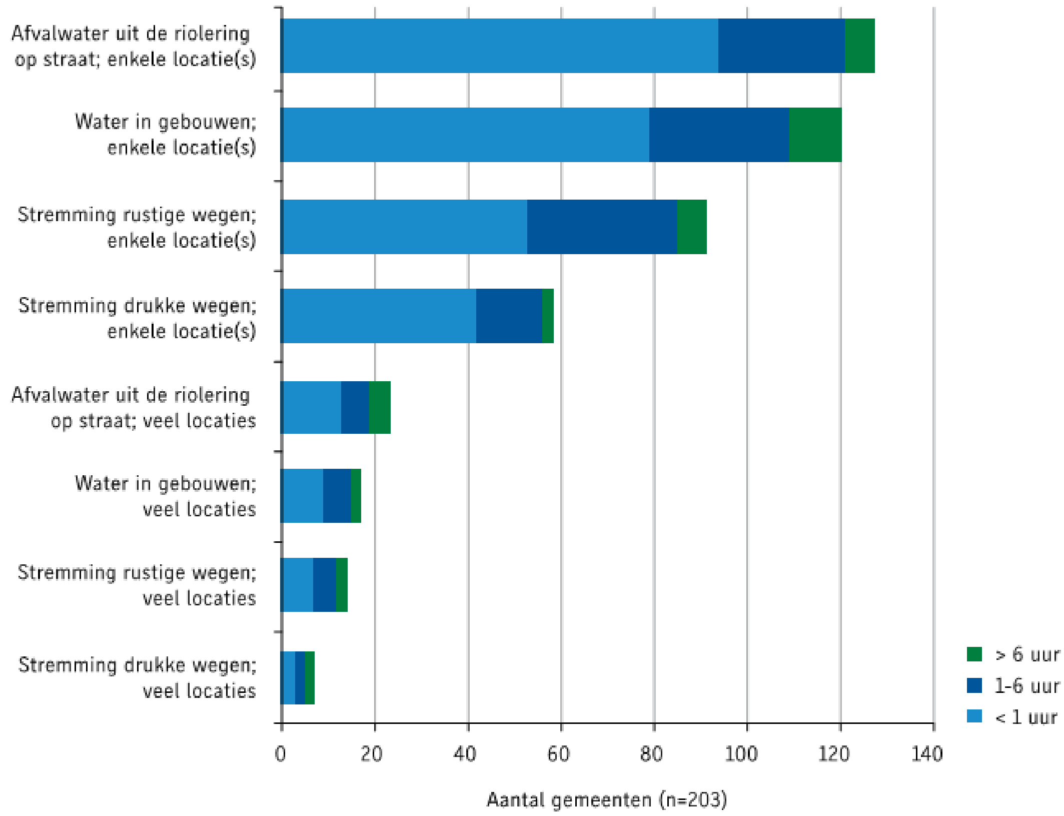


**Figure 3 Pluvial flooding according to type, size and duration (Oosterom, 2011, p.99)**

Table 4 summarises the impacts of traffic nuisance, flooded buildings and wastewater on the streets. This list can be considered as an overview of the most prominent consequences of pluvial flooding. In the interviews with representatives of Dutch municipalities, traffic nuisance and flooded buildings have been indicated as most 'important' impacts, along with health impacts, but the extent to which this occurs is not known.

**Table 4 Impacts of pluvial flooding on urban areas (e.g. van Riel, 2011, Van de Ven et al., 2010 and interviews)**

| Impact categories | Direct effects | | Indirect effects | |
|---|---|---|---|---|
| | **Tangible** | **Intangible** | **Tangible** | **Intangible** |
| Traffic nuisance | | -Number of affected people<br>-Inconvenience<br>-Extra travel time<br>-Roads flooded | -Total economic damage due to reduced accessibility of areas | -Emergency services are hindered |
| Flooded residential buildings | -Total costs of cleaning and reparation | -Total number of people who experience inconvenience | | |
| Flooded commercial buildings | -Total costs of cleaning and reparation | | -Total loss of turnover | -Water enters the first floor |
| Wastewater on street | | -Number of people exposed to health risks | -Increased health care costs | |

### 3.1.3 Quantification of pluvial flooding and its impacts

In order to quantify outcome vulnerability to pluvial flooding, it is necessary first to model floods themselves in relation to climate change, and on the basis of these results it is possible to quantify the effects of climate change on the impacts and damages of pluvial flooding. In the context of pluvial flooding, the first step is to apply flood models. After this has been done, it is possible to use methods for impact and damage assessment.

Table 5 shows multiple types of methods that can be applied for flood modelling, ranging from simple methods that can be applied at all times and require no or little data to highly complex methods with high data requirements. At this moment, most municipalities apply sewer models only for their entire territories. Overland flow models are not yet applied on municipal scale, but sometimes they are applied in the context of research projects and/or at problem locations (e.g. Rotterdam, Amsterdam Watergraafsmeer and Nijmegen). Analysis methods for land elevation (e.g. WOLK, developed by TAUW, 2010) are sometimes applied on municipal scale, but they do not take into account rainfall events. They only involve the direction of water flows and depressions in the land surface. Integrated coupled sewerage and 2D overland flow models are the most complex models. These models are very resource and labour intensive and can at this stage only be applied on small scale.

**Table 5 Methods for quantities assessment (Vergroesen and Brolsma, 2011)**

| | **Data requirements** | **Application** |
|---|---|---|
| | Little | Always |
| General knowledge | ↓ | ↑ |
| Knowledge of area and experience | | |
| Standard numbers | | |
| Models 1st order (e.g. water balances, analysis of surface elevation) | | |
| Models 2nd order (e.g. sewer models, surface water models, 2D overland flow models, groundwater models) | | |
| Integrated, coupled flow models | Many | Seldom |

If floods are modelled it is possible to estimate the impacts in terms of, for example, its ecological, economic and social damage. A common way of damage estimation in flood management is the use of stage-damage curves. Stage damage curves relate inundation depths to the costs suffered for cleaning, reparation and replacement of assets. There are no separate stage damage curves for different types of floods. Pluvial and fluvial floods differ from each other in terms of the flood duration and the flood depths. Pluvial flooding lasts shorter and the flood depths are lower, which makes damage estimation much more difficult. Because of this it is questionable what is the validity of the estimated damage costs. Ten Veldhuis (2010) argued that stage-damage functions are not suitable for estimating damages due to pluvial flooding. However, it is a field of research in which there is a lot of development (Stone et al., 2011).

Another limitation to the estimation of the impacts of pluvial flooding is the lack of empirical data. All interviewed municipalities have general systems for registering complaints regarding damage and nuisance. Municipalities might also call other parties, such as the fire station or the general alarm number. Analysis of calls is complicated since not all residents call the municipality with their complaints and the actual causes of the complaints are often not included, which makes analysis difficult. Despite these difficulties, Ten Veldhuis (2010) succeeded in using municipal call registers for a quantitative risk assessment of pluvial flooding. Insurance companies can be used as source of empirical data as well (e.g. Ririassa and Hoen, 2010, Spekkers, 2011). Research still has to be performed to make it feasible for municipalities to estimate the amount of damage due to pluvial flooding and the increase of damages due to climate change.

### 3.1.4 Factors for contextual vulnerability

This subsection addresses the factors that describe contextual vulnerability to pluvial flooding: exposure, sensitivity and adaptive capacity. These factors can be used for the development of a vulnerability index. Not all factors that are described in this subsection will be part of the case studies.

Factors that determine the exposure of an urban area to *extreme rainfall events* depend on the amount and intensity of extreme rainfall events in this specific area. These events do not vary on the local scale of a municipality. However, there are differences between regions in the Netherlands. Coastal regions are exposed to more extreme rainfall events than inland regions. (Klein Tank and Lenderink, 2009).

The factors that determine the exposure to *pluvial flooding* are largely related to the capacity of an area to store, retain and discharge rainwater, which varies from location to location. Major factors for exposure to pluvial flooding in Dutch urban areas are sewer capacity and the capacity of other urban drainage facilities, as well as the ratio of paved areas versus green areas and open water (Zevenbergen et al., 2008).

The sensitivity of Dutch urban areas to *extreme rainfall events* is determined by the number and type of assets. The most important urban assets are buildings, people and roads/traffic. Other assets-at-risk are power houses and open water bodies that receive water from mixed sewer overflows.

The adaptive capacity of Dutch urban areas with regard to municipalities is determined by factors such as the availability of municipal financial resources, the municipality's possibilities of influence behaviour and decisions of other stakeholders, the availability of feasible adaptation options and the frequency and extent of expected spatial reconstructions in existing areas.

Table 6 shows examples of factors for contextual vulnerability to pluvial flooding of buildings.

**Table 6 Examples of factors for contextual vulnerability of urban geographical areas to pluvial flooding within municipalities with a focus on pluvial flooding of buildings**

| Exposure | Sensitivity | Adaptive capacity |
|---|---|---|
| Capacity of urban drainage system<br>- Sewerage system<br>- Infiltration facilities<br>Ratio paved area, half-paved area, green areas and open water. | Number and types of residential buildings<br>- Doorstep height<br>- Presence of inventory below street level<br>Number and types of commercial buildings<br>- Doorstep height<br>- Street profile<br>- Daily turnover<br><br>Number and importance of roads<br><br>Amount of people<br><br>Economic production in area | - Available municipal resources<br>- Number of feasible adaptation options (e.g. building density of area, number of parcel owners)<br>- Frequency and extent of adaptation mainstreaming opportunities for spatial reconstructions in existing areas<br>- Building density |

## 3.2 Groundwater flooding

Groundwater flooding is related to high groundwater levels. A commonly used definition of groundwater nuisance is: "a situation in which the use function of a parcel is harmed because of a drainage depth that is structurally too low" (KPMG and Grontmij, 2001, p. 16). It thus refers to situations in which the problems occur regularly and/or over a prolonged time period. In comparison with pluvial flooding, the processes that lead to groundwater flooding take place on a longer time scale and have a larger spatial scale.

### 3.2.1 Effect of climate change on groundwater flooding

Climate change will affect nuisance from groundwater in the following ways (Van de Ven et al., 2010):

- Increasing precipitation will lead to higher groundwater tables and an increase in the amount of areas in need of artificial drainage.
- Increasing periods of high water levels in rivers will increase the groundwater level in a number of areas in cities along rivers.
- Periods of drought will increase the amount of land subsidence, which in turn (on the long term) will increase the problems regarding groundwater flooding.

The groundwater level also strongly depends on other factors, such as temporary drainage for construction works, sheet piles and changes in surface water levels (Van de Ven et al., 2010).

### 3.2.2 Impacts in relation to groundwater flooding

In The Netherlands, the most important impacts of high groundwater levels relate to water and moisture in or around buildings and infrastructure and to the quality of ecology (Van de Ven et al., 2010). In 2001 it was estimated that approximately 260.000 residential buildings suffered from groundwater flooding (KPMG and Grontmij, 2001). Table 7 describes the most important impacts that relate to groundwater flooding.

**Table 7 hazards related to groundwater flooding (Van de Ven et al., 2010)**

| Affected stakeholder | Asset | Impact |
|---|---|---|
| Municipality | Public vegetation, mainly trees | Suffocation/damage to vegetation |
| Municipality | Public infrastructure | Damage/reduced life time |
| Municipality and private house owners | Buildings/houses | Moisture in houses, Health, Damp, Fungus, Stench |
| Municipalities and private owners | Parks and gardens | Nuisance due to high groundwater table in parks and gardens. |
| General | General | Reduced infiltration, higher chance of pluvial floods, due to land subsidence |
| Road managers (municipality, province) | roads | Damage to roads in periods of frost. |

Since the problems regarding groundwater flooding in residential buildings is considered as the most important impact by municipalities, as became clear during the interviews, the remainder of this section will address this problem only. In addition, this is the theme about which most information on impacts is available according to Stone et al. (2011). Table 8 shows examples of impacts of groundwater flooding in relation to residential buildings.

**Table 8 Groundwater flooding in buildings: potential indicators for outcome vulnerability**

| Impact categories | Direct effects | | Indirect effects | |
|---|---|---|---|---|
| | **Tangible** | **Intangible** | **Tangible** | **Intangible** |
| Groundwater flooding in buildings | Costs for making buildings insensitive (not responsibility of municipality)<br>Costs for spatial measures | Health problems inhabitants | Loss of property values<br>Economic costs of health problems inhabitants | Reduced liveability and attractiveness of area |

### 3.2.3 Contextual vulnerability to groundwater flooding

The exposure to groundwater flooding is determined by factors that affect the extent of groundwater fluctuations in urban areas. Van de Ven et al. (2010) state that these factors include soil characteristics, the groundwater flow system, the interaction of groundwater with surface water and the type of land use(i.e. paved versus unpaved).

A commonly used indicator for the sensitivity of areas to groundwater floods is the difference between the groundwater level and the surface level (SBR, 2007). The dynamics of the groundwater table depend on the type of area. In drainage-dependent areas, the chance that the drainage depth is insufficient is high, while this chance is low in areas that are independent of drainage. Table 9 shows criteria for drainage depth for some urban functions.

**Table 9 Criteria for drainage depth (SBR, 2007, p.7-8)**

| Urban function | Required minimal drainage depth (m below surface) |
|---|---|
| Main roads | 1,00 |
| Secondary roads | 0,70 |
| Gardens, parks and sports areas | 0,50 |
| Buildings (with crawl space) | 0,70* |
| Buildings (without crawl space) | 0,50* |

Regarding sensitivities of buildings it can be said that houses that were built before the '60s are most sensitive to groundwater levels and houses that were built between the '60s and the '90s are moderately vulnerable (Van de Ven et al., 2010). Houses that were built before the 60s have wooden ground floors and crawl spaces, which are not water proof. Houses that were built between the 60s and the 90s have concrete ground floors, but these are often not built in a water proof way. Van de Ven et al. (2010) used the following table to assess the contextual vulnerability of assets to groundwater flooding.

**Table 10 (contextual) vulnerability factors for assessing groundwater nuisance (Van de Ven et al., 2010).**

| Urban function | Drainage dependent areas | Intermediate areas | Drainage independent areas |
|---|---|---|---|
| City parks | strong | substantial | limited |
| Roads | substantial | substantial | limited |
| Buildings before '60 | strong | substantial | limited |
| Buildings from '60 to ' 90 | substantial | substantial | limited |
| Buildings after '90 | limited | limited | limited |

Table 11 summarises potential indicators for contextual vulnerability to moisture in houses.

**Table 11 Moisture in houses: potential indicators for contextual vulnerability**

| Exposure | Sensitivity | Adaptive capacity |
|---|---|---|
| - soil characteristics<br>- distance between drainage facilities and/or open water<br>- Type of groundwater regime: drainage-dependent, intermediate or drainage-independent<br>- Distance to open water bodies with fluctuating water levels<br>- Type of land use(i.e. paved versus unpaved). | Difference between mean groundwater level and bottom of buildings.<br><br>Sensitivity of buildings<br>- Age of buildings | - Building density<br>- Frequency of spatial reconstructions<br>- Measures at building level (not responsibility of municipality) |

### 3.2.4 Modelling and data

In order to assess the outcome vulnerability to groundwater flooding, it is necessary to have models that predict the groundwater levels and fluctuations. If data is available on the characteristics of houses that make them vulnerable to groundwater flooding, it is possible to indicate which houses are affected by pluvial flooding. It then is possible to count the number of affected buildings in an area. Assessment of the damage is the next step. Stone et al. (2011) concluded on the basis of literature research that no methods have yet been developed for quantification of damages due to groundwater flooding. The methodology of stage damage curves, that is developed for pluvial flooding, could be adapted to groundwater flooding (Stone et al., 2011). Information about basements and building materials on the basis of manual research or classifications would then be required (Stone et al., 2011).

Groundwater models require groundwater monitoring networks to validate them on the basis of groundwater level measurements within an area. Results of an inventory of groundwater monitoring networks (ten Bras et al., 2006) showed that:

- 40% of the municipalities have a monitoring network
- 20% do not have a monitoring network
- 40% did not respond.

For damage assessment of groundwater flooding, no methods are yet available (Stone et al., 2011)

## 3.3 Drought

Multiple definitions of drought exist. In this thesis, the definition of groundwater nuisance ("a situation in which the use function of a parcel is harmed because of a drainage depth that is structurally too low" (KPMG and Grontmij, 2001, p. 16)) is freely translated to drought: "a situation in which the use function of a parcel is harmed because of a groundwater level that is structurally too low".

### 3.3.1 Effect of climate change on drought

Drought can be caused by a number of different factors (Stone et al., 2011, Van de Ven et al., 2010):

- Low amount of rainfall, leading to temporary low groundwater tables
- A precipitation deficit (the amount of rain cannot compensate for the dry periods in the summer), leading to permanently lower ground water levels.
- Low river discharge
- Suboptimal distribution of water

Since the processes causing drought are different, the effects of climate change will be different as well. It is beyond the scope of this thesis to elaborate extensively on the effect of climate change on the different processes specifically, but in general it can be said that drought will increase under all climate change scenarios that have been calculated by the Royal Dutch Meteorological Institute (KNMI). For example, the return-period of the precipitation deficit of 2003 will decrease from 9,7 years in the current situation to 2,0 years in 2050 under the most extreme scenario W+ (KNMI, 2012b), and the river discharges of the Rhine and Meuse can decrease considerably (KNMI, 2012a).

### 3.3.2 Impacts in relation to drought

Table 12 summarises some impacts of drought. Major impacts are: damage to wooden foundation pillars due to soft-rot decay, land subsidence, damage to vegetation and water quality problems (Stone et al., 2011).

**Table 12 Selection of stakeholders and impacts of drought (selected from Van de Ven et al., 2010)**

| Affected stakeholder | Asset | Impact |
|---|---|---|
| Municipality, private owners | Historical buildings | Damage to wooden foundation pillars |
| Municipality, private owners | Historical buildings, Roads, Underground infrastructure | Damage of buildings, pavement and underground infrastructure due to variable land subsidence |
| Municipality /water board | All assets | Increased flood risk due to extra land subsidence |
| Province/water board | Swimming water, surface water | Pollution of surface and swimming water |
| Municipality, inhabitants | People | Increased illness and mortality due to high amount of surface and airborne particles |
| Municipalities and private owners | Vegetation, parks, gardens | Loss of urban vegetation (soil moisture/salinization) |
| Companies | industrial and electricity companies | Extra costs because of shortage of cooling water |

As an example, the remainder of this section addresses vulnerability of wooden foundation pillars to drought. Table 13 describes the type of impacts that drought has on buildings with wooden foundation pillars, only involving the costs for repairs, which can be considerable.

**Table 13 Damage to wooden foundation pillars: potential indicators for outcome vulnerability**

| Impact categories | Direct effects | | Indirect effects | |
|---|---|---|---|---|
| | Tangible | Intangible | Tangible | Intangible |
| Damage to wooden foundation pillars | - Costs for repair | - | - | |

### 3.3.3 Contextual vulnerability to drought

The exposure to drought in relation to buildings with wooden foundation pillars is similar to the exposure to groundwater flooding, since damage is caused by groundwater fluctuations as well.

Buildings in peat and clay areas are especially sensitive to drought, because these are the areas which are prone to land subsidence and which contain sensitive buildings with wooden foundation pillars (Van de Ven et al., 2010).

The adaptive capacity in relation to vulnerability because of damage due to wooden foundation pillars is largely determined by the question of who is responsible for the required repairs, the costs of which amount to €40.000 to €200.000 per building (Stichting Platform Fundering Nederland, 2005, in Stone et al., 2011).

Table 14 describes potential indicators for contextual vulnerability.

Van De Ven et al. (2010) performed a rough contextual vulnerability assessment of urban areas on national scale about their vulnerability with regard to damage to wooden foundation pillars. This simple analysis considered locations that are prone to land subsidence and where the average age of the buildings is older than 50 year (construction before 1960) as vulnerable. On a more local scale, this analysis could have resulted in more detailed results.

**Table 14 Damage to wooden foundation pillars: potential indicators for contextual vulnerability**

| Hazard | Exposure | Sensitivity | Adaptive capacity |
|---|---|---|---|
| Damage to wooden foundation pillars | - soil characteristics<br>- distance between drainage facilities and/or open water<br>- Type of groundwater regime: drainage-dependent, intermediate or drainage-independent<br>- Distance to open water bodies with fluctuating water levels<br>- Type of land use (i.e. paved versus unpaved). | - Presence of buildings with wooden foundation pillars | - Depends on liability: availability of financial resources of municipality or owner of building. |

### 3.3.4 Modelling and data

Impacts of drought depend on the expected declines and variations of the ground water level under different climate scenarios. In order to estimate the future damage to wooden foundation pillars it is necessary to monitor and possibly model groundwater levels. Modelling methods for groundwater levels are available. No scenario calculations of groundwater dynamics on national scale are available to date (Van de Ven et al., 2010), so municipalities need to perform them by themselves.

Impact and damage assessment of damages due to drought are only poorly developed. For damage to wooden foundation pillars some implicit rules of thumb are available, as well as estimates of costs for reparation. Land subsidence is rarely monitored and ecological damage is difficult to assess and not monitored as well (Stone et al., 2011).

## 3.4 Heat stress

The last problem that is included in this thesis relates to high temperature in urban areas. Temperatures and the occurrence of heat waves increase because of climate change. Because of the urban heat island effect, temperatures within urban areas are higher than the temperatures in rural areas, which is illustrated in Figure 4 and briefly described in subsection 3.4.3. During the heat wave in 2003, between 1400 and 2200 people died because of the heat and related air pollution in The Netherlands (Salcedo Rahola et al., 2009). Apart from increased mortality, heat leads to an increase of morbidity (hospitalisation) and a decrease of personal comfort and well-being. Heat stress can be caused outside building and inside buildings. Municipalities can affect the local outside temperature in neighbourhoods by decreasing the urban heat island effect through measures such as the creation of green areas and open water.

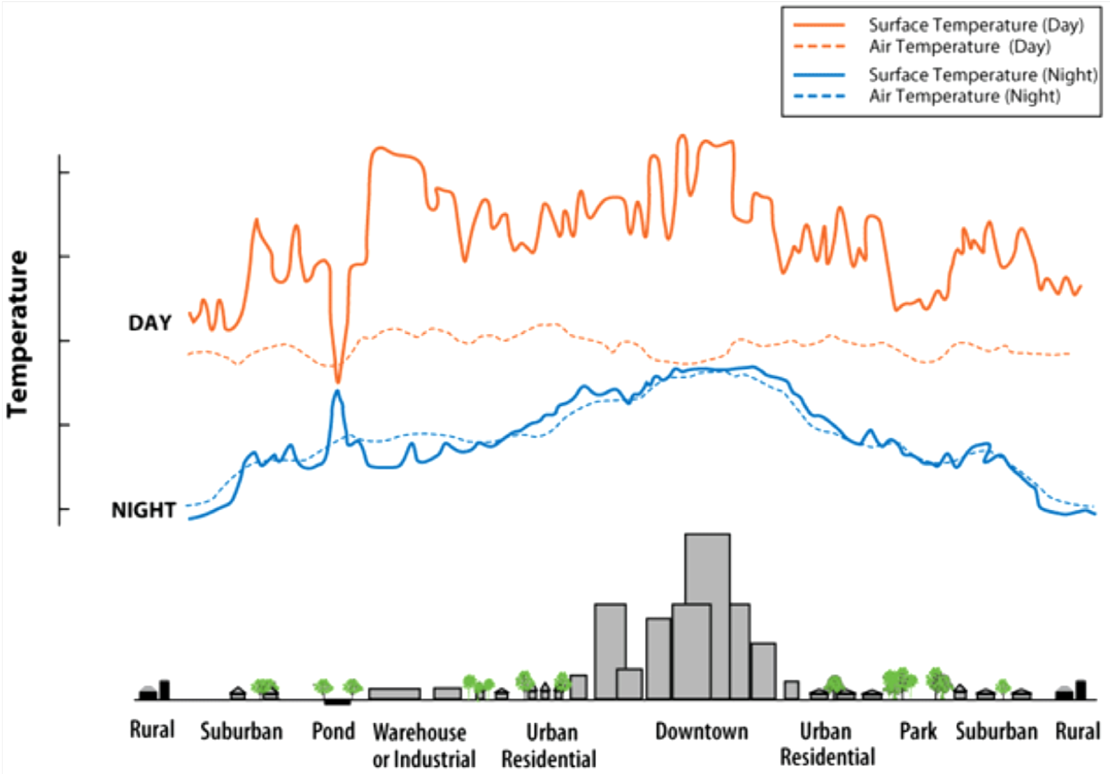


Figure 4 Urban Heat Island effect (EPA, 2012, p.4)

### 3.4.1 Effect of climate change on heat

As a result of climate change, the number of tropical days will increase in The Netherlands. Table 15 shows the increase of tropical days (with a maximum temperature of 30$^0$C or more) in different measurement stations in the Netherlands. It can be seen that the increase in tropical days under the W+ climate scenario could amount up to 6 days.

Table 15 Mean number of tropical days per year in the reference period 1976-2005 and an indication of the number of days in the four KNMI Climate Scenarios around 2020, on the basis of transformed time series (KNMI, 2012c).

| Tropical days (max. temperature >=30°C) | 1976-2005 | G 2020 | G+ 2020 | W 2020 | W+ 2020 |
|---|---|---|---|---|---|
| De Kooy | 1 | 1 | 1 | 1 | 2 |
| De Bilt | 4 | 5 | 6 | 7 | 9 |
| Eelde | 4 | 4 | 5 | 6 | 8 |
| Vlissingen | 1 | 2 | 2 | 2 | 4 |
| Eindhoven | 5 | 7 | 8 | 8 | 11 |
| Maastricht | 5 | 7 | 8 | 8 | 11 |

### 3.4.2 Impact with regard to heat stress

The interviews that have been performed in the context of this thesis showed that municipalities are mostly interested in the effects of heat on human health and thermal comfort (Stone et al., 2011). Table 16 shows a selection of the impacts of heat on different assets. Both the indoor and outdoor temperatures contribute to increased impacts.

**Table 16 Most important heat-related impacts (based on Stone et al., 2011, Salcedo Rahola et al., 2009)**

| Affected stakeholder | Asset | Impact |
|---|---|---|
| People | people | Higher mortality, hospitalization and sleeping problems, more aggression |
| Workers | people | Less productivity and concentration |
| Building owners | buildings | Material degradation |
| Municipality/province | Roads, rail, bridges | Top layer melting, rail buckling, top layer expansion |
| Province | people | Increase in pathogenic micro-organisms in recreational water |
| Drinking water companies | people | Increased amount of bacteria and other microorganisms in drinking water |

Table 17 shows indicators for outcome vulnerability with regard to increased mortality due to heat stress. The direct effect is measurable in terms of the increase in mortality, while the most important indirect effect can be (theoretically) measured in terms of the economic losses due to the increased mortality. Quantification of other impacts of urban heat is more difficult due to the lack of methods and data (Stone et al., 2011).

**Table 17 Increased mortality: potential indicators for outcome vulnerability**

| Impact categories | Direct effects | | Indirect effects | |
|---|---|---|---|---|
| | Tangible | Intangible | Tangible | Intangible |
| Increased mortality | - | - Increased mortality | - Economic losses due to increased mortality | |

### 3.4.3 Contextual vulnerability

The exposure of elements within urban areas is determined by the outdoor and indoor temperature. Indoor temperatures fall within the responsibility of the owners of buildings. The outdoor temperature depends on the amount of urban heat island effect (UHI). This effect is caused by (Stone et al., 2011, Salcedo Rahola et al., 2009, Döpp, 2011):

- Higher absorption of solar radiation by paved surfaces in the city compared to vegetation, unpaved soil and water.
- Reduced cooling through evapotranspiration, caused by the presence of less vegetation and surface water in cities
- Reduced cooling through wind, caused by barriers such as buildings
- Increased heating of the city through anthropogenic heat sources such as buildings and traffic.

The sensitivity of areas is determined on the one hand by the number of sensitive elements and on the other hand by the individual sensitivity of these elements. Not all persons are equally sensitive to the effects of high temperatures. Risk groups of heat stress are (Salcedo Rahola et al., 2009):

- People who are unaware of risks regarding extreme heat
- People who cannot leave a very hot place

- Babies, young children, ill and elderly people
- People with cardiovascular diseases and people who are subject to the additional risks of heart failure.

The (municipal) adaptive capacity comprises the capacity to take structural measures in the urban environment, measures within buildings as well as behavioural measures and communication (Döpp, 2011). Table 18 shows a number of potential indicators for contextual vulnerability in relation to increased mortality due to the urban heat island effect.

**Table 18 Increased mortality: potential indicators for contextual vulnerability**

| Hazard | Exposure | Sensitivity | Adaptive capacity |
|---|---|---|---|
| Increased mortality due to UHI-effect | - Extent of UHI | - Number of people living and working in an area<br>- % of risk groups, living and working in area | - Building density<br>- Frequency of spatial reconstructions<br>- Measures at building level (not responsibility of municipality) |

### 3.4.4 Models and data

Several cities developed heat maps, indicating relatively warm and cold areas (Döpp, 2011). Urban Climate Analysis maps provide insight into the distribution of heat within an area. Urban Climate Recommendation maps also suggest spatial measures that can reduce the effect of the urban heat island effect (Chao et al., 2010). These maps can be used as vulnerability assessment (Lindley et al., 2006) A number of Dutch municipalities have developed heat maps of their areas, such as Rotterdam, The Hague, Arnhem and Nijmegen (Döpp, 2011).

On the basis of these maps it is possible to assess the contextual vulnerability of different areas to heat stress. The assessment tool that has been developed in the context of the GRaBS project (GRaBS, 2012) combines heat maps with an index based on social neighbourhood characteristics. In this way not only the structural factors that determine the vulnerability of an area to heat are assessed, but also the socio-economic factors.

These tools cannot be used for calculating the effect of heat on human health, since they do not provide quantitative insight into the increase of the temperature because of the UHI-effect. Modelling of temperatures within cities is difficult. It requires a comparison of many spatial characteristics with climatic data. At this moment, no generally accepted method is available for doing this (Döpp, 2011).

In addition, creating functions for prediction of mortality on the basis of temperatures is virtually impossible, due to a large number of interrelated factors that determine mortality and the lack of data on appropriate scales. For example, the impacts of heat on people's health are to large extent affected by factors such as the length of a heat wave and the specific features of the urban area, as well as physiological and behavioural factors (Stone et al., 2011). Within the Knowledge for Climate programme, first attempts are made to model the impact of heat on national and regional level. Possibly these attempts can be translated to smaller scales.

With regard to human comfort, infrastructure and water systems, even more difficulties arise when quantifying the effect of high temperatures, due to the lack of methods and data (Stone et al., 2011).

## 3.5 Conclusions

This chapter provided an overview of the effect of climate change on pluvial flooding, groundwater flooding drought, and heat stress. The following conclusions can be drawn:

It is confirmed that climate change will increase the occurrence of pluvial flooding, groundwater flooding, drought and heat stress. it is useful for the method to address all of the four themes.

There are important differences between the themes:

- Pluvial flooding occurs in a matter of hours, while groundwater flooding, drought and heat stress occur in the order of days or longer. This can have consequences for the type of measures that can be taken. For example, if the impacts are caused in a very short period of time, it is most appropriate to focus on prevention of impacts and recovery after the impacts. If the impact is caused over a long period of time more focus could be placed on coping.
- The spatial distribution of impacts is different as well. Pluvial flooding occurs mainly locally on the level of parts of streets or in worse cases on a number of streets, while groundwater-related impacts and (outdoor) heat stress occur on the higher geographic scales mostly.

Developing one method for assessment of contextual vulnerability to all of the themes is difficult. Apart from the arguments that have been mentioned above, the variety of actors and objects that are harmed during the different extreme events is large. The factors that make these actors and objects vulnerable vary per theme, over time and per location. The indicators for contextual vulnerability to the different themes show that many of the factors are theme-specific, especially regarding the exposure and sensitivity. The adaptive capacity of areas with regard to physical measures that municipalities can take is relatively similar for the different themes.

The impacts of the extreme weather events that cause pluvial flooding, groundwater flooding, drought and heat stress comprise negative economic, ecological and social effects as well as effects on human health. Direct objective comparison of outcome vulnerability thus requires conversion of these different types of effects into one common quantity.

# 4. Municipalities and need for vulnerability assessment

Chapter three described in what ways Dutch urban areas are vulnerable to climate change and what kind of indicators can be used to quantify them. This chapter describes how municipalities deal with the assessment of their vulnerability and how municipalities formulate their adaptation policies. 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 in the field of general adaptation, urban water management and heat stress. Appendix 2 contains the names and positions of all interviewees.

This chapter starts with describing the general goals and responsibilities of municipalities and other stakeholders in section 4.1, followed by a description of municipal responsibilities, policies, norms and current vulnerability assessments and monitoring regarding pluvial flooding in section 0. Groundwater flooding, drought and heat stress are addressed in sections 4.3, 4.4 and 4.5. After that it will be explained what problems municipalities have regarding the assessment of their vulnerability and realising adaptation policies in section 4.6 on the basis of conducted interviews. This leads to the formulation of criteria for the choice of the method. Additional criteria for the choice are described in section 4.7. The conclusions of this chapter are included in section 4.8

## 4.1 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.

## 4.2 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.

### 4.2.1 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).

### 4.2.2 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 19 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 takes measures to increase the amount of open water.

**Table 19 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.

### 4.2.3 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 handle rainfall events with a return period of 100 years (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 20 shows the norms that are commonly used within The Netherlands for pluvial flooding.

**Table 20 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, Runoff 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** | Storage in sewerage system and discharge | Extreme rainfall events, (less) storage in |

| | | |
|---|---|---|
| **normal circumstances** | capacity towards overflows | 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 21 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 21 Difference between inconvenience and nuisance (Stichting RIONED, 2006)**

| Type of pluvial flooding | Description |
|---|---|
| **Inconvenience** | Limited quantities of water on the street.<br>Duration: 15-30 min<br>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,<br>Duration: 30-120 min<br>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.<br>Duration: 120 min and more<br>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.

### 4.2.4 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). A model calculation is performed to see whether the capacity of the sewerage system is sufficient to deal with a rainfall event of once in two years (Bui 8). This way of assessment is suitable only for relatively average situations. The behaviour and consequences of water on the streets are not addressed, while these effects cannot be ignored for more extreme rainfall events (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).

## 4.3 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).

## 4.4 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 development (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.

## 4.5 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).

## 4.6 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.

### 4.6.1 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.

### 4.6.2 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.

### 4.6.3 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.

### 4.6.4 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.

### 4.6.5 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.

### 4.6.6 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.

### 4.6.7 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).

## 4.7 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 listed in section 4.6. 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.

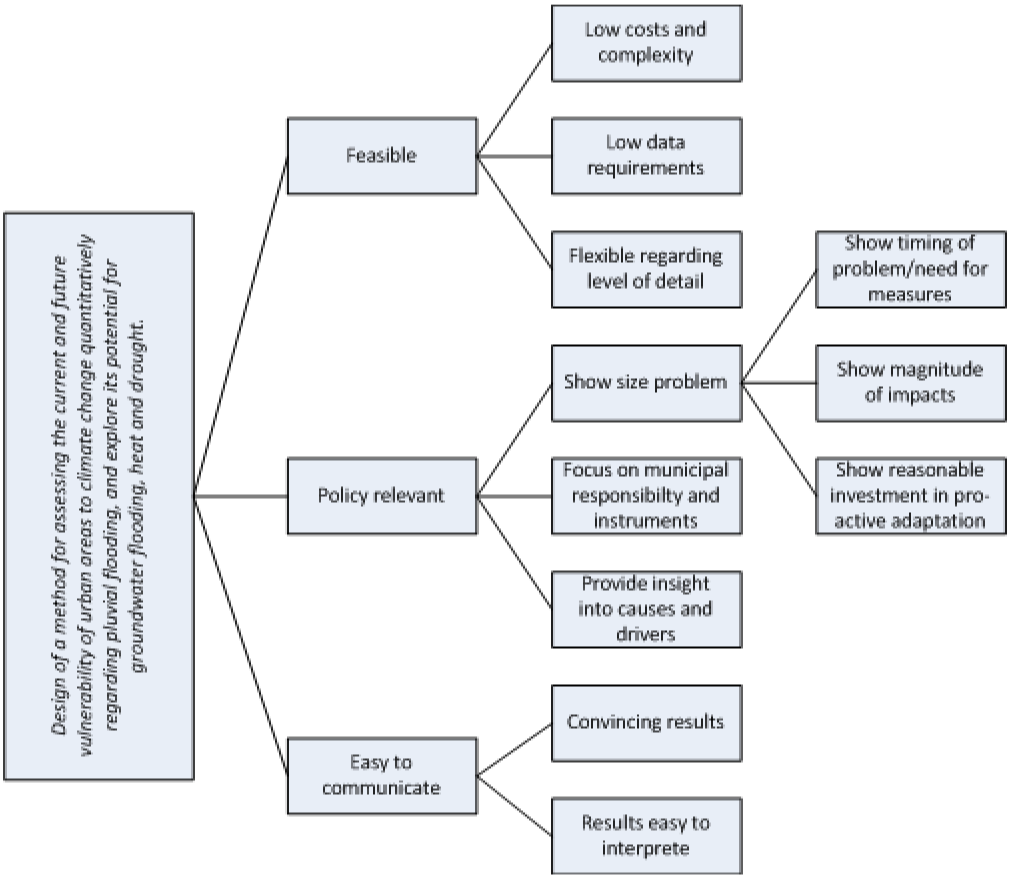


**Figure 5 Design criteria**

## 4.8 Conclusions

This chapter describes the way in which municipalities currently deal 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 thesis.

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.

# 5. Vulnerability assessment methods

The number of methods that can be used for vulnerability assessment over the years is very large. An overview of many tools can be found on: weadapt.org (WeADAPT, 2012). One method is selected that assesses contextual vulnerability and one method has been preselected that assesses outcome vulnerability. These two methods will be further explained in section 0 and 5.3 and evaluated on the basis of the requirements of the municipalities in section 0.

## 5.1 Pre-selection of methods

In order to select the basis of the method for vulnerability assessment two methods have been pre-selected for further analysis. Subsection 5.1.1 addresses methods for contextual vulnerability. Subsection 5.1.2 addresses methods for outcome vulnerability. A reflection on this selection is included section 10.3.

### 5.1.1 Pre-selection of method for contextual vulnerability assessment

There are plenty of methods for assessment of contextual vulnerability. There are two main categories of methods for contextual vulnerability assessment: vulnerability indices and vulnerability profiles. The main difference between the two is that vulnerability indices aggregate their underlying vulnerability indicators, whereas vulnerability profiles do not aggregate their underlying indicators. Combinations of the two are possible as well. Both categories of contextual vulnerability assessment can be presented in many forms, such as graphs, tables and maps. Within the Dutch context a number of interesting methods are available within this category, such as Duurzaamheid op Locatie (IVAM, 2011) and Klimaatkaart (Bosch Slabbers Landschapsarchitecten, 2010), which have been briefly described in Appendix 1 along with a number of other tools that are available in the Dutch context. In addition, a contextual vulnerability assessment of Dutch urban areas on national scale has been performed by Van de Ven et al. (2010).

Since the objective of this study is to quantify vulnerability and indices are the most direct way of quantifying vulnerability in an integrated way in terms of a single number, the method of indices has been preselected for further assessment.

### 5.1.2 Pre-selection of a method for outcome vulnerability assessment

Outcome vulnerability is measured in terms of the impacts minus the potential adaptation. It thus requires modelling of impacts and adaptation. Carter et al. (2007) describes different approaches for climate change impact, adaptation and vulnerability assessment.

Cause-based methods work from driver, to pressure, to state, to impact and ten finally to response (Gersonius, 2012). The response then should ensure that the system will remain functioning under the assumed climate scenario (Gersonius, 2012). Examples of cause-based types of assessments are:

traditional impact modelling on the basis of climate scenarios, cost benefit analysis, real options analysis and decision analysis. In this type of assessment, it needs to be predicted what the extent of climate change will be (Van der Sluijs and Dessai, 2007). Considering the large uncertainties in the outcomes, it can be problematic to apply this type of assessment in planning and decision making (Gersonius, 2012). In addition, it is difficult to involve decision makers in the analysis .

Effect-based types of assessment start by specifying an outcome, such as a vulnerability criterion. It then is assessed under what conditions and what the likelihood is that this vulnerability criterion is exceeded under the influence of climate change drivers. (Lempert et al., 2004). Examples of effect-based type of assessments are (Gersonius, 2012): the Adaptation Tipping Point method, Exploratory modelling and Adaptation Pathways .Effect-based assessment, in principle, does not need a prediction of one future, but it reasons from multiple future climate conditions, especially exploratory modelling (Ebskamp, 2009). Because this type of assessment first requires the formulation of the specification of a (un)desired situation, it better connects to local decision making.

This thesis intends to develop a method for municipal vulnerability assessment. Because of this it is important that the method supports local decision making. Because of this it is most appropriate to pre-test an effect-based method.

Which of the effect-based methods is the most suitable for the purpose of this thesis? Apart from policy relevance it is important that the method is feasible and communicable. The Adaptation Tipping Point method can be seen as a simplified version of exploratory modelling. Whereas the ATP-method typically holds all input variables constant, except for one variable that is assessed, exploratory modelling varies multiple input variables. The outcomes of exploratory modelling consist of a range of ATPs, whereas an ATP-analysis only results in one tipping point. Therefore exploratory modelling is more complex, and it leads to results that are more difficult to explain than the ATP-method. Adaptation pathways (e.g. Haasnoot et al., 2012)  can be simpler to apply and they can be based on expert judgement (e.g. Asselman et al., 2008) but they result in an assessment of suitable combinations or sequences of adaptation strategies in relation to climate change and other developments (Haasnoot et al., 2012). Because of this, Adaptation Pathways cannot be used to "measure" vulnerability. Adaptation Pathways can be based on an ATP-analysis though.

Therefore, the ATP method has been chosen for further assessment on the basis of the criteria that have been formulated in chapter 4 on the basis of the needs of municipalities regarding assessment of their vulnerability.

Sections 0 and 5.3 further describe vulnerability indices and the Adaptation Tipping Point Method. These methods are compared in section 0, which also contains the argumentations for the choice for application of the Adaptation Tipping Point Method in the case studies.

## 5.2 Vulnerability index

This section addresses indices, also called non-dimensional composite indicators. Balica (2012) makes a distinction between parametric modelling and physical modelling, which resembles the distinction between methods for assessment of contextual vulnerability and outcome vulnerably. Subsection 5.2.1 introduces indices. In subsection 5.2.2 it is explained how indices can be constructed. Subsection 5.2.3 describes a number of earlier applications. Subsection 5.2.4 describes the suitability of indices. Finally it has been described in subsection 5.2.5 what the relation is of indices to vulnerability.

### 5.2.1 Introduction

Vulnerability indices are numbers that are based on indicators that assess a quantity (of vulnerability) in relation to a base period (Sullivan, 2002). By aggregating several or more indicators it is possible to indicate the relative vulnerability of an area. Examples of indices include indicators for exposure, sensitivity and adaptive capacity, such as population at risk, recovery rate and economic development. The use of indices started in the 1920s (Edgeworth, 1925, Fisher, 1922, in , Balica, 2012). Numerous indices have been made (for overviews, see Gall, 2007, Birkmann, 2006, Balica, 2012), although most of them are on global and (sub)national scale.

Vulnerability indices are very suitable for assessing contextual vulnerability, since they are able to aggregate all kinds of variables that affect the vulnerability of an area. It is, however, challenging to select the indicators in such a way that the indices represent vulnerability in a comprehensive way. Vulnerability indices can also include indicators for outcome vulnerability.

### 5.2.2 Steps of index development

Indices can be developed on the basis of deductive strategies and on the basis of inductive strategies. Deductive strategies are based on understanding and characterisation of the vulnerability in an area. Inductive strategies are based on statistics. The steps to calculate vulnerability indices are as follows:

- The analyst selects the factors or determinants of vulnerability, based on theoretical frameworks, statistics, data availability and normative arguments (Hinkel, 2011, Gall, 2007), sometimes with local inputs (Smit and Wandel, 2006). The number of indicators ranges from several to several dozen.
- The scores on the indicators are collected, which usually comprise aggregate surrogates from secondary data (Smit and Wandel, 2006). These can also be complemented with surveys, depending on the scale and goal of the index.
- The scores on the indicators can be rescaled, normalized, weighted and be grouped in sub-indices (Gall, 2007) in order to finally calculate the vulnerability of an area (or more generally: system).
- Finally a sensitivity analysis can take place. This step, however, is often omitted or conducted in a limited way (Gall, 2007).

### 5.2.3 Earlier applications

The amount of indices that have been developed in the past is too large to present in this subsection. The following two indices are addressed below, because they apply the same definition of vulnerability as is used in this thesis to a number of hazards that are also addressed in this thesis. Both indices are composed of indicating variables for exposure, sensitivity and adaptive capacity, although Balica uses different words for sensitivity and adaptive capacity. The Flood Vulnerability Index, which has been developed by Balica (2007), applies the vulnerability approach to floods in general on the scale of river basins, sub catchments and urban areas, but focuses on multiple types of floods. The index consists of a number of sub indices representing physical, economic, social and environmental vulnerability. A few years later, Balica also developed a Flood Vulnerability Index for Coastal Cities, using the same methodology (Balica, 2012). This index enables comparison of different coastal cities. Preston et al. (2008) developed indices for vulnerability to 'extreme rainfall and storm water management', 'extreme heat and human health', 'sea-level rise and coastal management', bushfires and 'ecosystems and natural resources' in the Sydney Coastal Councils Group region in Australia. This is an area covering multiple cities. The vulnerability of the areas is calculated on the basis of a grid with aggregated information per grid cell.

The described methods are not yet suitable for application on the scale of Dutch municipalities, since the indicators are too rough to support Dutch municipal decision making. In addition, the indicators do not represent vulnerability of Dutch municipalities in a satisfactory way. For example, the indicator "percentage of households connected to internet" does not reveal large differences. It is questionable whether an indicator such as average neighbourhood income would represent adaptive capacity in the Dutch welfare state. The methodologies could, however, be used for the development of an index that is customised for the small scale of Dutch municipalities and their specific vulnerability factors.

### 5.2.4 Suitability

Indices have the characteristics of methods for assessment of contextual vulnerability, which in general have been described in section 2.2. Vulnerability indices are especially suitable for quantification of contextual vulnerability. For example, it is possible to select a set of indicators for exposure, sensitivity and adaptive capacity, that together indicate the relative vulnerability of an area. Although it is possible to include outcomes of physical modelling, even without knowledge about the size of impacts it can be analysed what areas are more vulnerable to climate change than others.

The outcomes of contextual vulnerability assessment can be used for identifying vulnerability hotspots, assessment of effectiveness of adaptation measures and monitoring of climate change vulnerability (Füssel, 2007). If all relevant contextual vulnerability factors are taken into account, municipalities can use an index to manage their vulnerability to climate change. Comparison of vulnerabilities between pluvial flooding, groundwater flooding, drought and heat stress is difficult, however. The factors that determine the vulnerability to these themes are to a large extent different. However, it is possible to compare the relative vulnerability of areas with regard to the themes. An area that is relatively vulnerable to all of the themes should certainly be considered as a hotspot area.

Füssel (2007) states that assessment of contextual vulnerability is mostly suitable for situations in which data is scarce, resources for the assessment are small, vulnerability to climate change has to be seen in relation to other developments, the time horizon of adaptation planning is low and climate uncertainty is high. Costs and data requirements are low because of the high flexibility in the selection of indicators and the absence of a need for physical modelling. It is relatively easy to take into account social aspects of vulnerability and other aspects that are difficult to implement in physical modelling. Since no modelling of future impacts is done, the results of the assessment have a shorter validity. Assessment of contextual vulnerability is, however, suitable in situations in which uncertainty is high. Physical modelling would then result in a large range of possible impacts, which would make it difficult to justify policy recommendations.

### 5.2.5 Relation of indices to vulnerability

An index is the most direct indication of the full concept of vulnerability, since all aspects of vulnerability can be integrated in it. Since all indicators are expressed in one number, a lot of information is lost. By definition, vulnerability indices provide for a relative "measure" of vulnerability. This enables comparison of areas and makes it possible to analyse which vulnerability indicator causes a high overall vulnerability.

## 5.3 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.

The structure of this section is similar to section 0. The ATP-method is further introduced in subsection 0 and the steps of the ATP-method have been described in subsection 5.3.2. Earlier applications have been described in subsection 5.3.3. Subsection 5.3.4 describes the suitability of the ATP-method and subsection 5.3.5 describes the relation of the ATP-method with vulnerability.

### 5.3.1 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).

### 5.3.2 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 thesis, since this thesis 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 thesis, 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 thesis, 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.

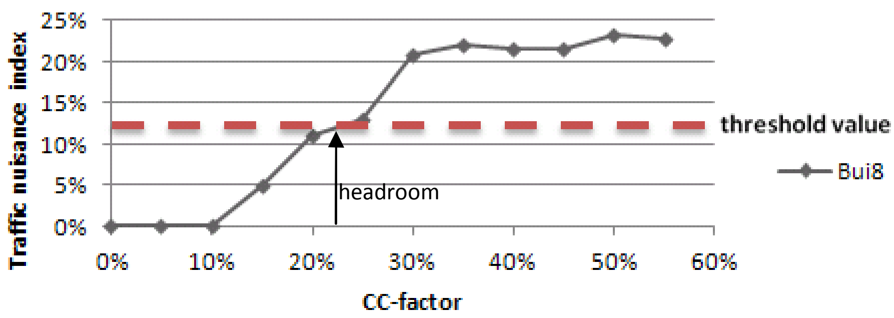


Figure 6 Explanation of calculation of ATP

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.

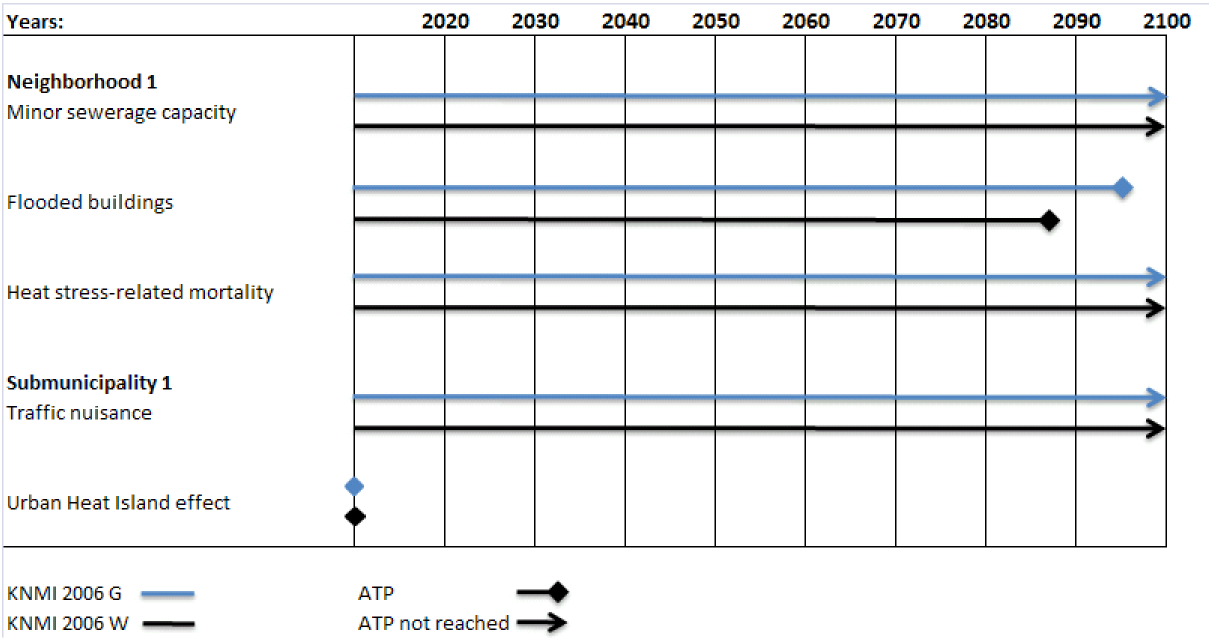


Figure 7 Fictive example of end result of the ATP method

### 5.3.3 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 drainage system for climate change and calculated the effect of certain 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.

### 5.3.4 Suitability

Assessment of outcome vulnerability in general is particularly suitable for raising awareness and identifying research priorities for long-term planning, and for investigating whether risks levels are effectively controlled. In addition, the modelling needs to be sufficiently detailed and climate change impacts need to be modelled sufficiently reliable (Füssel, 2007). Since physical models are the basis of the modelling, social factors and other factors that are not accounted for in the models are underrepresented in assessment.

The Adaptation Tipping Point method is currently applied in two ways (Jeuken and te Linden, 2011):

- Assessment of the urgency of problems
- Comparison and evaluation of adaptation measures and strategies with regard to their robustness.

### 5.3.5 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.

## 5.4 Comparison of ATP-method with indices

This section compares the two methods on the basis of the criteria that have been formulated in the previous chapter.

**Table 22 comparison of the ATP-method with indices.**

| | ATP-method | Index |
|---|---|---|
| **Policy relevance** | | |
| Helps allocating resources | Helps identifying most vulnerable places and gives insight into urgency of measures | Helps identifying most vulnerable places and gives insight into most significant factors |
| Creates awareness | Creates awareness in terms of sense of urgency, vulnerability hotspots and locations for further research | Creates awareness in terms of vulnerability hotspots and most significant vulnerability factors |
| Helps engaging stakeholders | Engagement of stakeholders that are involved in the formulation of vulnerability indicators and thresholds | No, but index can be the start of engagement process on vulnerability hotspots |
| Facilitates pro-active spatial adaptation strategies | Enables indicating the urgency of adaptation measures, outcomes can be updated easily when new climate scenarios become available. | No, but it facilitates identifying suitable adaptation options. |
| Helps monitoring of vulnerability | Yes: outcomes can be updated easily when new climate scenarios become available. | Yes |
| Identification of vulnerability hotspots | Yes, on the basis of physical modelling | Yes, on the basis of contextual factors and possibly physical modelling |
| | | |
| **feasibility** | | |
| Low data requirements | Considerable data is required, depending on the type of modelling. If expert judgement is used, no data is required. | Depends on selection of indicators |
| Flexible regarding level of detail | Yes | Yes |
| Low costs | No, in principle, impact modelling is necessary for each area. | Depends on indicator selection. If index is developed and indicators are selected beforehand, costs for applying method are low. |
| | | |
| **Communication** | | |
| Convincing results | Depends on type of modelling. Uncertainty of outcomes might be underestimated. | Depends on type of modelling. Uncertainty of outcomes might be underestimated and limitations regarding the representation of vulnerability might be underestimated. |
| Easy interpretation of results | Outcome of analysis: time until the vulnerability/impacts become unacceptably high, which is easy to understand. When digging deeper, interpretation is more difficult. | Outcome of analysis: a relative number for vulnerability, which is easy to comprehend. When digging deeper, interpretation is more difficult. |

**Sources: interviews, own interpretation and (Eriksen and Kelly, 2007, Hinkel, 2011, Balica, 2012, Kelly and Adger, 2000)**

On the basis of Table 22 it is not possible to assign an undisputed winner. Both methods serve different goals. The differences that are shown amount to the general differences between assessment methods for contextual vulnerability and outcome vulnerability. Methods for outcome vulnerability provide more insight into the urgency of the climate change problem, but they require modelling of future impacts, which makes them less feasible. Methods for assessment of contextual vulnerability provide more information about the drivers and causes of vulnerability and about the selection of adaptation measures and are more feasible, since they do not require modelling of impacts. Methods for contextual vulnerability assessment only provide a relative indication of vulnerability.

Referring to the analysis of the need for vulnerability assessment in Dutch municipalities, it has been found that many of the problems that municipalities have regarding their vulnerability to climate change, relate to a lack of awareness, a lack of methods for justifying a certain sense of urgency and convincing internal and external stakeholders. In addition, some methods for contextual vulnerability assessment have been found and a rough vulnerability assessment of urban areas on national scale has been performed already by van de Ven et al. (2010). These arguments together lead to the choice for further assessment of the ATP-method in the case studies.

# 6. Case 1: Rotterdam-Noord

The first case study in this thesis has been conducted in Rotterdam-Noord. This case study serves as a proof of concept, rather than as a substantive vulnerability assessment. The case study and its results have not been discussed with the municipality. Section 6.1 introduces the area and describes a number its characteristics. Section 0 describes the application of the method and section 6.3 discusses the results of the method. Section 6.4 contains the conclusions of the application of the case study. At last, the evaluation of the case study in terms of its applicability to municipal vulnerability assessment is included in section 6.5. A more detailed description of the case study is included in Appendix 3 to Appendix 6

## 6.1 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 is shown in Table 23. The neighbourhood Blijdorpse Polder is mainly an area of industry and recreation.

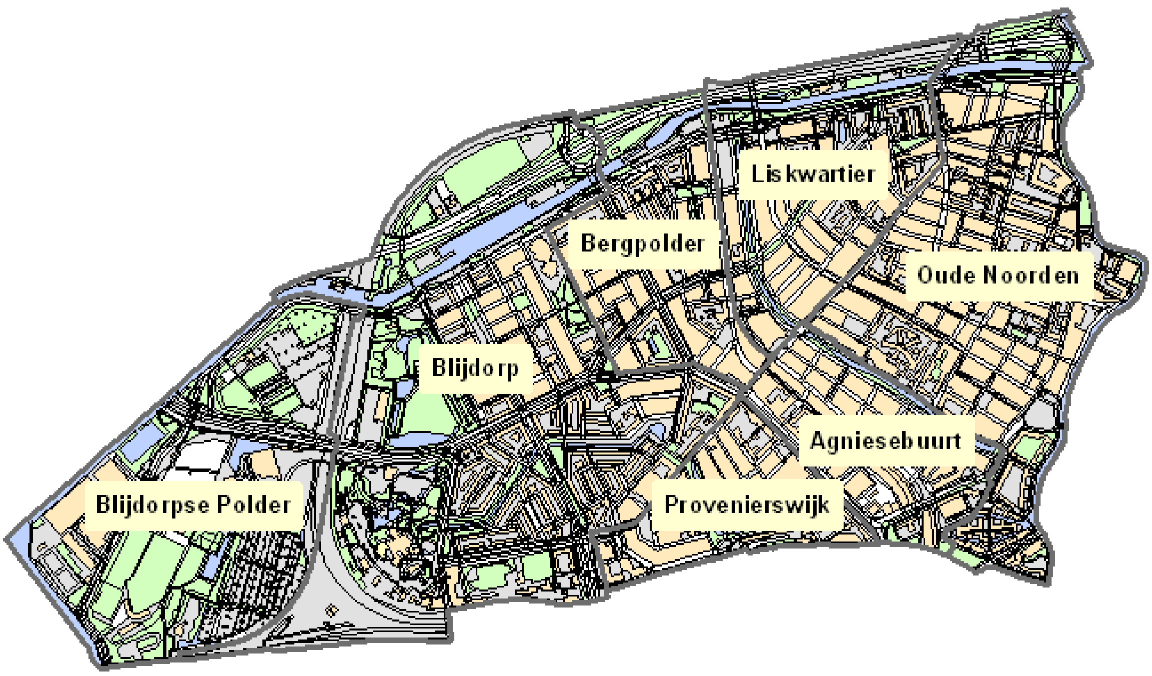


Figure 8 Overview of Rotterdam-Noord

Table 23 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 submunicipal 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).

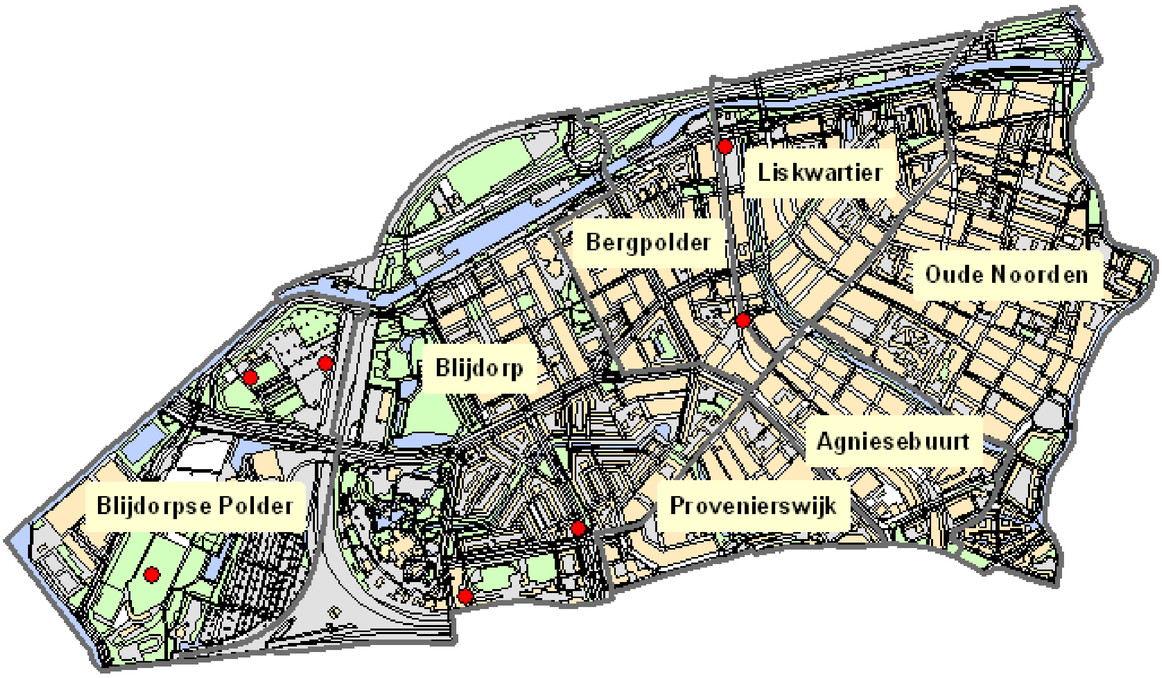


**Figure 9 Map with flooding locations as mentioned in the submunicipal water plan of Rotterdam-Noord (Nelen & Schuurmans, 2009)**

## 6.2 Application of method

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

### 6.2.1 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 case study focused on pluvial flooding in relation to flooded residential and commercial buildings. The inclusion in this case study of public buildings, such as schools and healthcare service buildings, as a separate category, has also been considered, but their number is low and after analysis it turned out that none of them were flooded.

Pluvial flooding of roads has also been taken into account. Only large roads have been taken into consideration, that are of great importance with regard to the accessibility of the city. Because of this, it is not interesting to look at different neighbourhoods specifically, because then smaller streets should have been taken into account as well. Therefore, with regard to traffic nuisance, Rotterdam-Noord has been chosen as geographic level of scale.

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, Basic map GKBN, standard administration of addresses and contours of buildings, as included in BAG and Google Streetview. This makes it possible to re-do the analysis in other areas with more or less the same sources of data.

The modelling of overland flow of the rainwater has been performed by William Veerbeek of UNESCO-IHE with the application TUFLOW (2011) in combination with AQUAVEO (2012). Further analysis has been performed with standard software packages like ArcGIS and Microsoft Excel.

### 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 thesis considers vulnerability on geographic scale, rather than on the scale of individual assets, the indicators should indicate the vulnerability of geographic areas. 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 24 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 6 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 24 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%<br>Percentage of flooded commercial buildings < 0,1 %<br>Traffic nuisance index = 10% |
| Bui 50 (T=1/50 year) | 50 years | Percentage of flooded houses in neighbourhood < 0,5%<br>Percentage of flooded commercial buildings < 0,5%<br>Traffic nuisance index = 30% |
| Bui 100(T=1/100 year) | 100 years | Percentage of flooded houses in neighbourhood < 1%<br>Percentage of flooded commercial buildings < 1%<br>Traffic nuisance index = 35% |

## Step 3: Calculate ATP and express 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 conditions under which the ATPs are reached have been determined on the basis of the 2D overland flow model TUFLOW (2011), using the 5 by 5 meter Digital Elevation Model AHN (Actueel

Hoogtebestand Nederland). It has been assumed that a rainfall event falls uniformly distributed over the entire area and that the sewer capacity is 20 mm/hour. 0describes further assumptions in the model. The 2D overland flow model has been applied by William Veerbeek of UNESCO-IHE, as well as the intersection of the buildings with the outcomes of the outcomes of the model. The remaining activities in this case study have been performed by the author of this thesis.

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.

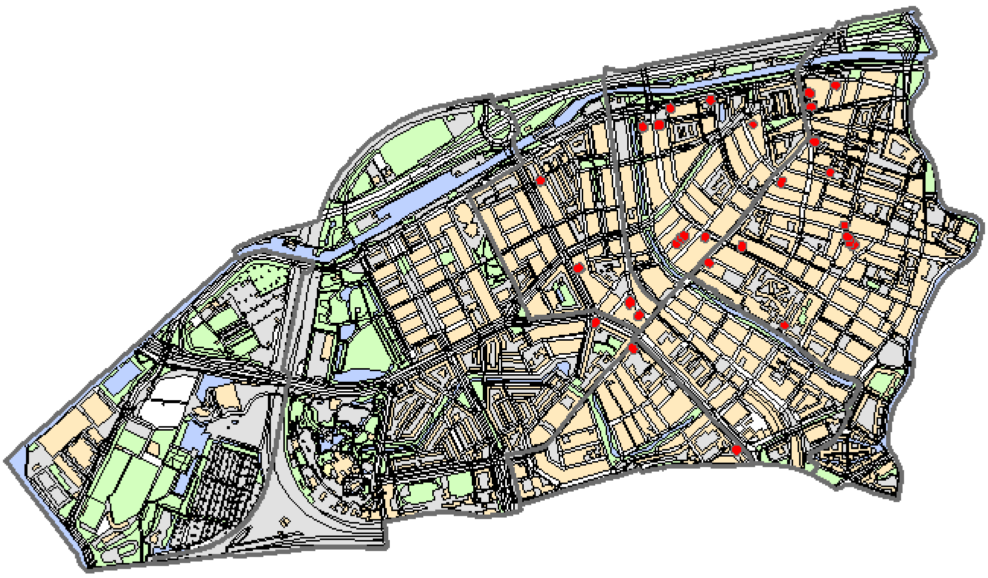

**Figure 10 Map with all buildings that flood in any of the modelled scenarios**

Table 25 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 25 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 26 shows headroom of Rotterdam-Noord with regard to traffic nuisance.

Table 26 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 5 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.

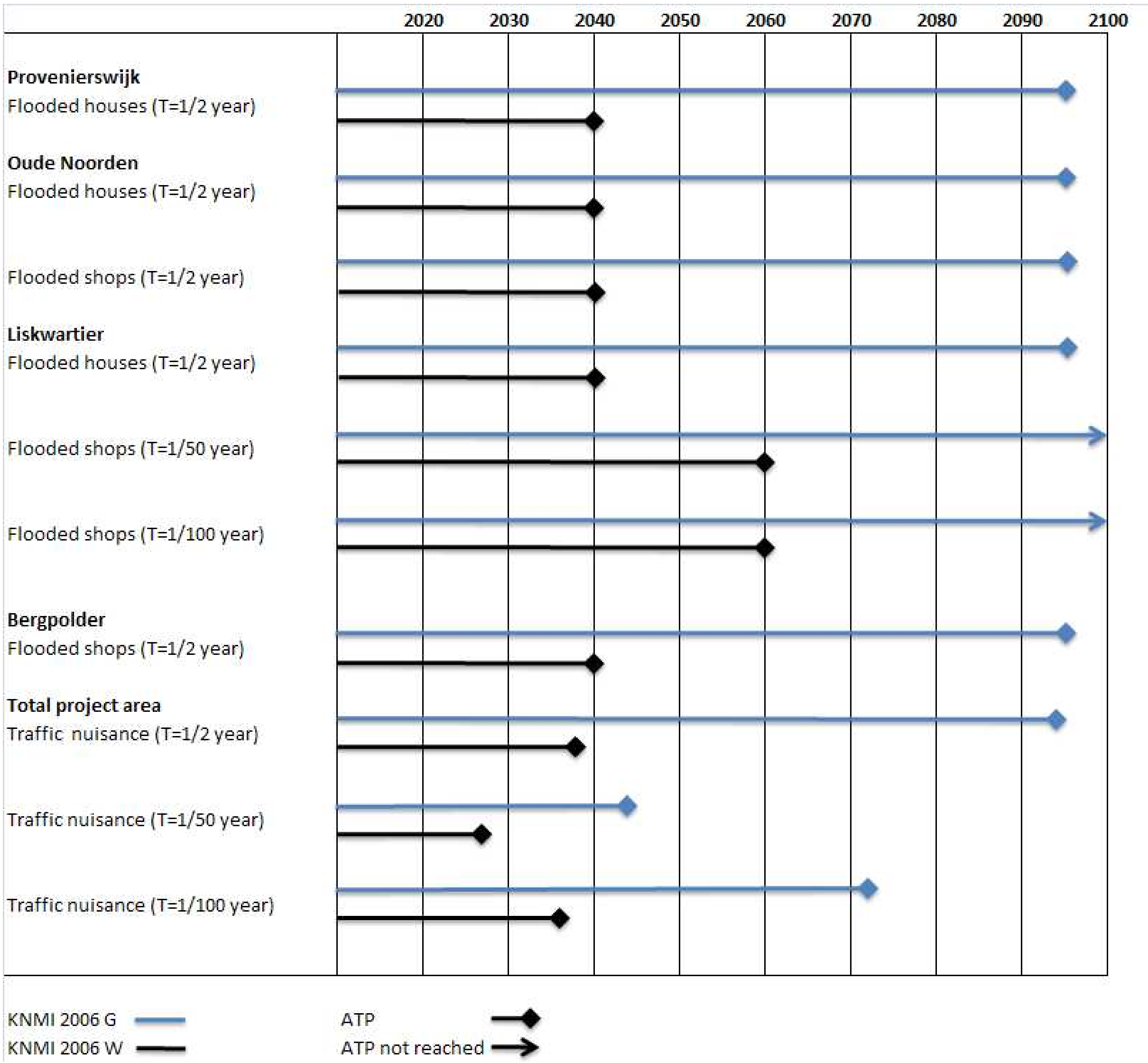


**Figure 11 Calculated ATPs. Not shown are the ATPs that were not reached within the range of calculated scenarios. These scenarios have a headroom of more than 55%, as shown in Table 25.**

## 6.3 Discussion

The focus of this case study is to show whether the ATP-method is suitable for application on municipal level as vulnerability assessment. The calculation of the ATPs is 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. This section discusses the results of the flood modelling in subsection 6.3.1, the analysis of flooded buildings in subsection 6.3.2 and the assessment of traffic nuisance in subsection 6.3.3.

### 6.3.1 Flood modelling

In order to understand the results of the case study it is important first to evaluate the applied modelling.

Previous studies indicate that pluvial flooding is overestimated by models, since their results indicate more pluvial flooding than is expected on the basis of (scarce) empirical data (Nelen & Schuurmans, 2009, Vergroesen, unpublished). Residents of the area do not report major water nuisance and pluvial flooding. The submunicipal water plan (Nelen & Schuurmans, 2009) suggests that the high amount of surface that is attached to the sewerage and the interaction between surface water and sewerage, as well as high slopes of canals could reduce the effects of extreme rainfall on pluvial flooding. Vergroesen (unpublished)states that the reasons for the differences between the modelled pluvial flooding and experience pluvial flooding could be explained by:

- More infiltration in half-paved areas than is assumed in the models
- Overflow threshold levels are lower than assumed in the models
- The capacity of the pumping stations is higher than assumed in the models

Apart from these general observations from previous studies, the following limitations in the modelling that is applied in this thesis should be addressed:

- The capacity of the sewer is not included in the modelling. It is assumed that the sewer is able to discharge 20 mm/hour. This is a norm that is often used for the design of sewerage systems. However, the assumption that the sewer capacity is uniform is not realistic, since the capacity may vary from place to place and from time to time. For example, the distance from a manhole to an overflow location affects the capacity, the amount of maintenance has influence on the sewer capacity and the discharge capacity also depends on previous rainfall conditions.
- The applied modelling is based on a five by five meter grid. Because of this, details such as sidewalks, traffic barriers and other details that affect the water flow are not taken into account. Especially in the case of low flood levels, however, these details can make a large difference. They can determine whether a building floods or not. At higher water levels the details are less relevant, since the water height then exceeds these details.
- The Digital Elevation Model is not checked and corrected manually. This could lead to inaccuracies and false results
- The standard rainfall events are assumed to be falling uniformly in the project area. In reality, every rainfall event is different.

The outcomes of the modelling are different from the results from previous efforts. The outcomes of the flood modelling were not in line with past flood locations, which were identified in the submunicipal water plan (Nelen & Schuurmans, 2009) and previous research of Vergroesen (unpublished). Vergroesen modelled a part of the project area (Oude Noorden and parts of Liskwartier and Agniesebuurt) on the basis of a sewer model. His results were not in line with the results from the models that were applied in this thesis. The differences in the results can be explained by the differences in modelling techniques.

Even though the flood model should be considered as a rough first order estimation of the flood levels within Rotterdam-Noord, it still is possible to use it for identifying locations with higher risk of flooding, since the modelling shows where water accumulates regardless of the sewerage system. The locations where the modelled flood heights are high, can be considered as locations with high risk and should be researched further. The results from the 2D overland flow modelling should be seen as a what-if analysis for the water flow and water heights under different spatially uniformly-distributed standard rainfall events. Locations that are vulnerable due to a limited sewerage capacity only are not indicated as vulnerable by 2D overland flow analysis.

### 6.3.2 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 12 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 12 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. There is no plausible explanation that could justify these model results. 0 elaborates on the possible reasons for the unexpected modelling results.

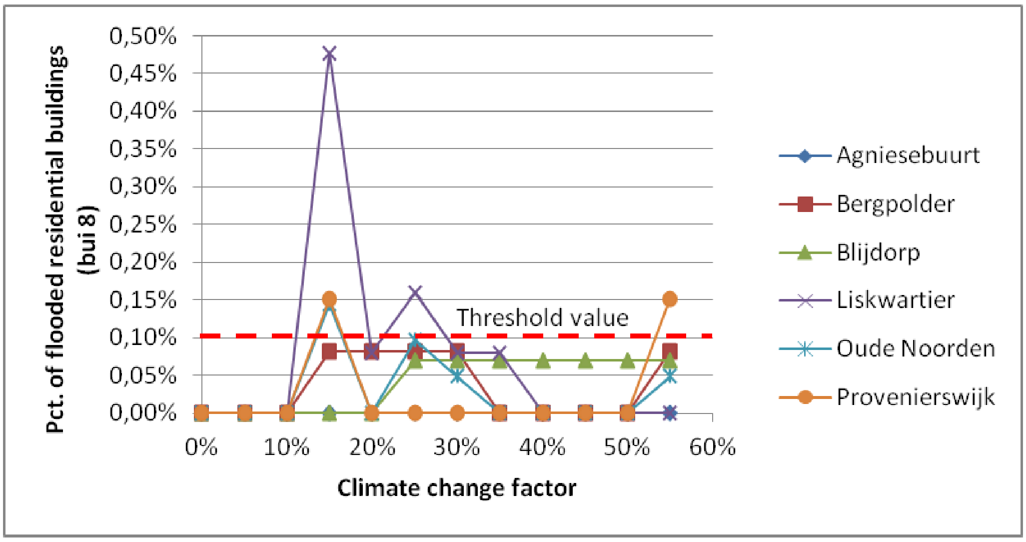


**Figure 12 Percentage of flooded residential buildings in different neighbourhoods under bui 8**

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

- The number of buildings that flood under Bui 8 (CC-factor 15%) is larger than in any other scenario. This result cannot be explained.
- 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 13 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.

### 6.3.3 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 14 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.

The following observations are 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.

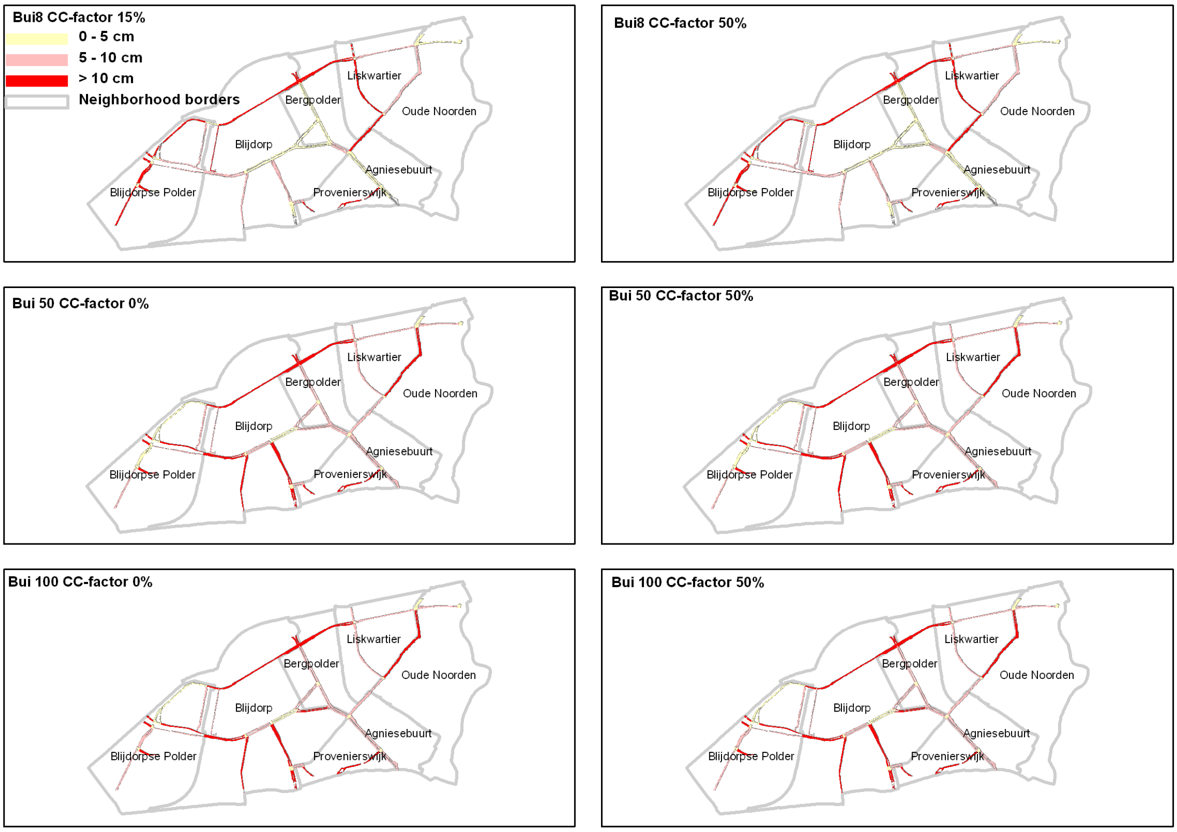


**Figure 14 Traffic nuisance under all scenarios at climate change factor 0% (current situation) and 50%. Under bui 8 no flooding takes place, so for this rainfall event, climate change factor 15% has been included.**

## 6.4 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.

## 6.5 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.

### 6.5.1 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.

It seems that the ATP-method, as it has been applied in Rotterdam, is more suitable for policy and strategy development on higher scale than for identification and timing of specific measures on the short term.

- The analysis showed that few buildings flooded, so immediate measures were not necessary. But what if the amount of flooded buildings was higher? Are the indicators in which point to the percentage of commercial and residential buildings per neighbourhood pivotal to the decision whether measures should be taken? It seems that these kinds of decisions are based on a large number of other criteria, such as costs, types of buildings, possible alternative options (i.e. geographic spread of floodings), political preference and so on. The indicators do not provide any information about the graduality and the spatial distribution of impacts.
- The outcomes of the 2D overland flow modelling are very uncertain, not only because it disregards the sewerage system, but also because of general uncertainties in the form of a relatively large resolution of the Digital Elevation Model compared to the size of objects in urban areas and low water levels in flat areas.

### 6.5.2 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.

In this case study, a 2D overland flow model has been applied, which requires considerably more computer capacity than simpler GIS-based surface analyses (van Dijk et al., 2012). For even better results, integrated (1D) sewer modelling and 2D overland flow modelling could be performed. In this way a more realistic estimation of floods can be provided. These models are however much more complex and expensive. They are not suitable for modelling complete municipalities (van Dijk, 2011).

### 6.5.3 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 6.5.1, they are also surrounded by a large amount of uncertainty. The method only provides additional information to decision makers.

# 7. Case 2: Nijmegen

The second case study was performed in Nijmegen. This case study only involves pluvial flooding of buildings. The structure of this chapter is the same as that of chapter 7. Section 7.1 introduces the case study area. Section 7.2 briefly describes the application of the ATP and presents the results. Section 7.3 includes the discussion of the case study results. Section 8.4 contains the conclusions and recommendations. The final section describes the lessons that have been learnt from this case study for the design of the method for vulnerability assessment on municipal scale. Appendix 7 describes the steps of this case study in more detail.

## 7.1 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.

## 7.2 Application of ATP-method

This section briefly describes the application of the ATP-method in Nijmegen. Appendix 7 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.

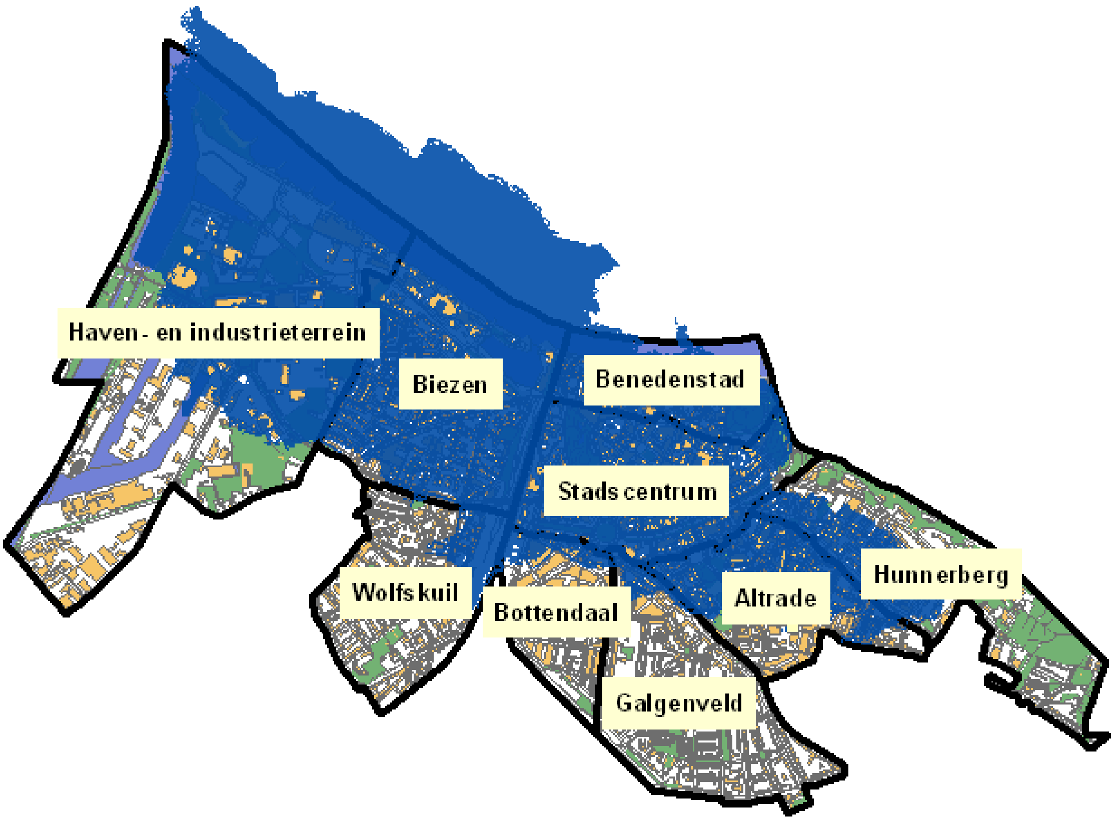


Figure 15 Geographical extent of the case study. Blue area represents geographical scale of the flood model.

### Step 2: Determine indicators and threshold values

Table 27 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 27 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 7.3.


**Figure 17 Flooded buildings in Nijmegen Centrum and Benedenstad.**

The results of the ATP-analysis are shown in Figure 18. 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.

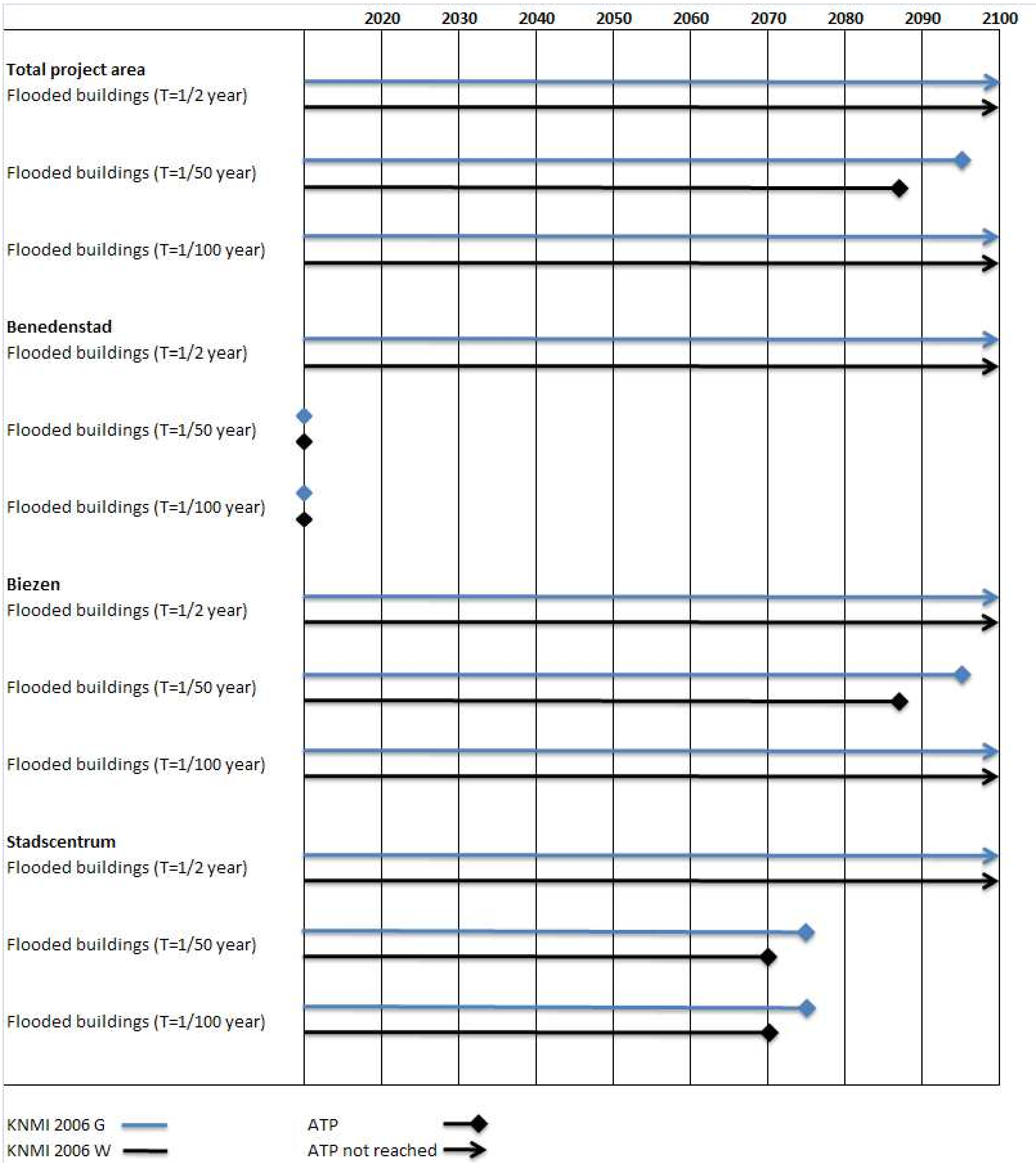


**Figure 18 Timings of ATPs in total project area and in the neighbourhoods Benedenstad, Stadscentrum and Biezen.**

## 7.3 Discussion case study Nijmegen

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.

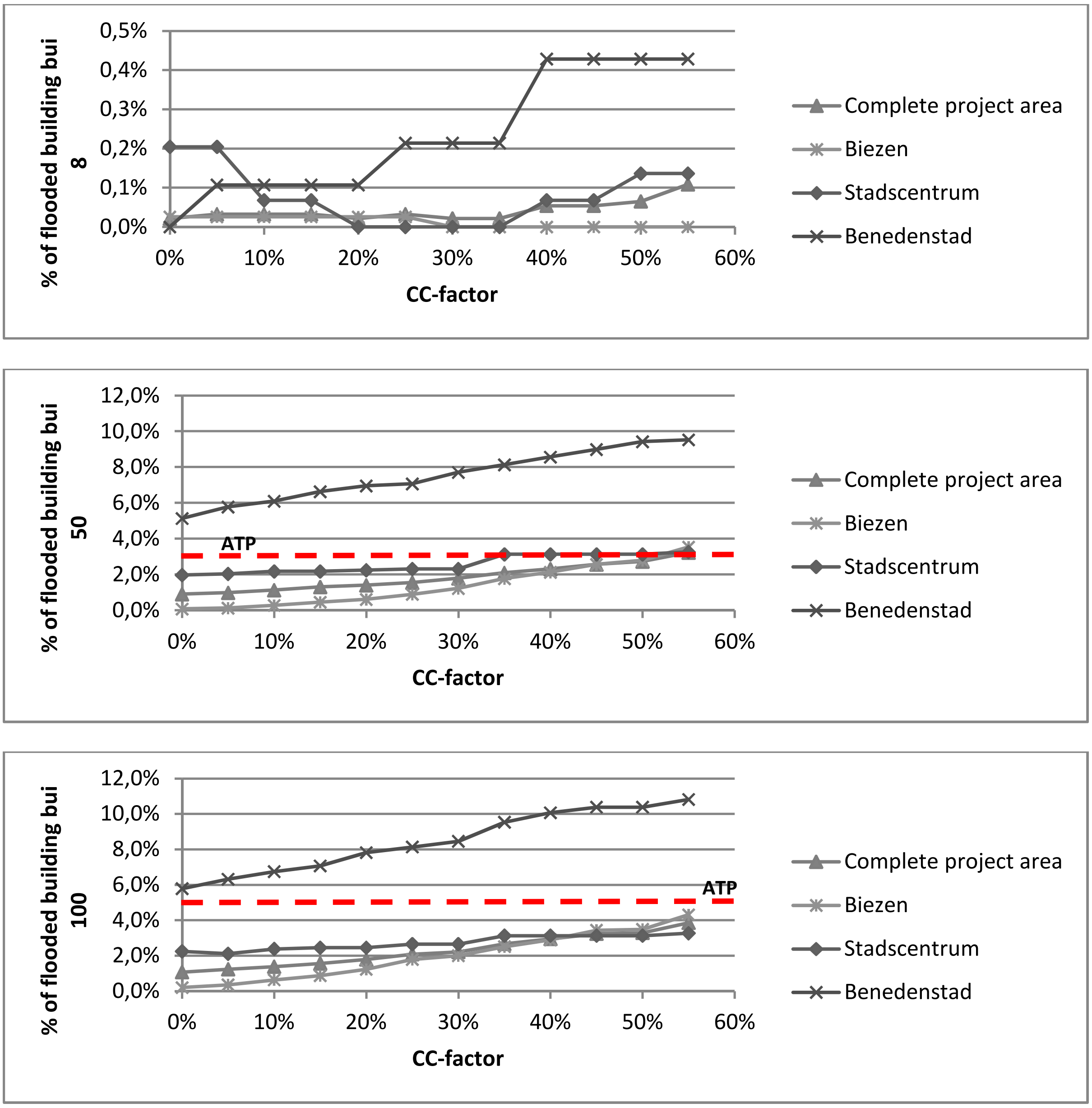


**Figure 19 Percentage of flooded buildings under different rainfall events in the compete project area and in the neighbourhoods**

Figure 19 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.

Figure 20 presents the end results of the analysis.

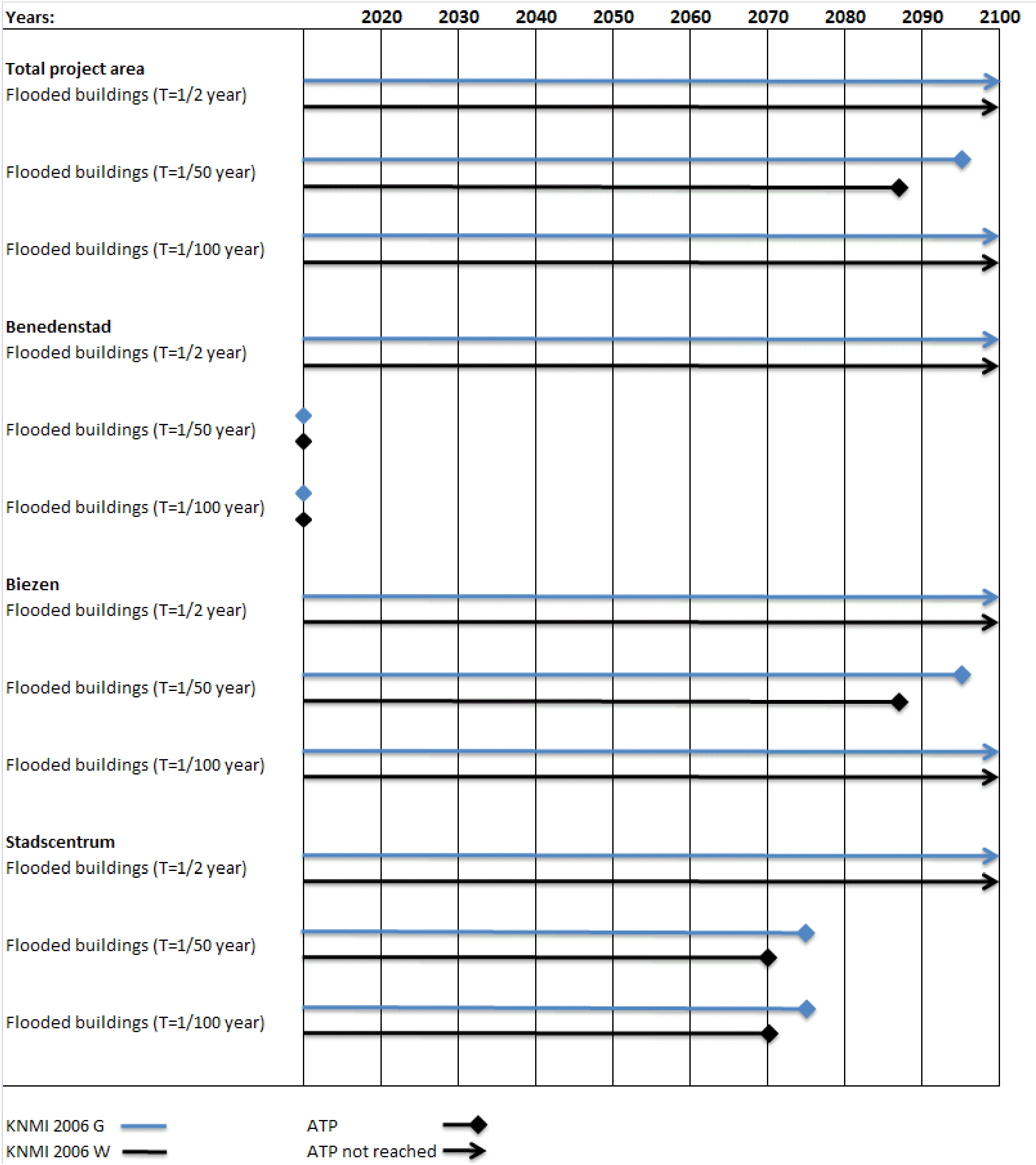


**Figure 20 Timing of ATPs in Nijmegen**

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 28. 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 28 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.

## 7.4 Conclusions and recommendations

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 sensitivity analysis showed that the results are highly sensitive to assumptions regarding the doorsteps. If a standard doorstep of 3 cm is assumed instead of one of 10 cm, timings of ATPs can occur up to 90 years sooner. The differences between 10 and 15 cm are much smaller. In order to get a more reliable estimation of flooded buildings, doorsteps (or the lowest point of a building where water can enter) should be manually assessed.

The results of the ATP analysis showed that under any of the assumed doorstep heights, the threshold values for bui 50 and bui 100 have already been exceeded. Do these outcomes of the analysis suggest that immediate action is required to reduce the amount of flooded buildings in Benedenstad? This conclusion might be a bit strong, taking the rough nature of the flood modelling into account, but priority should be given to further investigation in this area. It should be further investigated why the buildings in this area are flooded, where it is most important to take measures, and where it is easiest to take measures. The ATP analysis only showed that the number of buildings that flood under bui 50 and bui 100 is higher than what is accepted on the basis of the vulnerability threshold. The ATP-method itself did not supply information about the location of the flooded buildings and it does not provide information about the measures that can be taken.

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

- In the current situation, if a doorstep height of 10 cm is assumed, the project area in total is not vulnerable to pluvial flooding, since the first ATP on project area level is reached after 2080. In addition, the most frequent rainfall event (once in 2 years) does not lead to an exceeding of the threshold value in any of the calculated scenarios, even if a doorstep of only 3 cm is chosen. Therefore generic adaptation measures on city level, such as general increases of sewer capacity, are not recommended.
- 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.

## 7.5 Lessons learnt from case study Nijmegen

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

### 7.5.1 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. .

### 7.5.2 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 there is some extent of relief in Nijmegen. Since actual pluvial flooding is rare in Nijmegen, it is not possible to verify the results with empirical evidence. The results for Nijmegen.

### 7.5.3 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.

# 8. 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.

## 8.1 Strengths

The method proves to be very flexible in terms of the climate change impacts. 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.

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.

Traditional modelling focuses more on the geographical extent of problems and fails to give insight into the temporal characteristics of time. It is often based on one or a number of climate change scenarios, but gives limited insight into the question when municipalities or other stakeholders should act. The ATP-method is very useful in presenting the time component of problems, since the resulting indicator of timing of ATP directly addresses this issue.

Another important advantage 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.

## 8.2 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 addition, the ATPs are based on imperfect vulnerability indicators.

- Ideally the indicators should include all relevant aspects of vulnerability that affect the urgency of the problems regarding a specific extreme event. It is for example important to take into account the sensitivity of the exposed objects, the relative importance of the urban area, and the adaptive capacity of the people in the area. This is however not feasible.
- In this thesis, vulnerability indicators are based on the level of neighbourhoods and submunicipalities, 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.

If ATPs are based on modelling, a large number of scenarios have to be calculated. In the case studies, for example, 3 to 6 scenarios have been calculated per rainfall event. In order to generate values for all 5% intervals between climate change factors 0% and 55%, interpolation has been performed.

The ATP-method is difficult to apply when impacts of extreme events depend on multiple drivers of climate change or socio-economic developments. For example, vulnerability to pluvial flooding might not only be increased because of climate change, but also by urbanisation. Presentation and communication of the results then becomes more challenging.

As in any method for assessment of outcome vulnerability, social factors are more difficult to include. For example, it is difficult to include the social factors that affect the adaptive capacity of an urban area in the indicator for vulnerability. Because of this, the type of recommendations on the basis of ATP-analysis might have a more technical nature and opportunities for taking non-structural measures and developing non-structural policies might be missed.

The ATP-method requires municipalities to define in a very explicit way under what conditions the vulnerability of an urban area is higher than accepted. This could imply normation. It is possible that municipalities are afraid that this normation could become legally enforceable. This could be a reason for them to set the threshold values of the vulnerability indicators loosely. This would mean that adaptation measures could be taken too late. So 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 make an urban area vulnerable.

## 8.3 Opportunities

The ATP-method as applied in this thesis 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.

## 8.4 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.

## 8.5 Summary

The results of the SWOT analysis have been included in Table 29.

**Table 29 SWOT analysis of ATP-method**

| **Strengths** | **Weaknesses** |
|---|---|
| - Flexible method<br>- Results are easy to explain<br>- Clear indication of urgency of climate change vulnerability.<br>- Bottom-up approach: municipalities and stakeholders need to indicate the acceptable outcome vulnerability to hazards.<br>- Comparison of vulnerability between themes can be done without relative weighting and indirect valuation.<br>- Modelling does not have to be repeated when new climate scenarios are made available | - Misleading sense of objectivity and certainty<br>- The acceptance of vulnerability levels can be easily adapted to changing political preferences. The method is susceptible to opportunistic behaviour<br>- Dependence on climate impact models<br>- High amount of scenarios needs to be calculated<br>- Lack of attention to social vulnerability factors<br>- Difficult to include multiple drivers of ATPs<br>- Vulnerability indicators do not capture all factors relevant to decision making. |
| **Opportunities** | **Threats** |
| - Assessing opportunities for combining measures with other urban projects by applying the ATP-Adaptation Mainstreaming Opportunities method.<br>- Options are available to use expert judgment if modelling would be too complicated.<br>- Impact studies on typical areas can be used as basis for assessment of specific neighbourhoods.<br>- General framework for vulnerability indicators and threshold values for all Dutch municipalities. | - Municipalities and/or other stakeholders need to explicitly define situations that are considered as vulnerable or invulnerable. Are municipalities prepared to do that?<br>- Impact models will not be improved and made more accessible for municipalities |

# 9. Conclusions and recommendations

The research objective of this thesis 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 thesis v*ulnerability* 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.

## 9.1 Vulnerability of Dutch urban areas to climate change

This thesis 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.

## 9.2 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.

## 9.3 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.

## 9.4 Case studies

Two case studies have been performed during this thesis: 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 9.5.

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 is virtually invulnerable to 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 the amount of flooded buildings increases 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 0.

## 9.5 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 30. 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 feasible.

## 9.6 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 thesis. 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 thesis, 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.

# 10. Reflection

## 10.1 Reflection for municipalities

At the start of the thesis, I thought that climate change adaptation strategies were of crucial importance to the proper management of municipalities, as had been confirmed by various authors (VROM-Inspectie, 2010, Runhaar et al., 2012, Kabat et al., 2005). After this thesis, my thoughts about this topic have become more nuanced. For example, the 1-hour rainfall volumes will increase by 25% at maximum in 2050 according to the KNMI climate scenarios (Klein Tank and Lenderink, 2009), which seems to be not a very large increase. On the other hand, current rainfall events that occur with a return period of two years, might happen once a year in 2050 (Stone et al., 2011). It seems that the effects of climate change on the topics that are addressed in this thesis are relevant, but not to such extent that radical policy changes yet are justified. This research did not prove that the currently dominant strategy of taking no-regret measures and reacting to experienced problems is unsuitable for the urgency of the problem. On the other hand, a conclusion that this strategy is appropriate would be too strong. In Nijmegen it has been shown that the threshold values for pluvial flooding of buildings were already reached in the current situation. In addition, the most extreme climate change scenario that the KNMI developed (W+) is not taken into account in this study, since projections of 1-hour rainfall volumes are unavailable. Consequences of climate change for pluvial flooding might be worse than they are modelled in this thesis.

Currently, many municipalities use 1D models for pluvial flooding only. Especially if municipalities state that more attention should be paid to acceptance of pluvial flooding and reducing the impacts of pluvial flooding, it is necessary that analyses on the basis of 2D overland flow models are made. GIS-based surface models can be used effectively for a first assessment. Integrated sewer and overland flow models are more complex and require considerable more resources (van Dijk et al., 2012).

## 10.2 Reflection on application of ATP-method on municipalities on national scale

The application of the ATP-method in this thesis focused on the vulnerability within municipalities. It would also be interesting to apply the method to the comparison of the vulnerability of multiple municipalities. Performances of a municipality can be important drivers for change. Public pressure will arise if the performance of a municipality is not good. This was also mentioned during one of the interviews. In order to make the method suitable for intermunicipal comparisons, standardisation is required. This thesis showed how sensitive the results of the ATP analysis can be for the vulnerability indicators, threshold values, type of modelling and underlying assumptions. So this standardisation should not only address the indicators and threshold values, but also the methods and assumptions that are used for the physical modelling.

In order to realise such a benchmark, it first is necessary to improve the feasibility of the method in terms of resources and data requirements.

## 10.3 Choice of ATP-method

The initial plan of action was to develop an index for vulnerability of urban areas to pluvial flooding. After a while it became clear that this would not satisfy, because some work had already been done in this field and the focus of the thesis would then shift to civil engineering. It was a while after the midterm meeting when the final decision was made to select the ATP-method as basis for the case studies. The ATP-method might not be the first method that comes into one's mind, when thinking about quantification of vulnerability. In addition, outcome vulnerability is not by everyone seen as "vulnerability", but as risk or consequences of climate change.

In the thesis report, the choice for the ATP-method is described in two phases. First, the most attractive method for assessment of outcome vulnerability has been chosen and the most attractive method for assessment of contextual vulnerability. The methods had, in principle, to be suitable for pluvial flooding, groundwater flooding, drought and heat stress. This pre-selection should have been justified better, although it has been improved since the "green light" moment. There are many methods that could, in principle, be used for vulnerability assessment and this range of possible methods should have been described better. Second a choice has been made between indices and the ATP-method on the basis of the criteria that have been developed on the basis of the interviews and literature research. The formulation of the criteria could have been done in a more thorough way, for example on the basis of a survey among more municipalities. The way in which the criteria are matched to the ATP-method and indices was rather qualitative and too much based on the personal view of the author. Despite this weak foundation of the choice for the ATP-method, I still have the opinion that the choice for the ATP-method suits the needs of municipalities. The application of the ATP-method is difficult in the context of pluvial flooding and even more difficult in the context of groundwater flooding, heat stress and drought, but it can provide very useful information to municipalities. The choice for the ATP-method had to be justified in retrospect, but in my view, the choice of the ATP-method is defendable from the viewpoint of municipalities.

## 10.4 Personal reflection

At the start of the thesis I thought that I knew a lot about vulnerability already. During this thesis I got to know that there was much more than I was aware of, at the time. In a relatively short period of time, I have gained a lot of knowledge about amongst others urban vulnerability to climate change, vulnerability assessment methods, modelling of pluvial flooding and of course the Adaptation Tipping Point method. Further I gained additional experience in writing a report in which quantitative analysis was used for making policy recommendations.

At the start of the project a number of ambitious goals have been set. The thesis required thorough research into different definitions and conceptualisations of vulnerability. The field of vulnerability research turned out to be highly complex. Although the case study only focussed on pluvial flooding, the thesis required research to (vulnerability to) pluvial flooding, ground water flooding, drought and heat stress. It was necessary to get to know the wishes and requirements, as well as the constraints of municipalities and their adaptation policies. An analysis had to be made of the extremely large variety of existing methods for vulnerability assessment. This all had to be brought together in the selection of the method, which then had to be pre-tested. The broadness and complexity of the subject, made it difficult to structure the activities for this thesis. Possibly the ambitions at the start of the project were not realistic, which caused a delay in the completion of the project.

In the end it has to be concluded that not all ambitions have been accomplished. First of all, the initial research plan was based on a stepwise approach in which each question was answered more or less after the previous question had been concluded. In reality this turned out to be difficult, since the research questions were highly interrelated. Completing the theoretical part before conducting the case studies was not possible either. Because of delays regarding the theoretical part, it was not possible to put the intended time into the case studies. Initially it was planned to use the first case study as vehicle to design the method into a completely operational method, and the second case study as a validation of the method in collaboration with external stakeholders. In the end, both cases served as a proof of principle and were to a large extent executed without involvement of stakeholders, which can be seen as a weak point of the study, since the method should, in the end, be appreciated and applied by municipalities. On the other hand, this is the reality of doing research. There always is a next action to improve the quality of the research...

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# 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 thesis 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[1]) 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. Methods that are described in section 5.1 are not repeated here.

**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

[1] http://www.ruimtevoorklimaat.nl/home

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 thesis 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".

# 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, Antal Zuurman | Gemeente Nijmegen |

# Appendix 3 Standard rainfall events and climate change factors

This appendix describes the rainfall events that have been used for the modelling in this thesis 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 21 and Table 30 describe the rainfall intensities of the rainfall events that were used in this thesis. 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 30 total rainfall volume and return period for bui8, bui50 and bui100 (Wonink and Kok, 2010, p.40)**

| | Bui 8 | Bui 50 | Bui 100 |
|---|---|---|---|
| **Total rainfall volume (mm)** | 227 | 509 | 539 |
| **Return period (years)** | 2 | 50 | 100 |

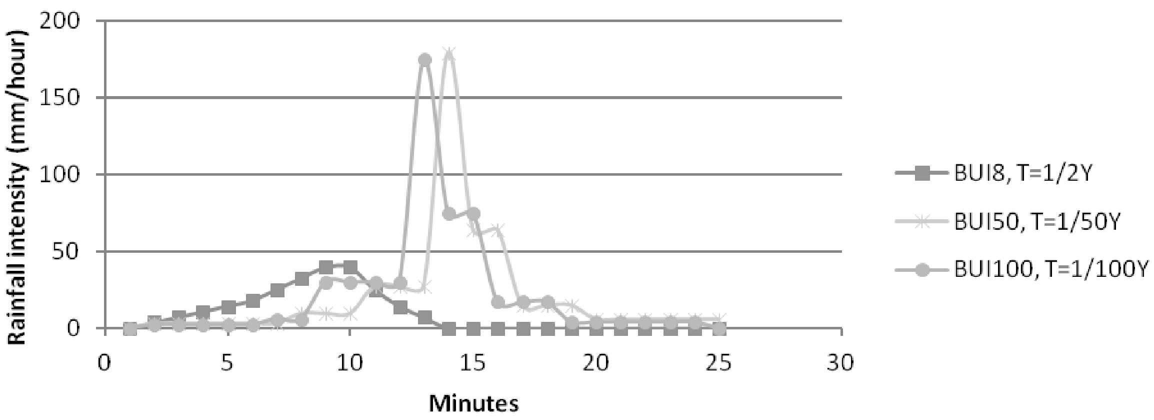



**Figure 21 Bui8, bui50 and bui100**

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 22 illustrates the effect of a number of climate change factors on bui 8.

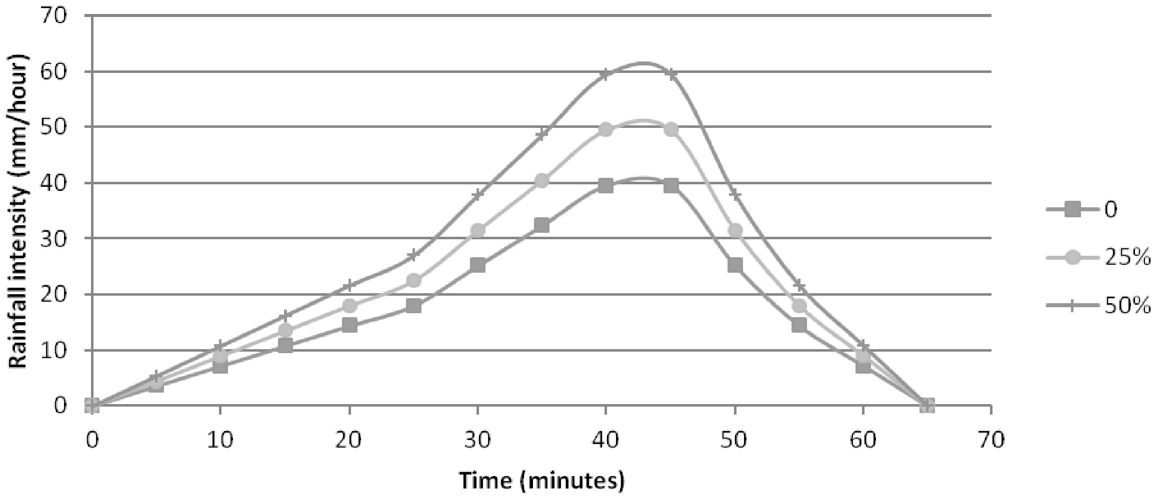



Figure 22 Influence of the climate change factor on Bui 8

# Appendix 4 Flood modelling

This appendix describes the modelling tools and methods that have been applied during this thesis to calculate the amount of pluvial flooding in Rotterdam-Noord and Nijmegen. All steps that are described in this appendix are executed by William Veerbeek of UNESCO-IHE. The appendix contains the following sections:

- A4.1 2D Overland Flow Modelling
- A4.2 Limitations of applied modelling method
- A4.3 Attribution of flood levels to buildings

## A4.1 2D Overland flow modelling

The modelling of flooded houses is conducted with the software packages TUFLOW and SMS Surface-water Modelling Solutions (respectively TUFLOW, 2011, AQUAVEO, 2012). The 2D overland flow model simulates surface water flows on the basis of a Digital Terrain Model. As input the following data is used:

- Digital Terrain Model
    - o Rotterdam: AHN with a resolution of 5 meter.
    - o Nijmegen: Model based on LIDAR Data on a resolution of 1 meter on average, which is interpolated using Inverse Distance Weighted Interpolation to a resolution of 3 meter, supplied by the municipality of Nijmegen.
- Characteristics of standard rainfall events (Bui8, Bui9, Bui10, bui50 and Bui100).

The model takes the sewerage into account by assuming a sewer capacity of 20mm/h in a uniform distribution. Further, the water flow is not only based on land elevations, but also on the roughness of the area and the infiltration rate.

- Housing is schematized as areas with very high roughness (3.0) and infiltration capacity. This means effectively that housing is not used in the flow model;
- Surface water is given a very high infiltration capacity; water flowing into surface water bodies will therefore be absorbed;
- Materials applied as in Table 31;

**Table 31 Material characteristics that have been used in the overland flow modeling.**

| Material | Roughness (Manning n) | Infiltration (initial/continuing) mm/h |
|---|---|---|
| Green zones | 0.06 | 60/20 |
| Housing | 1.0 | 500/500 |
| Impervious | 0.02 | 20/20 |
| Surface water | 0.03 | 500/500 |

Other settings that have been applied are listed below:

- Time step set at 1 second (less than half the size of the grid cells which is recommended);
- Wetting/Drying is only applied for inundation values below 2mm;
- No data values (housing blocks) interpolated to obtain continuous surface;
- Simulations cover 3 hours;
- Rainstorm contour follows geometry of the area. Within that contour rainfall is distributed uniformly;
- Boundary condition: outside area elevations are set to lower altitudes. This effectively means that water can flow away from the study area.
- Max. Depth values have been reclassified in cm inundation <0,1],[1,2], etc.

## A4.2 Limitations of applied modelling method

The model should be treated as a rough method for assessing overland flow. The following drawbacks to the method reduce the validity of the model results:

- Capacity of storm water drainage network is never uniformly distributed; the 20mm/h capacity might in some areas be overestimated while in others underestimated (Vergroesen, unpublished);
- Since the model is exclusively a 2d overland flow model, no sewer overflow is taken into account (1d-2d);
- AHN 1, 5m grid used ad DTM might be too coarse. Height differences in sidewalks are not expressed. Relative cell size is large compared to buildings;
- DTM is not checked on the spot and corrected;
- Rainfall contour does not reflect actual rainstorm conditions; ideally historical events should be used with accurate space/time distribution. Currently, radar rainfall imaging in NL is too coarse for this;
- Materials are not verified on the spot. Local roughness and infiltration might be under- or overestimated;
- Schematization of houses causes underestimation of flow especially in dense urban areas;

## A4.3 Attribution of flood levels to buildings

The outcomes of the Overland Flow model comprise a grid-file with water depths. In order to determine the dominant flood level of a building, the following steps have been taken:

- The grid-file with water levels is overlaid with the contours of the building.
- The minimum value of the surrounding grid cells is attributed to the buildings.

This procedure might lead to an underestimation of the flood depths, since it is not known whether the flood level at the doorsteps of buildings is indeed the minimum water level of the surrounding grid cells. The minimum flood level is taken as the flood level of a building, because low lying (not periodically elevated) gardens at the back of buildings might otherwise have resulted in an overestimation of the amount of flooded houses.

# Appendix 5 Calculation of ATPs regarding buildings in Rotterdam

This appendix describes the application of the Adaptation Tipping Point Method in Rotterdam-Noord with regard to flooding of buildings. This appendix describes the steps that have been undertaken in order to calculate the ATPs regarding flooded buildings only. The interpretation of the case study and the description of its policy implications are described in the main text of this thesis. The structure of this appendix is in line with the steps of the Adaptation Tipping Point method:

- A5.1 Define scope, indicators and threshold values
- A5.2 Calculate ATPs
- A5.3 Translate ATPs to time

## A5.1 Define scope, indicators and threshold values.

The scope of the analysis comprises all neighbourhoods in Rotterdam-Noord. ATPs will be calculated on the basis of 2D Overland Flow Modelling (TUFLOW, 2011, AQUAVEO, 2012) on the basis of different standard rainfall events. A distinction is made between residential, commercial and public buildings. Public buildings were initially included, but in the end removed again, so they are not mentioned in the remainder of this case study. In none of the calculated scenarios, they were flooded. Further explanation of the choice for the scope of the analysis, the vulnerability indicators and the threshold values is described in chapter 0. Table 32 repeats the vulnerability thresholds that have been applied in this case study.

**Table 32 Scope of the ATP analysis regarding buildings**

| Rainfall event | Return period | Threshold |
|---|---|---|
| Bui 8 | 2 years | Percentage of flooded houses in neighbourhood < 0,1%<br>Percentage of flooded commercial buildings < 0,1 %<br>Number of flooded public buildings < 2 |
| Bui 50 | 50 years | Percentage of flooded houses in neighbourhood < 0,5%<br>Percentage of flooded commercial buildings < 0,51%<br>Number of flooded public buildings < 2 |
| Bui 100 | 100 years | Percentage of flooded houses in neighbourhood < 1%<br>Percentage of flooded commercial buildings < 1%<br>Number of flooded public buildings < 2 |

## A5.2 Calculate ATP

A number of steps have been taken to calculate the ATPs. First, a 2D overland flow model (TUFLOW, 2011, AQUAVEO, 2012) has been used to calculate the water levels for all rainfall scenarios and climate change factors. Second, an intersection has been made of the grid-based model outcomes and a vector-based file with the buildings, resulting in one water level per building. These steps have been described more extensively in 0 Third, doorstep heights have been investigated with the use of Google Streetview to determine the maximum water level that does not enter buildings. Fourth, the doorstep height has been subtracted from the water level. In this step it is assessed which buildings were flooded. Fifth, the file with flooded buildings is analysed in order to determine whether the threshold value is reached. Sixth, the scenario with the lowest climate change factor that leads to exceeding of the vulnerability threshold determines the driver-based headroom.

### A5.2.1. Flood modelling

0describes the steps that have been taken by William Veerbeek in order to calculate the water depths at buildings. For each of the rainfall events, bui 8, bui 50 and bui 100, in combination with climate change factors of 0%, 5%, 10%, 15%, 25%, and 50%, flood levels have been modelled. In order to get all missing flood depth values for the 5% intervals, a simple linear interpolation has been applied. The flood depth values at a climate change factor of 55% have been extrapolated linearly on the basis of the 25%-50% values.

The flood maps of Figure 23 show that the extent of flooding increases when the climate factor increases. This is an expected result. It was also expected that the rainfall events that statistically happen less frequently (with a higher return period), lead to a higher extent of flooding. This can also be observed in the results.

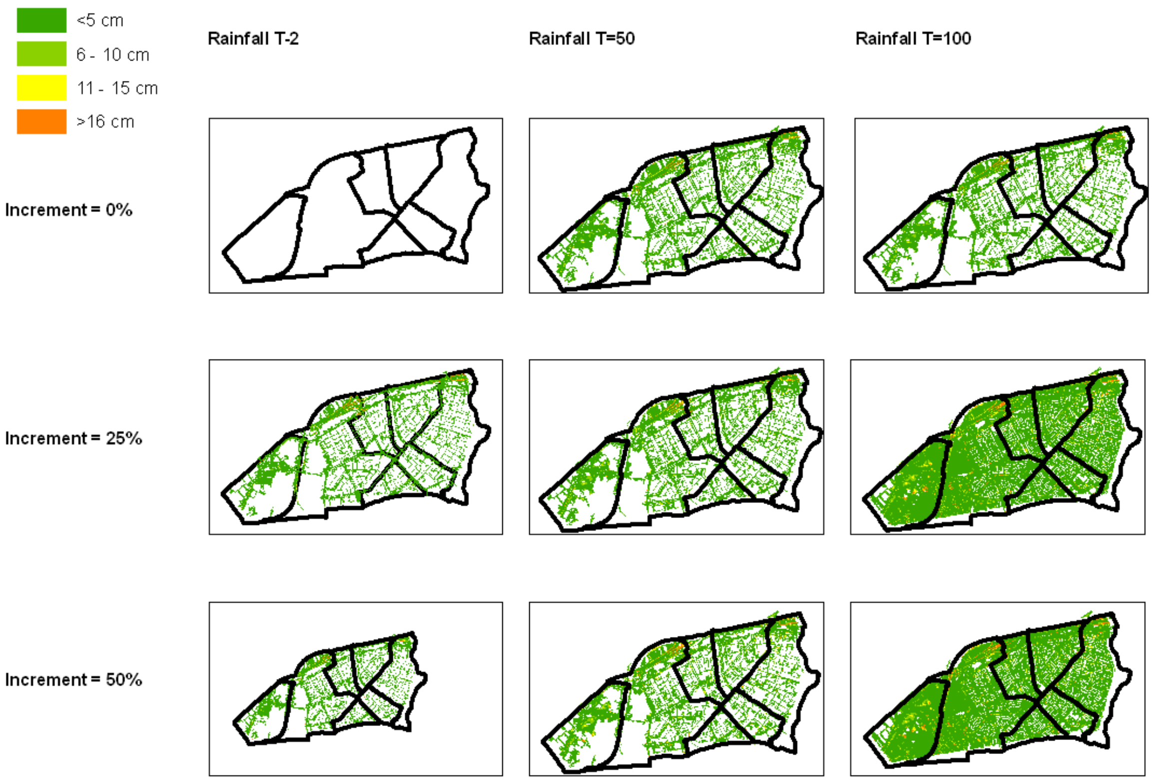



Figure 23 outcomes of the 2D overland flow modelling (T=2, 50 and 100 years and increment=0%, 25% and 50%)

Figure 24 shows the flood extent. It can be seen that the curves have a plausible shape. There is a large flooded area with limited water levels and a limited area with high water levels. Increasing climate change factors lead to an increase of water depths. Further it can be seen that the curves for Bui8, 50 and 100 with increasing return periods and rainfall volumes are positioned in the expected order, thus rainfall events with a higher return period lead to higher water levels and a larger flooded area.

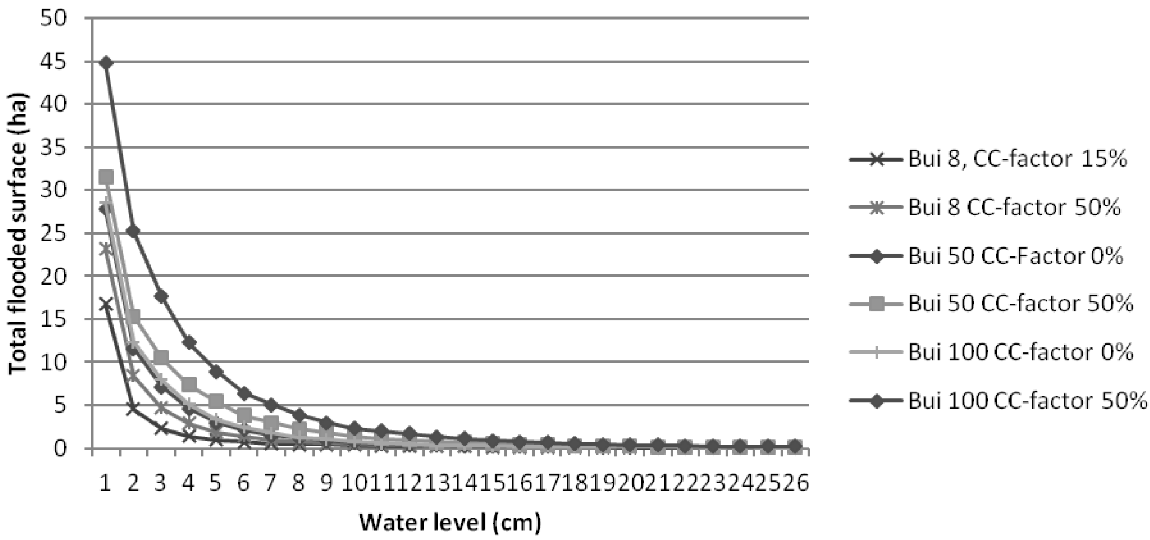



Figure 24 Extent of flooding, based on a count of the number of grid cells with water level

## A5.2.2 Step 2: Analysis of flooded houses

Figure 25 shows the number of buildings that have the water level that is shown on the horizontal axis under bui 8. The doorstep height is not taken into account in this graph. Although the number of buildings with low water levels is higher for high climate change factors, it can be seen that lower climate change factors generate a higher number of buildings with higher water levels. This result is not in line with the expected increase of water levels at increasing rainfall volumes and intensities.

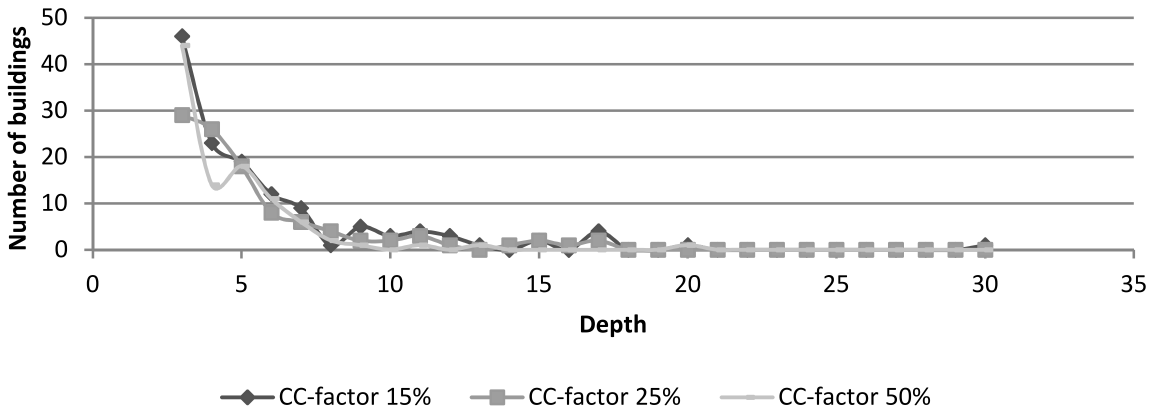



Figure 25 Distribution of water levels at different buildings at Bui 8 for different climate change factors

Figure 26 shows the distribution of water levels at the buildings under bui 50 for different climate change factors. In this figure it can be seen that higher climate change factors in general lead to higher water levels at buildings, which is according to the expectations

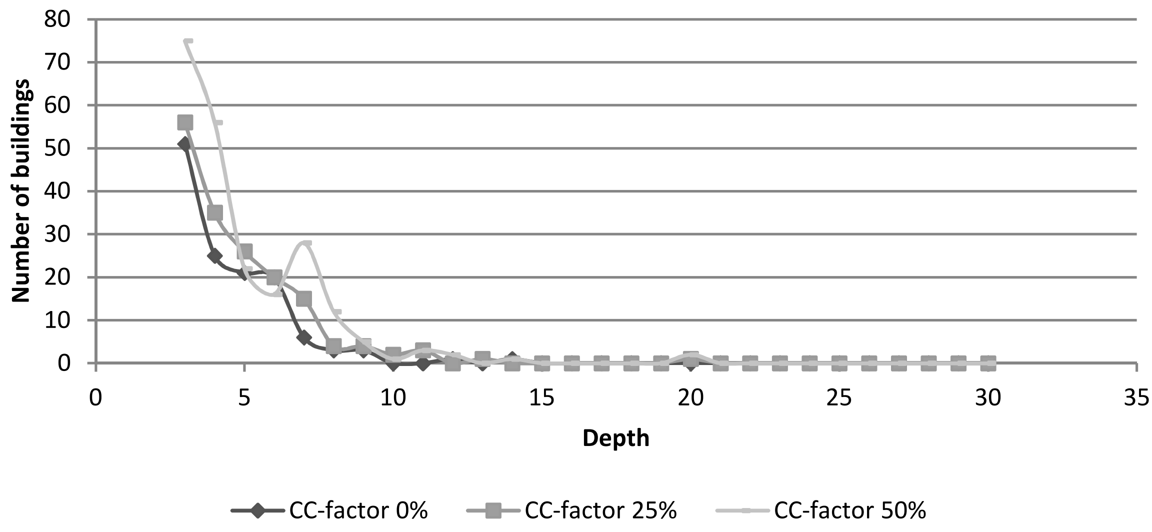



Figure 26 Distribution of water levels at different houses at Bui 50 for different climate change factors under bui 50.

Figure 27 shows that the results for bui 100 and climate change factors 0%, 25% show plausible results in terms of increasing water levels under increasing climate change factors. The water levels under climate change factor 50% are lower than those under smaller climate change factors, which is not expected.

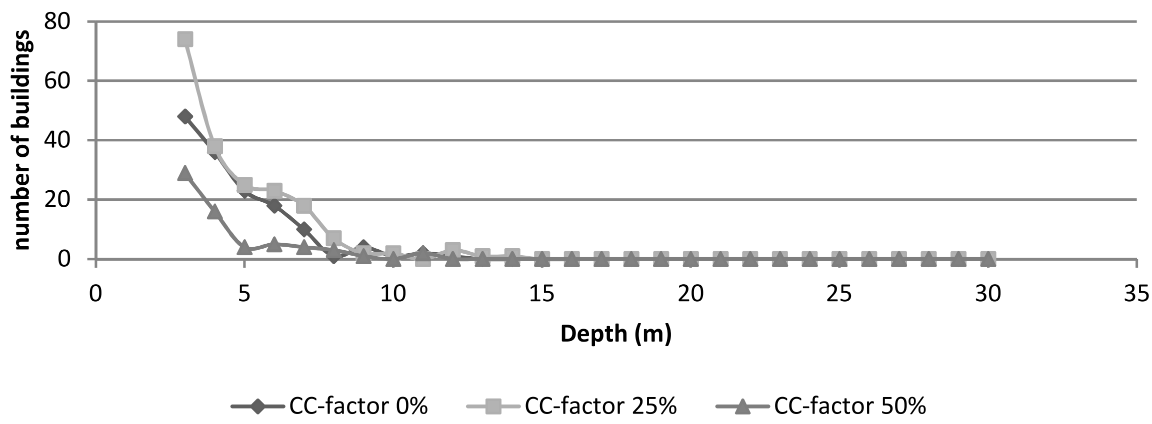



Figure 27 Distribution of water levels at different houses at Bui 100 for different climate change factors

Figure 28 shows the water levels of the different rainfall events under the same climate change factor. If the water levels at buildings are compared for different rainfall events under the same climate change factor, the following conclusions can be drawn:

- Under climate change factor 15% there are more houses with a relatively high water depth under bui 8 than under bui50 and bui100. This can lead to more flooded houses under bui8 than bui 50 and bui100, which is not plausible.
- The results of climate change factor 25% seem plausible
- Under climate change factor 50%, Bui 50 seems to lead to higher water levels than bui 100, which is not expected.

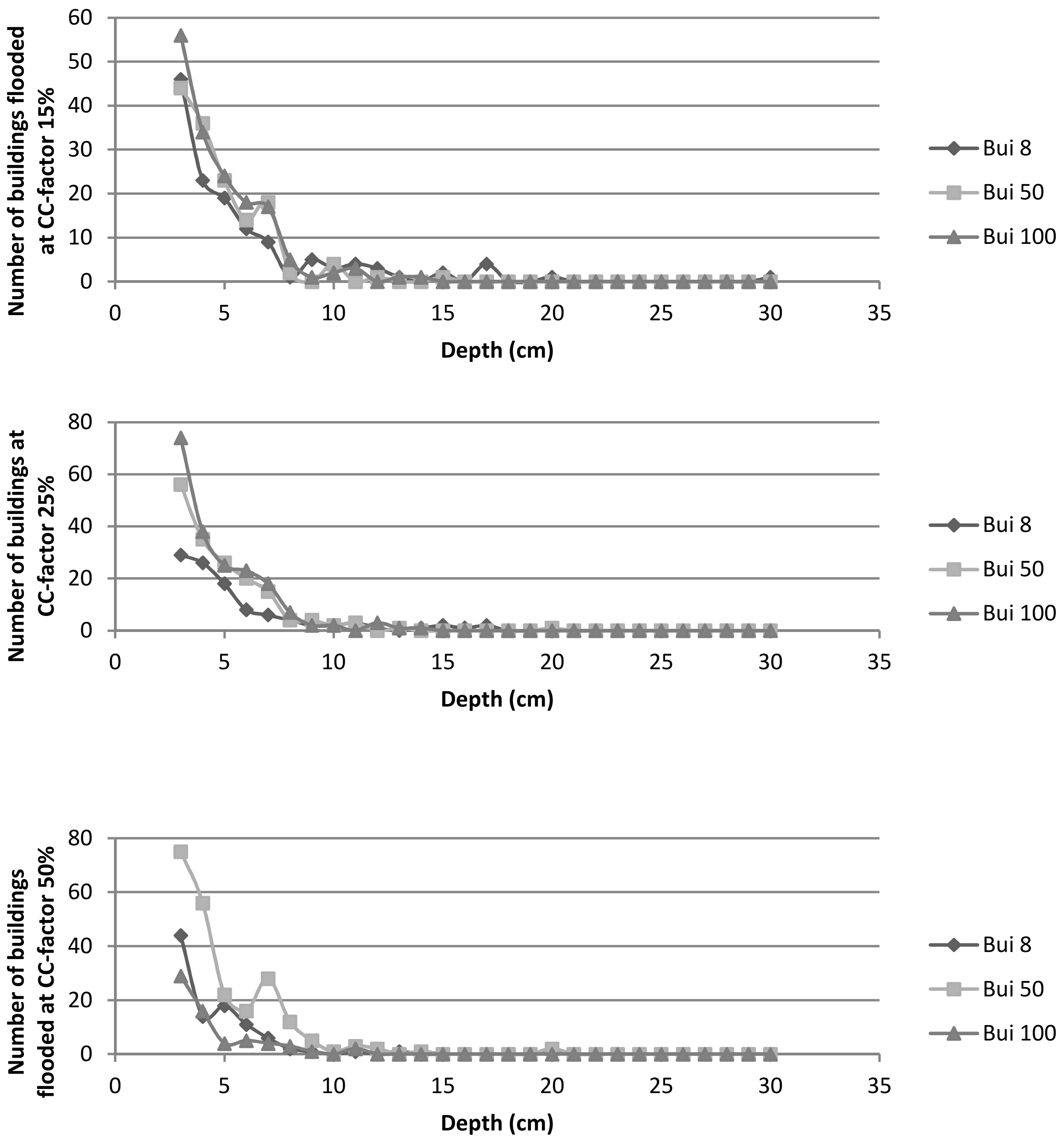



Figure 28 Comparison of flooded buildings under same climate change factor

### A5.2.3 Investigate the doorstep heights

Since flood heights are very low in flat areas, small details in the design of buildings can decide where the water is entering buildings and where water just remains outside. In order to avoid the need of making general assumptions about the doorstep heights, an analysis is made of the doorsteps with the use of Google Streetview. This analysis is conducted for residential buildings where the water level has been calculated as higher than 10 cm and commercial and public buildings where the water level was higher than 5 cm, according to the model. Estimating exact doorstep heights on the basis of Google Earth is difficult, but as a start, an analysis of the amount of stair steps is made. The doorstep height has been calculated on the basis of an assumed stair step height of 10 cm. A short field visit showed that most stair step heights were within the range of 10-18 cm. It was expected that many shops have lower doorsteps, but this could not be seen in most of the shops in the area. Factors that also could lead to flooding in houses, such as ventilation holes and potentially leaking cellar windows, have not been taken into account.

### A5.2.4 Calculate number of flooded buildings

A house floods if the flood depth exceeds the doorstep height. For each building the doorstep height has been subtracted from the flood depth. If the resulting value was positive, the house was assumed to be flooded.

### A5.2.5 Analysing the results

In order to analyse whether the vulnerability threshold is exceeded, it has been calculated how many residential, commercial and public buildings were flooded per neighbourhood. For each neighbourhood and for every climate change factor it has been calculated if the percentage of flooded buildings exceeded the vulnerability threshold. The results for bui8, bui50 and bui100 are shown in Table 33, Table 34 and Table 35 respectively. The shaded table cells indicate that the vulnerability threshold has been exceeded. Since no public buildings were flooded in any of the scenarios, they have not been included.

Bui8 leads to constraints to the headroom. Since the number of houses with high water levels is higher under the 15% climate change factor than under the other climate change factors, it is no surprise that the number of flooded buildings under the 15% climate change factor scenario is higher as well. Interpretation of this table is not straightforward. If the models are assumed to be plausible it should be concluded that the headroom in most of the neighbourhoods is 15%.

Under other standard rainfall events, bui 50 and bui 100, no buildings get flooded except for one commercial building in Liskwartier. Since there are only 53 shops in Liskwartier, this leads to exceeding of the vulnerability threshold, which is defined on the basis of the percentage of flooded shops in relation to the total amount of shops in the neighbourhood.

A table with all headrooms is presented in Table 36. The headrooms should be assessed with utmost care, since they are based on very strict vulnerability thresholds that allow very few buildings to flood. In effect, the model results are not plausible and more validation is strongly recommended.

**Table 33 Number of flooded buildings under bui8**

| Neighbourhood | Type of building | 0% | 5% | 10% | 15% | 20% | 25% | 30% | 35% | 40% | 45% | 50% | 55% |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Agniesebuurt | Commercial | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Residential | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Bergpolder | Commercial | 0 | 0 | 0 | 2 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Residential | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 1 |
| Blijdorp | Commercial | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Residential | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Liskwartier | Commercial | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Residential | 0 | 0 | 0 | 6 | 1 | 2 | 1 | 1 | 0 | 0 | 0 | 0 |
| Oude Noorden | Commercial | 0 | 0 | 0 | 1 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| | Residential | 0 | 0 | 0 | 3 | 0 | 2 | 1 | 0 | 0 | 0 | 0 | 0 |
| | Vacant | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Provenierswijk | Commercial | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Residential | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Table 34 Number of flooded buildings under bui50

| Neighbourhood | Type of building | 0% | 5% | 10% | 15% | 20% | 25% | 30% | 35% | 40% | 45% | 50% | 55% |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Agniesebuurt | Commercial | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Residential | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Bergpolder | Commercial | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Residential | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 |
| Blijdorp | Commercial | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Residential | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Liskwartier | Commercial | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 |
| | Residential | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| Oude Noorden | Commercial | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Residential | 0 | 0 | 0 | 1 | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 6 |
| | Vacant | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Provenierswijk | Commercial | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Residential | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

**Table 35 Number of flooded buildings under bui100**

| Neighbourhood | Type of building | 0% | 5% | 10% | 15% | 20% | 25% | 30% | 35% | 40% | 45% | 50% | 55% |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Agniesebuurt | Commercial | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Residential | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Bergpolder | Commercial | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Residential | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| Blijdorp | Commercial | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Residential | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Liskwartier | Commercial | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 |
| | Residential | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| Oude Noorden | Commercial | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Residential | 0 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 2 | 2 | 3 |
| | Vacant | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Provenierswijk | Commercial | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Residential | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Table 36 Overview of headrooms for all vulnerability thresholds in all neighbourhoods

| | Commercial buildings | | | Residential buildings | | |
|---|---|---|---|---|---|---|
| **Return periods** | **1/2 Y** | **1/50 Y** | **1/100 Y** | **1/2 Y** | **1/50 Y** | **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% |

## A5.3 Translate ATPs into time

The timing of ATPs has been calculated on the basis of current one-hour rainfall volumes and the projected one-hour rainfall volumes (see Table 37), which have been supplied by the KNMI (Klein Tank and Lenderink, 2009). Since the volumes of the rainfall events with the return periods that are used in this thesis are not provided, it is assumed that:

- the increase of the volume of bui 8 resembles the increase in one-hour rainfall event with a 1-year return period
- the increase of the volumes of bui 50 and bui 100 resemble the increase in one-hour rainfall event with a 100-year return period
-

Table 37 Current and projected one-hour rainfall volumes under KNMI G and W climate scenario (Klein Tank and Lenderink, 2009).

| | 2010 | 2050 | |
|---|---|---|---|
| **Return period** | | **G** | **W** |
| 1 year | 14 | 15 | 17 |
| 10 years | 27 | 30 | 33 |
| 100 years | 43 | 48 | 53 |

The conversion from the headroom to the timing of the ATP has been done with the use of the following formulae ($T_{ATP,G}$ and $T_{ATP,W}$ =timing of ATP under KNMI G and W, H = headroom):

$$\text{Bui 8: } T_{ATP,G} = \frac{2050 - 2010}{(15 - 14)/14} \times H + 2010 = 560 \times H + 2010$$

$$\text{Bui 8: } T_{ATP,W} = \frac{2050 - 2010}{(17 - 14)/14} \times H + 2010 = 186{,}7 \times H + 2010$$

$$\text{Bui 50 and Bui 100: } T_{ATP,G} = \frac{2050 - 2010}{(48 - 43)/43} \times H + 2010 = 344 \times H + 2010$$

$$\text{Bui 50 and Bui 100: } T_{ATP,W} = \frac{2050 - 2010}{(53 - 43)/43} \times H + 2010 = 172 \times H + 2010$$

Table 38 shows the end result of the calculations of the timings of ATPs. They should be interpreted with the strict vulnerability thresholds and the inaccuracy of the used methodology in mind. The results show that Bui 8 leads to an exceeding of the maximum percentage of flooded houses and shops in a number of neighbourhoods in 2038 under the KNMI W scenario (under the G scenario this threshold is reached in 2094). Other thresholds are exceeded after 2100.

**Table 38 Timings of ATPs in all neighbourhoods**

| Agniesebuurt | KNMI G | KNMI W |
|---|---|---|
| bui100, %houses_flooded<1% | 2199 | 2105 |
| bui100, %shops_flooded<1% | 2199 | 2105 |
| bui50, %houses_flooded<0,5% | 2199 | 2105 |
| bui50, %shops_flooded<0,5% | 2199 | 2105 |
| bui8, %houses_flooded<0,1% | 2318 | 2113 |
| bui8, %shops_flooded<0,1% | 2318 | 2113 |
| Bergpolder | KNMI G | KNMI W |
| bui100, %houses_flooded<1% | 2199 | 2105 |
| bui100, %shops_flooded<1% | 2199 | 2105 |
| bui50, %houses_flooded<0,5% | 2199 | 2105 |
| bui50, %shops_flooded<0,5% | 2199 | 2105 |
| bui8, %houses_flooded<0,1% | 2318 | 2113 |
| bui8, %shops_flooded<0,1% | 2094 | 2038 |
| Blijdorp | KNMI G | KNMI W |
| bui100, %houses_flooded<1% | 2199 | 2105 |
| bui100, %shops_flooded<1% | 2199 | 2105 |
| bui50, %houses_flooded<0,5% | 2199 | 2105 |
| bui50, %shops_flooded<0,5% | 2199 | 2105 |
| bui8, %houses_flooded<0,1% | 2318 | 2113 |
| bui8, %shops_flooded<0,1% | 2318 | 2113 |
| Liskwartier | KNMI G | KNMI W |
| bui100, %houses_flooded<1% | 2199 | 2105 |
| bui100, %shops_flooded<1% | 2113 | 2062 |
| bui50, %houses_flooded<0,5% | 2199 | 2105 |
| bui50, %shops_flooded<0,5% | 2113 | 2062 |
| bui8, %houses_flooded<0,1% | 2094 | 2038 |
| bui8, %shops_flooded<0,1% | 2318 | 2113 |
| Oude Noorden | KNMI G | KNMI W |
| bui100, %houses_flooded<1% | 2199 | 2105 |
| bui100, %shops_flooded<1% | 2199 | 2105 |
| bui50, %houses_flooded<0,5% | 2199 | 2105 |
| bui50, %shops_flooded<0,5% | 2199 | 2105 |
| bui8, %houses_flooded<0,1% | 2094 | 2038 |
| bui8, %shops_flooded<0,1% | 2094 | 2038 |
| Provenierswijk | KNMI G | KNMI W |
| bui100, %houses_flooded<1% | 2199 | 2105 |
| bui100, %shops_flooded<1% | 2199 | 2105 |
| bui50, %houses_flooded<0,5% | 2199 | 2105 |
| bui50, %shops_flooded<0,5% | 2199 | 2105 |
| bui8, %houses_flooded<0,1% | 2094 | 2038 |
| bui8, %shops_flooded<0,1% | 2318 | 2113 |

# Appendix 6 Traffic nuisance Rotterdam

This appendix describes the steps that have been taken to calculate the ATPs regarding traffic nuisance in Rotterdam-Noord. The appendix is structured in accordance with the steps of the Adaptation Tipping Point-method (ATP-method):

1. Define scope
2. Determine indicators and threshold values
3. Calculate ATPs
4. Translate ATPs into time

## A6.1 Define scope

Only the larger traffic roads have been taken into account. Blockage of streets has not been considered to affect the accessibility of the area to a great extent. Figure 29 shows the roads that have been taken into account.

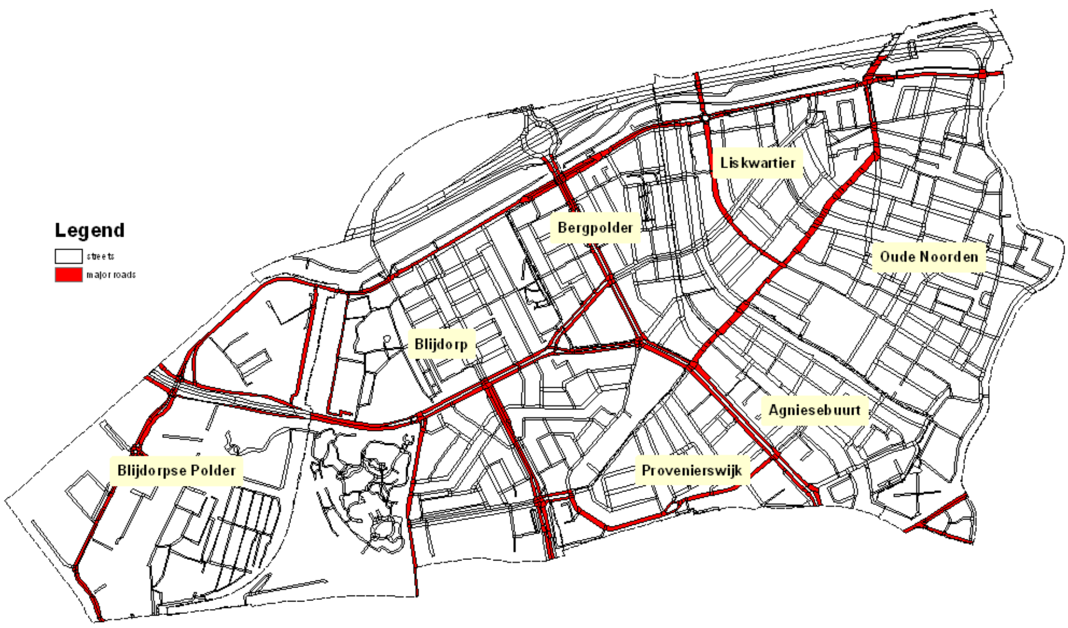



Figure 29 Major roads in Rotterdam-Noord

In order to prepare the data for analysis of traffic nuisance, the roads have been divided in road segments. A road segment can be a crossing or a single road that connects two crossings. These are the steps that made it possible to divide the road into road segments:

1. All original road segments have a different identifier, shown in the left part of Figure 30 through the different colours. First a common attribute has been given to the road segments, separating crossings and roads in between the crossings. The new division is shown in the right part of Figure 30
2. Then the dissolve tool in ArcGIS is used to combine the road segments.

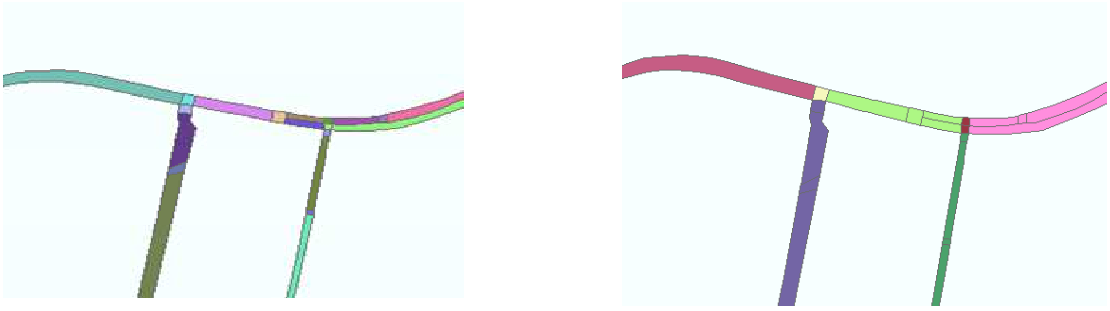


Figure 30 Dissolving road elements

## A6.2 Determine indicators and threshold values

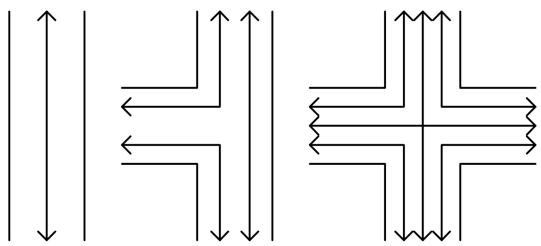
For traffic nuisance a simple indicator has been developed. The indicator is based on the multiplication of the Depth Classes (exposure) with the Road Importance (sensitivity). Table 39 shows the applied categories of depth classes. The most severe category of traffic nuisance is blockage, which has a value of 1. Severe traffic nuisance is considered to be half as important as blockage, so it gets a value of 0,5. These classifications have been determined on a subjective basis and should be further based on objective arguments or discussed with stakeholders.

Table 39 Depth classes

| Depth | Classification | Depth class(DC) |
|---|---|---|
| 0-5 cm | No nuisance | 0 |
| 5-10cm | Nuisance | 0,5 |
| 10 cm | Blockage | 1 |

In addition it has been taken into account how many major roads are connected to the road segments. The idea behind this is that the amount of traffic nuisance mainly depends on the number of accessible connections in the road network. A blocked straight road hinders 2 driving directions. A blocked T-crossing hinders 6 driving directions and a blocked normal crossing hinders 12 directions.

Table 40 Road Importance



| Type of road | Road Importance (RI) |
|---|---|
| Straight road segments without crossings | 1 |
| T-crossings | 3 |
| Regular crossings | 6 |

Dividing the multiplication of the Depth Classes with the Road Importances by the sum of the depth-classes is done to make the indicator easier to understand. The indicator has a value of 1 if all road segments are blocked and a value of 0 if none of the road segments are blocked and if no nuisance is cased in any of the road segments.

Traffic nuisance index $= \frac{1}{\sum DC_{ij}} \sum RI_i \times DC_{ij}$ , i = road segment and j=climate change factor

The indicator does not take into account the duration of the flooding. It also does not take into account actual traffic intensity, the number of lanes, possible easy detours, number of connections to small streets and the length of road segments. Further research into better measures for traffic nuisance on city or neighbourhood scales should be conducted.

In this case study the threshold values for traffic nuisance have been chosen arbitrarily. The chosen vulnerability indices are presented in Table 41.

**Table 41 Chosen threshold values for traffic nuisance in Rotterdam-Noord**

| Standard rainfall event | Vulnerability threshold |
|---|---|
| Bui 8 | Traffic nuisance index = 10% |
| Bui 50 | Traffic nuisance index = 30% |
| Bui 100 | Traffic nuisance index = 35% |

## A6.3 Calculate ATPs

In order to calculate the flood depths on the roads, the outcomes of the flood model (raster-file) have been intersected with the roads. After that, the flood depths have been dissolved on the basis of the maximum water depths in each road segment. This makes it likely that the method overestimated the flood depths, especially on large road segments.

Figure 31 shows the roads on which  only nuisance is caused and completely blocked road segments. Please note that each segment only has one colour, so large areas of red do not mean that the complete road segment is blocked over its entire length. There is at least one grid cell that exceeds 10 cm in this specific road segment.

It can be seen that the extent of flooding increases with the return periods of the rainfall events. Further it can be seen that most of the road segments that flood under rainfall events with lower return periods, also flood under rainfall events with higher return periods. Under bui 8 however, a small number of road segments flood while these do not flood under more extreme rainfall events. The figures do not show any further unexpected results.

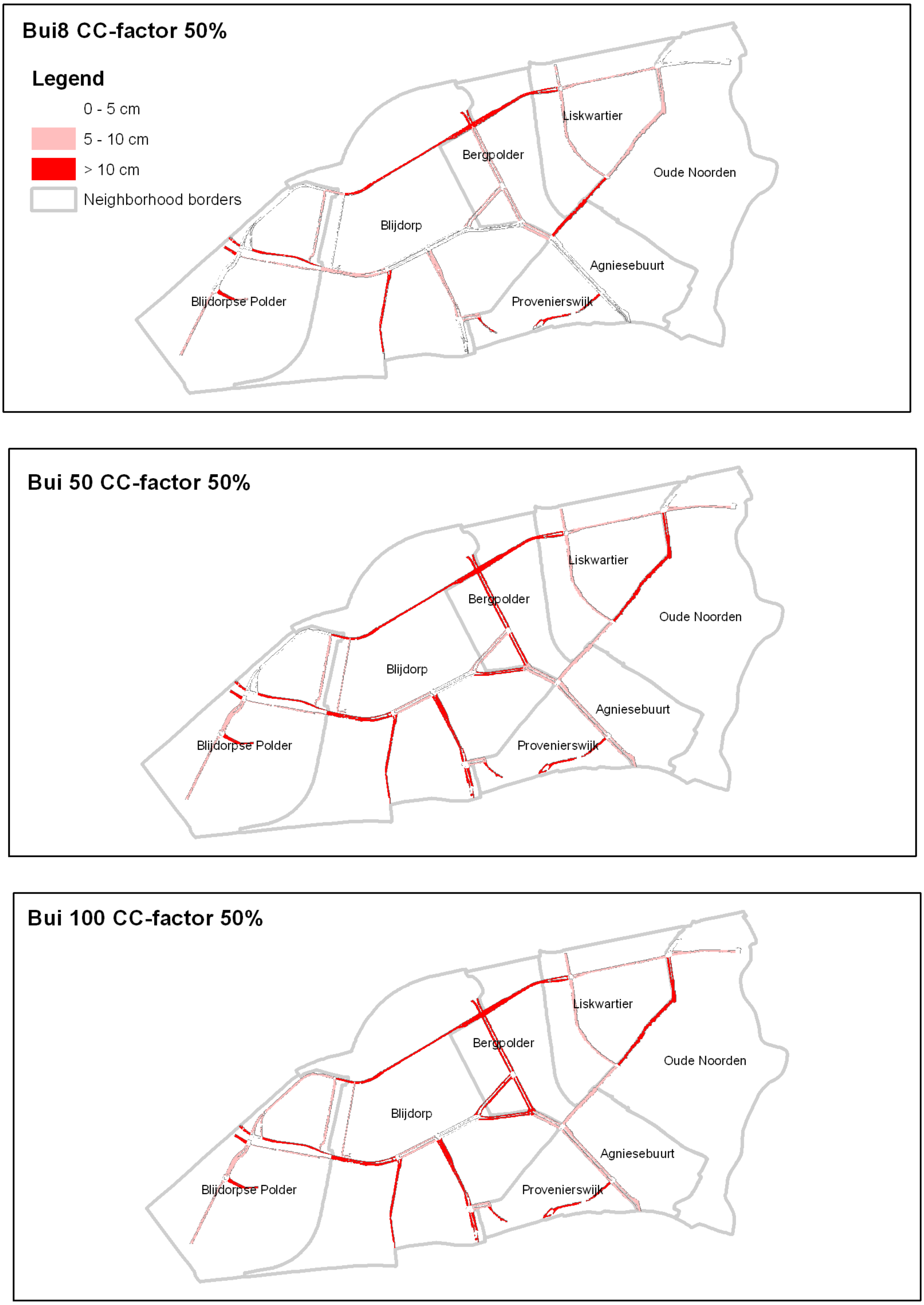



**Figure 31 traffic nuisance on roads for all rainfall events with CC-factor 50%**

The vulnerability thresholds have been calculated for all rainfall events and climate change factors. The climate change factors that have not been calculated are estimated on the basis of a linear interpolation. Then all calculated scenarios are compared with the vulnerability thresholds. The results of the calculations are shown in Figure 32.

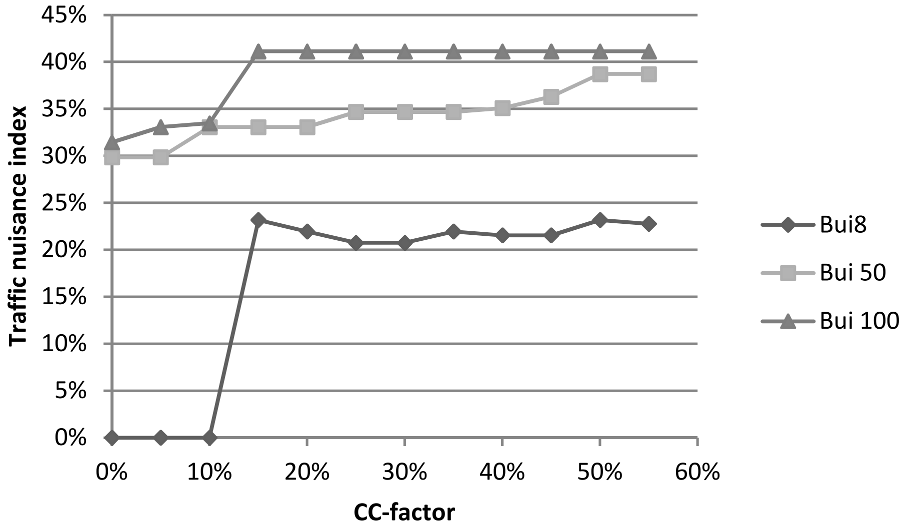



**Figure 32 Scores on traffic nuisance index**

The threshold values for each of the standard rainfall events are different, as shown in Table 41. Table 42 presents the headrooms that are calculated. The headrooms are determined by the maximum climate change factor that does not lead to an exceeding of the threshold value.

**Table 42 Headrooms regarding traffic nuisance**

| Standard rainfall event | Threshold value | Headroom |
|---|---|---|
| Bui 8 | 10% | 15% |
| Bui 50 | 30% | 10% |
| Bui 100 | 35% | 15% |

## A6.4 Translate ATPs into time

The timing of ATPs has been calculated on the basis of current one-hour rainfall volumes and the projected one-hour rainfall volumes (see Table 37), which have been supplied by the KNMI (Klein Tank and Lenderink, 2009). Since the volumes of the rainfall events with the return periods that are used in this thesis are not provided, it is assumed that:

- the increase of the volume of bui 8 resembles the increase in one-hour rainfall event with a 1-year return period
- the increase of the volumes of bui 50 and bui 100 resemble the increase in one-hour rainfall event with a 100-year return period
-

**Table 43 Current and projected one-hour rainfall volumes under KNMI G and W climate scenario (Klein Tank and Lenderink, 2009).**

| | 2010 | 2050 | |
|---|---|---|---|
| **Return period** | | **G** | **W** |
| 1 year | 14 | 15 | 17 |
| 10 years | 27 | 30 | 33 |
| 100 years | 43 | 48 | 53 |

The conversion from the headroom to the timing of the ATP has been done with the use of the following formulae ($T_{ATP,G}$ and $T_{ATP,W}$ =timing of ATP under KNMI G and W, H = headroom):

$$\text{Bui 8: } T_{ATP,G} = \frac{2050 - 2010}{(15 - 14)/14} \times H + 2010 = 560 \times H + 2010$$

$$\text{Bui 8: } T_{ATP,W} = \frac{2050 - 2010}{(17 - 14)/14} \times H + 2010 = 186{,}7 \times H + 2010$$

$$\text{Bui 50 and Bui 100: } T_{ATP,G} = \frac{2050 - 2010}{(48 - 43)/43} \times H + 2010 = 344 \times H + 2010$$

$$\text{Bui 50 and Bui 100: } T_{ATP,W} = \frac{2050 - 2010}{(53 - 43)/43} \times H + 2010 = 172 \times H + 2010$$

Table 44 presents the end/results of the calculation of the ATPs regarding traffic nuisance. It can be seen that the ATPs are quite urgent if the KNMI W climate scenario will come out. The analysis shows that further research to the vulnerability of traffic might be useful.

**Table 44 Timing of ATPs regarding traffic nuisance**

| | | | Timing of ATP | |
|---|---|---|---|---|
| **Event** | **Threshold** | **Headroom** | **KNMI G** | **KNMI W** |
| Bui 8 | 10% | 15% | 2094 | 2038 |
| Bui 50 | 30% | 10% | 2044 | 2027 |
| Bui 100 | 35% | 15% | 2062 | 2036 |

# Appendix 7 Case study Nijmegen

This appendix describes the application of the Adaptation Tipping Point (ATP) method in Nijmegen. This appendix is structured along the steps of the ATP-method:

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

## A7.1 Define scope

The analysis also covers parts the neighbourhoods, Stadscentrum, Benedenstad, Biezen completely and parts of Altrade, Hunnerberg, Bottendaal, Galgenveld, Wolfskuil and the industrial area in the west of the city. The neighbourhoods that have not fully been included in the extent of the flood model, are not addressed separately. They have, however, been included in the analysis of the complete project area.

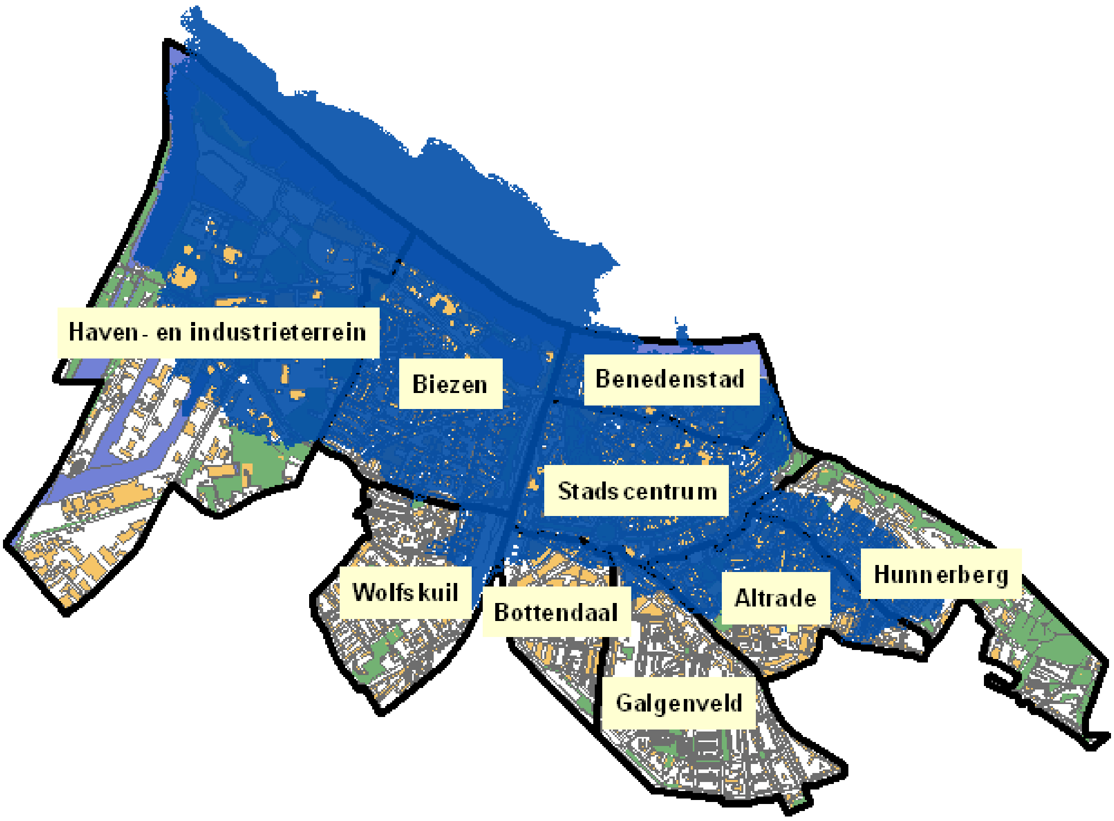



Figure 33 Spatial demarcation of 2D overland flow model

Table 45 shows the number of buildings in the total project area, as well as the neighbourhoods Stadscentrum, Biezen and Benedenstad. The total project area is larger than the sum of the neighbourhoods, since parts of the other neighbourhoods are also included in the total project area.

All types of buildings have been included in the analysis. Side buildings include for example garages, barns and stables (Wevers et al., 2009). There will certainly be side buildings that are not very sensitive to flooding, since their floors are most likely not damaged. However, there are many side buildings that have sensitive objects on the ground floor, such as lawn mowers.

**Table 45 Total number of buildings in the total project area**

| | Main building | Side building | Subsurface building | Planned building | Total |
|---|---|---|---|---|---|
| Total project area | 6421 | 2653 | 3 | 144 | 9221 |
| Benedenstad | 823 | 108 | 2 | 1 | 934 |
| Biezen | 2219 | 1677 | | 1 | 3897 |
| Stadscentrum | 1318 | 137 | 1 | 12 | 1468 |

## A7.2 Formulate indicators and thresholds

The impacts of flooding of buildings have been measured in terms of the number of flooded buildings. A file with all separate functions of buildings on the ground floor is not available. The Basisregistratie Adressen en Gebouwen (BAG), which is available on national scale, makes a distinction between buildings (Dutch: panden) and addresses (Dutch: verblijfsobjecten) (Wevers et al., 2009):

- Buildings are “the smallest functional and constructive independent units (at time of construction) that are directly and sustainably connected to the earth, and that are accessible and closable” (Wevers et al., 2009, p.7). For example, a block of flats is considered as one building. A vector-based file with the polygons of buildings (panden) is available.
- Addresses are “the smallest, independent units within one or multiple buildings that are suitable for residential, commercial or recreational functions...” (Wevers et al., 2009, p.7). Addresses are available in a point-based file.

Figure 34 shows the two files with buildings and use functions. Both files have their limitations. The building-files do not show how many addresses and use functions, such as shops, are integrated in a building. The addresses-file includes many use functions that are not exposed, for example, flat apartments above the first floor. Possibly, the point- file could be combined with the vector-based file. It might be possible to attribute addresses to buildings according a number of rules that eliminate the overestimation of exposed addresses. This could be done by preferring shops and other functions over residential functions in one building, since residential functions are mostly on top of other functions. If multiple shops are included into one building, it could be given a higher weight, since it is likely that many shops are situated on the ground floor. Still the accuracy of the model is limited. Field work should be performed to manually require better data.

Figure 34 Contours of buildings and registered functions. Yellow dots represent commercial function, pink dot represents residential function.

It is chosen to use buildings as basis for the vulnerability indicator in all areas that have not been manually investigated. The doorsteps of the buildings that have been investigated manually have been included separately. The lowest doorstep of all addresses in one building is attributed to the building. No weighting has been performed to account for multiple use functions within one building.

Table 46 shows the applied indicators for vulnerability in Nijmegen. These indicators comprise the percentage of flooded buildings in an area that are flooded. The indicators do not take into account the number of use functions of a building, the sensitivity of buildings and the surface of buildings.

Table 46 Indicators and threshold values in Nijmegen

| 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% |

## A10.3 Determine ATPs

This step of the ATP-method consists of different activities, which are similar to those undertaken in Rotterdam-Noord. Additionally, a sensitivity analysis to the doorstep heights is included.

1. 2D overland flow modelling
2. Combining it with the contours of the buildings.
3. Estimating the doorstep heights
4. Determining the percentages of flooded buildings.
5. Determining at which CC-factor ATPs are reached.
6. Sensitivity analysis

**Step 1: 2D Overland flow modelling**

Appendix 4 describes the steps that have been taken by William Veerbeek in order to calculate the water depths at buildings. For each of the rainfall events, bui 8, bui 50 and bui 100, in combination with climate change factors of 0%, 5%, 10%, 15%, and 50%, flood levels have been modelled. In order to get all missing flood depth values for the 5% intervals, a simple linear interpolation has been applied. The flood depth values at a climate change factor of 55% have been extrapolated linearly on the basis of the 25%-50% values.

The modelling techniques that have been applied in Nijmegen are similar to those applied in Rotterdam. The Digital Elevation Model was however different. In the case of Nijmegen it as based on LIDAR-data with a spread of 1 meter. With the use of Distance Weighted interpolation it has been converted to a 3 meter grid. The vegetation has been removed from the model. Figure 36 shows the outcomes of the analyses for a number of scenarios.

**Step 2: determine flood heights at buildings**

The procedure for this is similar to Rotterdam (see appendix 5). In Figure 37 the results of the steps are shown on maps.

**Step 3: Estimate doorstep heights**

All doorsteps have been assumed to be 10 cm. A sensitivity analysis has been perfumed to test this assumption. The doorstep heights of shops in the shopping areas in the city centre of Nijmegen have been manually assessed by municipality of Nijmegen. Basis of these doorstep heights are addresses, which correspond to "verblijfsobjecten". Since there are multiple "verblijfsobjecten" connected to one building, the lowest measured doorstep has been chosen as the doorstep of the building.

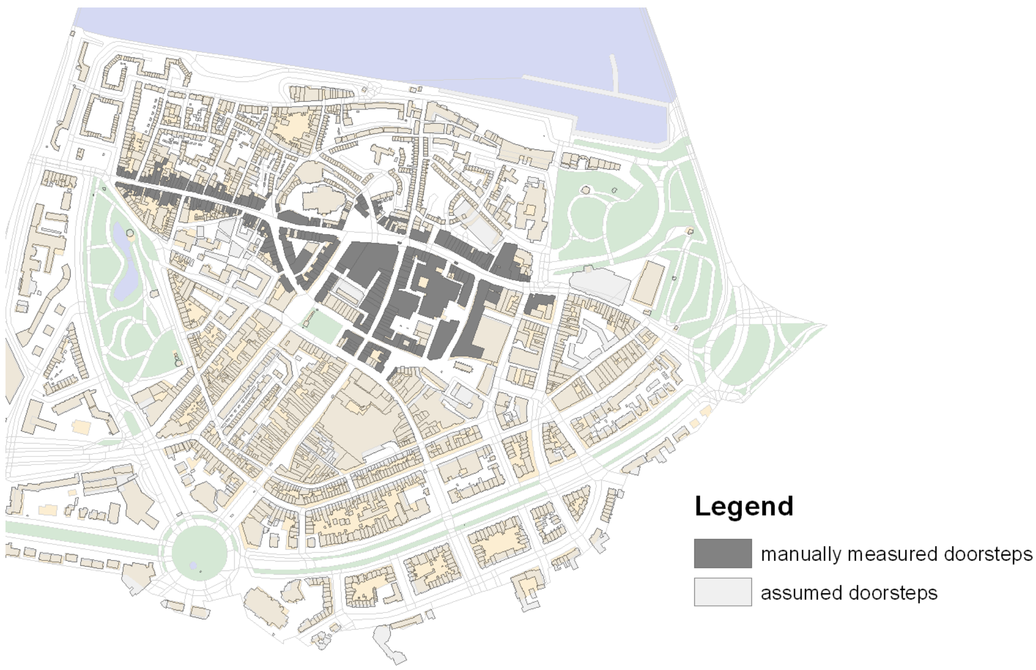



**Figure 35 Manually investigated doorsteps in Nijmegen**

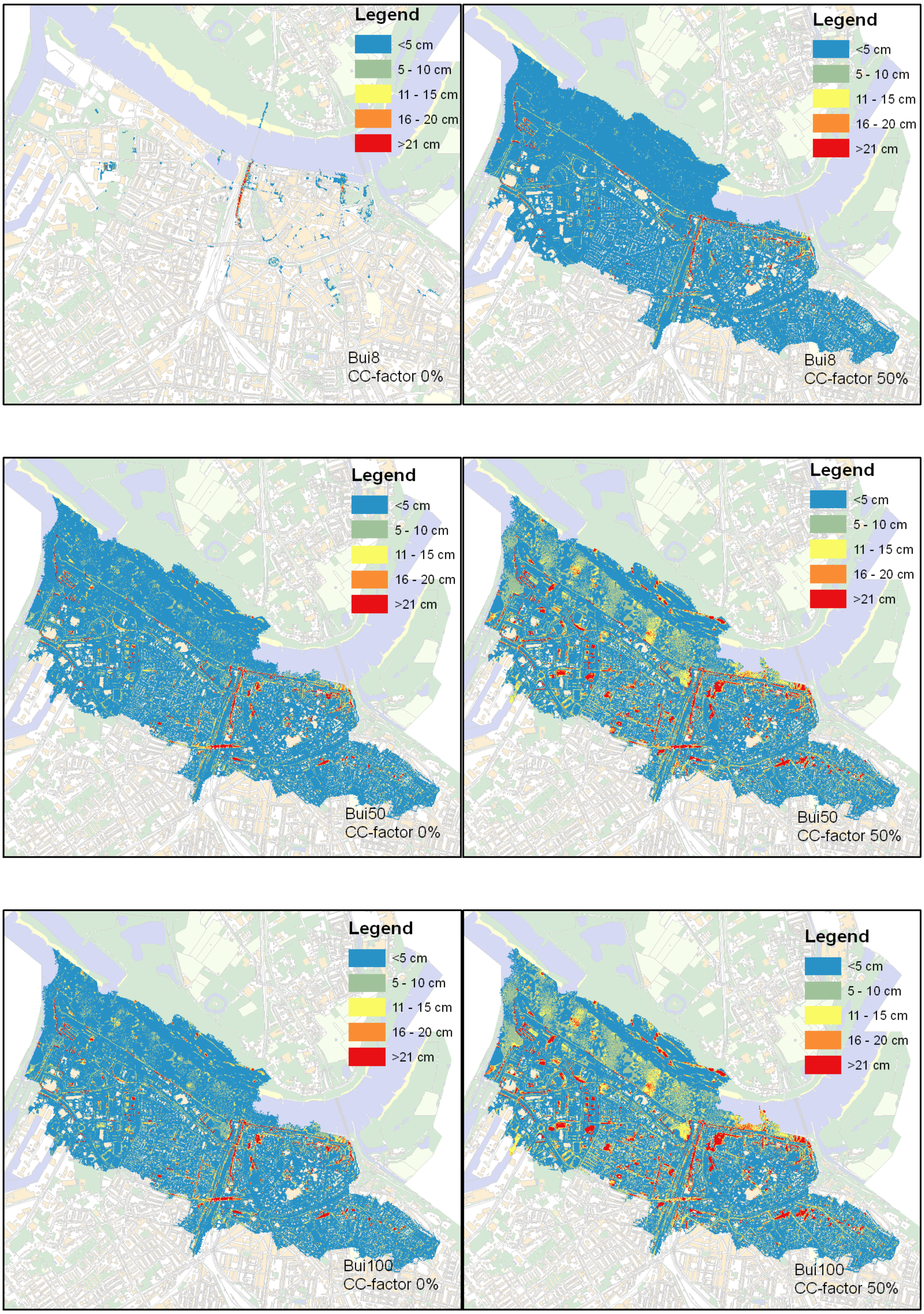



**Figure 36 Results of 2D Overland Flow Modeling**

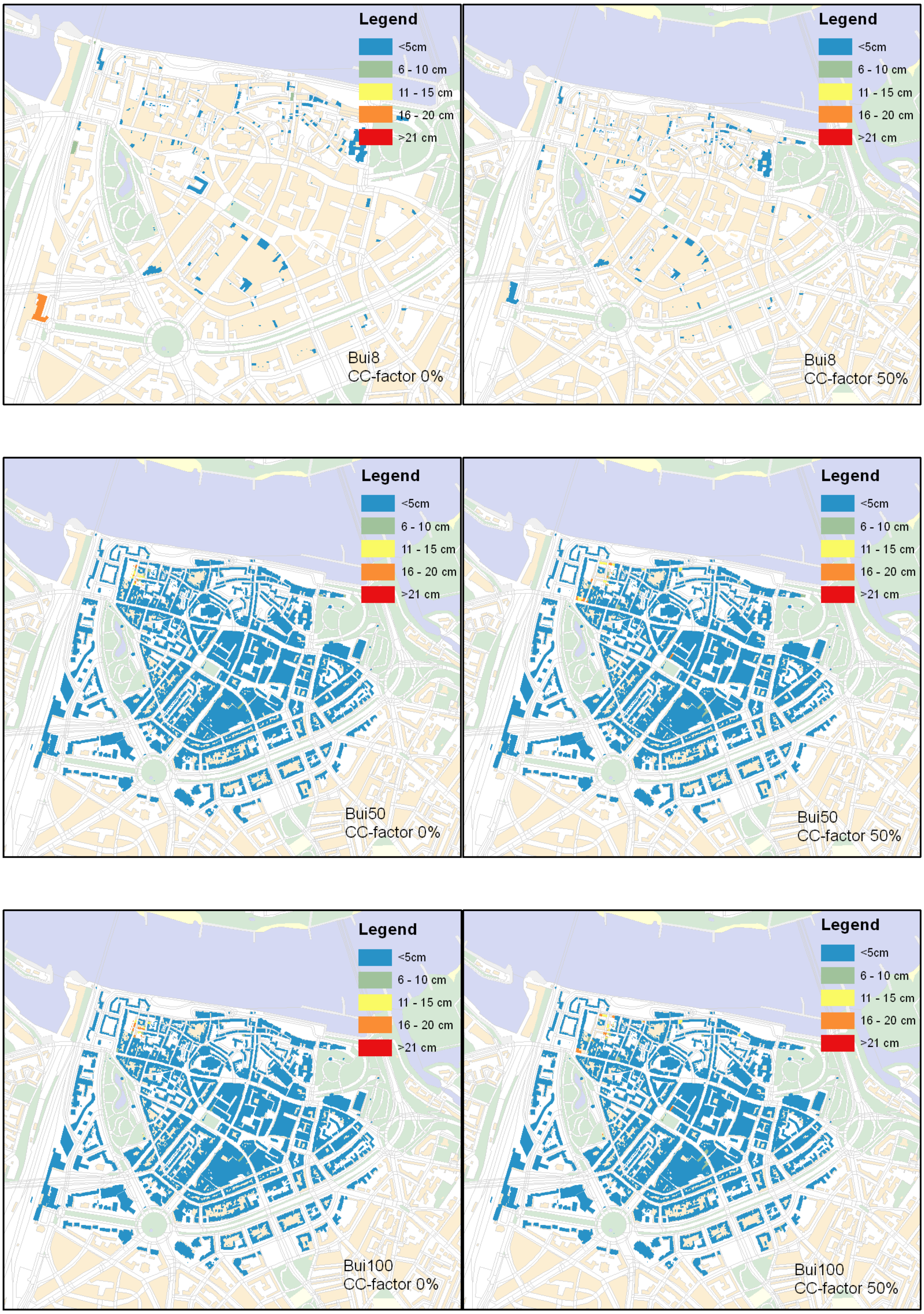



**Figure 37 Water depths at buildings**

**Step 4: determine percentage of flooded buildings**

A building has been considered to flood if the flood level exceeds the doorstep heights. Figure 38 shows maps of the flooded buildings. It can be seen that the amount of flooding under bui 8 is very limited. The differences between Bui 50 and Bui 100 are small. It can be seen that buildings that flood under bui 50 and bui 100 are different from the flooded buildings under bui 8. Figure 39 displays the graphs with the percentages of flooded buildings per neighbourhood and in the complete project area. The horizontal dashed line indicates the threshold value of the ATP. The headroom is determined by the lowest climate change factor at which the threshold value of the ATP-indicator is exceeded. Bars that are higher than the horizontal dashed line indicate that an ATP is reached.

It can be seen that Benedenstad is the area in which the largest percentage of buildings is flooded and in which the increase of flooded buildings under a changing climate is the largest of the areas that are shown. The area Biezen does not show significant flooding of houses in the current extreme situations, but in case of a climate change factor of 55% the percentage of flooded houses exceeds 4%.

Under Bui 8, which occurs once in two years, it can be seen that the percentage of flooded houses does not linearly increase. This is caused by the relatively low flood depths, which reduce the reliability of the results.


Figure 38 Flooded buildings (assumed doorstep height is 10 cm)

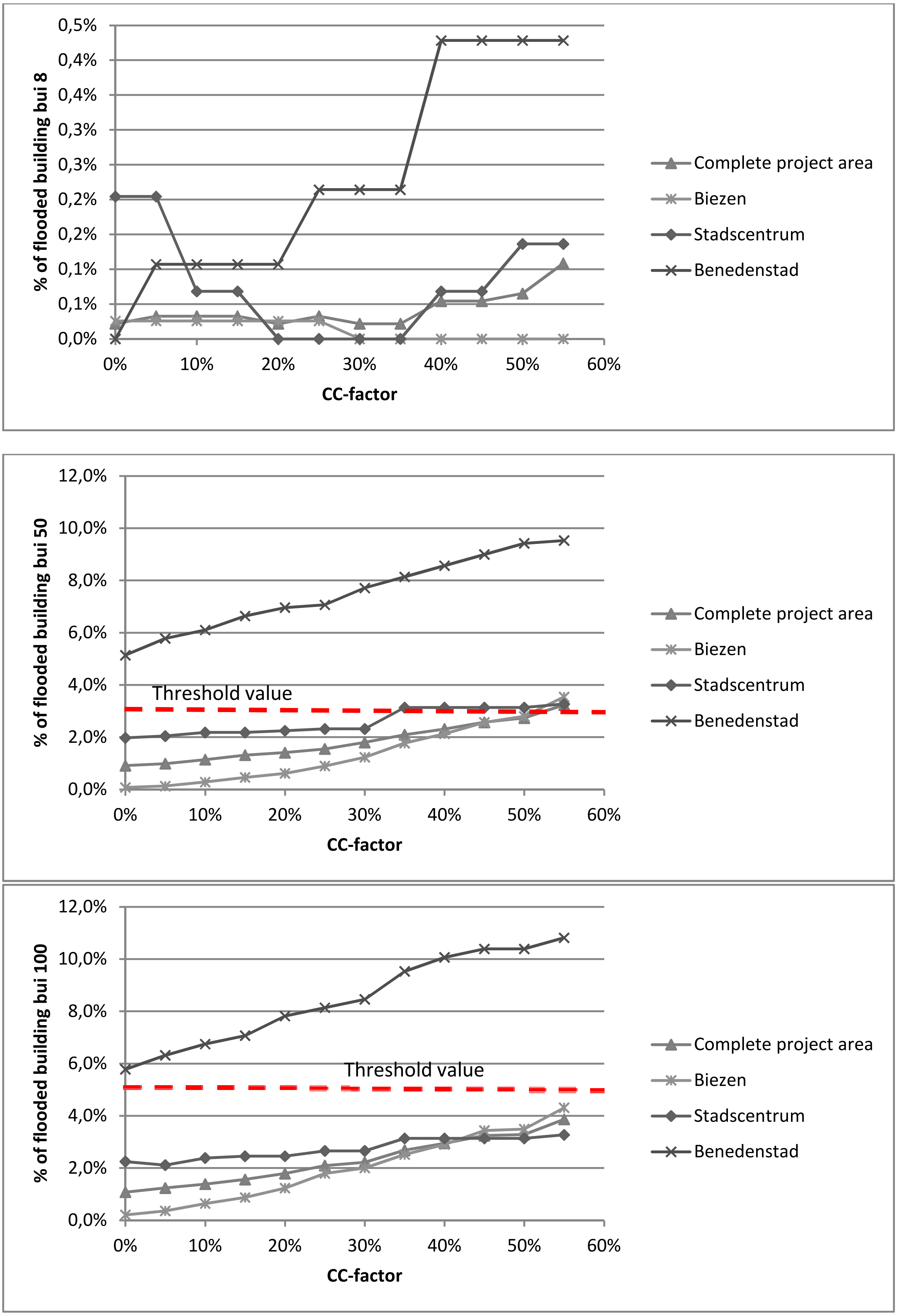


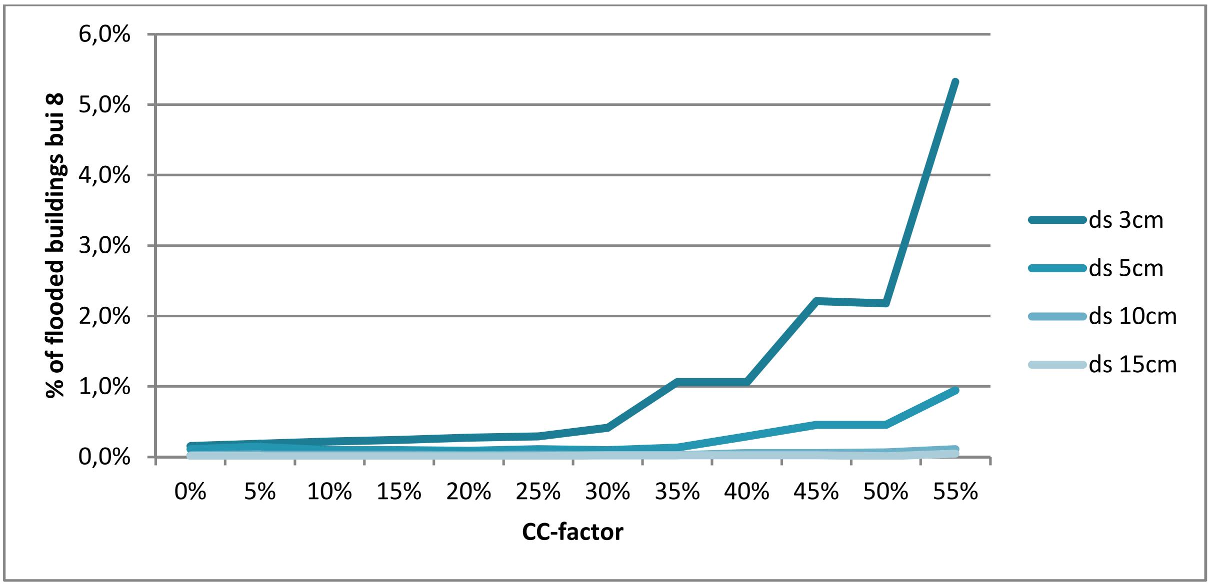

Figure 39Percentages of flooded buildings in all project areas in Nijmegen

## 7. Sensitivity analysis

Figure 40 shows the percentages of the buildings that are flooded under the different rainfall events with return periods 2, 50 and 100 years. The total amount of buildings in the area is 9221. For each rainfall event different doorstep levels are assumed. It can be seen that this has a large effect on the percentage and number of flooded buildings. Especially when the doorstep levels are lower than 10 cm, the effects of increased rainfall volumes are large. In addition, it seems that the increase in flooded houses is extra large from an increase of the CC-factor from 50% to 55%.

The most common rainfall event, bui 8, which occurs once in 2 years statistically, does not lead to large number of flooded buildings. From a CC-factor of 30% the number of flooded buildings increases rapidly if the doorstep is less than 5 to 10 cm. This result is as expected, since the sewer is assumed to be able to handle the current bui8.

The results of bui 50 and bui 100 are very similar, which is not surprising, since these rainfall events look quite similar. Under these rainfall events, it can be seen that the assumptions of the doorstep heights have a significant effect on the amount of flooded houses, not only for large CC-factors but also in the current situation. For example, if the doorsteps are 3 cm, 6% of the houses flood, while only 1% of the buildings flood if the doorsteps are assumed to be 15 cm. The maximum amount of houses that floods in these scenarios is around 15% under a CC-factor of 55%.



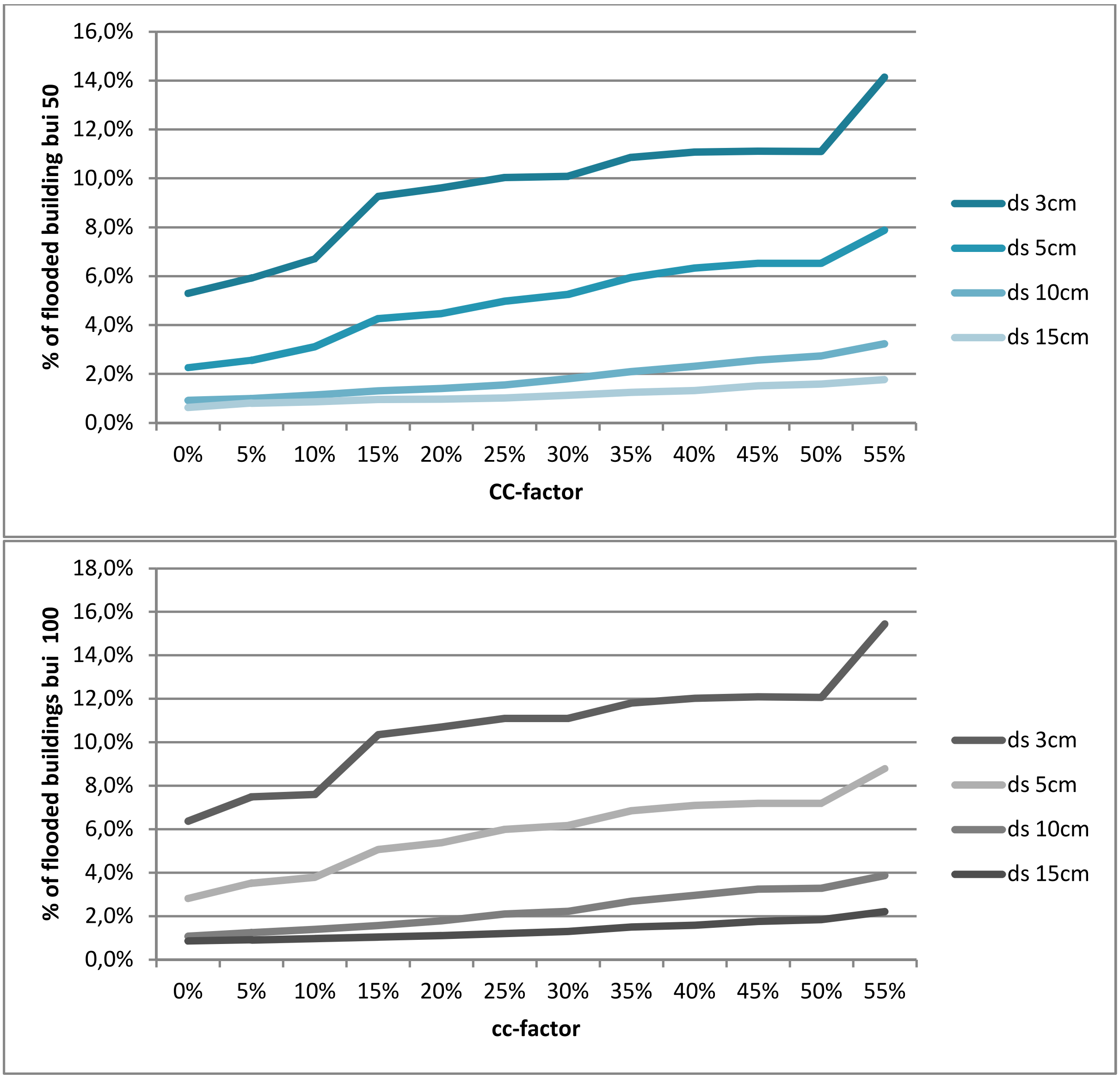



**Figure 40 Percentage of flooded buildings in the complete project area (ds=doorstep)**

Figure 41 shows the effects of the assumptions regarding the doorstep on the spatial distribution. It can be seen that the locations of flooded buildings get much more distributed over the entire area.


**Figure 41 Flooded buildings under an assumed doorstep level of 10 cm and 3 cm**


Legend
flooded at ds=10cm
flooded at ds=3cm
neighbourhood border
Bui8
CC-factor 0%
Bui8
CC-factor 50%
Bui50
CC-factor 0%
Bui50
CC-factor 50%
Bui100
CC-factor 0%
Bui100
CC-factor 50%

## A10.4 Translate ATPs to time

The timing of ATPs has been calculated on the basis of current one-hour rainfall volumes and the projected one-hour rainfall volumes (see Table 47), which have been supplied by the KNMI (Klein Tank and Lenderink, 2009). Since the volumes of the rainfall events with the return periods that are used in this thesis are not provided, it is assumed that:

- the increase of the volume of bui 8 resembles the increase in one-hour rainfall event with a 1-year return period
- the increase of the volumes of bui 50 and bui 100 resemble the increase in one-hour rainfall event with a 100-year return period
-

**Table 47 Current and projected one-hour rainfall volumes under KNMI G and W climate scenario (Klein Tank and Lenderink, 2009).**

| | 2010 | 2050 | |
|---|---|---|---|
| **Return period** | | **G** | **W** |
| 1 year | 14 | 15 | 17 |
| 10 years | 27 | 30 | 33 |
| 100 years | 43 | 48 | 53 |

The conversion from the headroom to the timing of the ATP has been done with the use of the following formulae ($T_{ATP,G}$ and $T_{ATP,W}$ =timing of ATP under KNMI G and W, H = headroom):

$$\text{Bui 8: } T_{ATP,G} = \frac{2050-2010}{(15-14)/14} \times H + 2010 = 560 \times H + 2010$$

$$\text{Bui 8: } T_{ATP,W} = \frac{2050-2010}{(17-14)/14} \times H + 2010 = 186{,}7 \times H + 2010$$

$$\text{Bui 50 and Bui 100: } T_{ATP,G} = \frac{2050-2010}{(48-43)/43} \times H + 2010 = 344 \times H + 2010$$

$$\text{Bui 50 and Bui 100: } T_{ATP,W} = \frac{2050-2010}{(53-43)/43} \times H + 2010 = 172 \times H + 2010$$

Table 48, Table 49 and Table 50 show the timings of ATPs for all neighbourhoods, in combination with all rainfall events and assumed doorsteps.

**Table 48 Timings of ATPs at doorstep of 10 cm**

| Area | Threshold | Return period (year) | Rainfall event | Doorstep (cm) | Headroom | KNMI G | KNMI W |
|---|---|---|---|---|---|---|---|
| complete project area | Bui 8, <1% | 0,5 | Bui 8 | 10 | 55% | 2318 | 2199 |
| Benedenstad | Bui 8, <1% | 0,5 | Bui 8 | 10 | 55% | 2318 | 2199 |
| Biezen | Bui 8, <1% | 0,5 | Bui 8 | 10 | 55% | 2318 | 2199 |
| Stadscentrum | Bui 8, <1% | 0,5 | Bui 8 | 10 | 55% | 2318 | 2199 |
| complete project area | Bui 50, <2,5% | 0,02 | Bui 50 | 10 | 45% | 2094 | 2087 |
| Benedenstad | Bui 50, <2,5% | 0,02 | Bui 50 | 10 | 0% | 2010 | 2010 |
| Biezen | Bui 50, <2,5% | 0,02 | Bui 50 | 10 | 45% | 2094 | 2087 |
| Stadscentrum | Bui 50, <2,5% | 0,02 | Bui 50 | 10 | 35% | 2075 | 2070 |
| complete project area | Bui 100, <5% | 0,01 | Bui 100 | 10 | 55% | 2113 | 2105 |
| Benedenstad | Bui 100, <5% | 0,01 | Bui 100 | 10 | 0% | 2010 | 2010 |
| Biezen | Bui 100, <5% | 0,01 | Bui 100 | 10 | 55% | 2113 | 2105 |
| Stadscentrum | Bui 100, <5% | 0,01 | Bui 100 | 10 | 35% | 2075 | 2070 |
| | | | | | | | |

**Table 49 Timings of ATPs at doorstep of 3 cm**

| Area | Threshold | Return period (year) | Rainfall event | Doorstep (cm) | Headroom | KNMI G | KNMI W |
|---|---|---|---|---|---|---|---|
| | | | | | | | |
| complete project area | Bui 8, <1% | 0,5 | Bui 8 | 3 | 35% | 2206 | 2130 |
| Benedenstad | Bui 8, <1% | 0,5 | Bui 8 | 3 | 5% | 2038 | 2027 |
| Biezen | Bui 8, <1% | 0,5 | Bui 8 | 3 | 45% | 2262 | 2165 |
| Stadscentrum | Bui 8, <1% | 0,5 | Bui 8 | 3 | 45% | 2262 | 2165 |
| complete project area | Bui 50, <2,5% | 0,02 | Bui 50 | 3 | 0% | 2010 | 2010 |
| Benedenstad | Bui 50, <2,5% | 0,02 | Bui 50 | 3 | 0% | 2010 | 2010 |
| Biezen | Bui 50, <2,5% | 0,02 | Bui 50 | 3 | 0% | 2010 | 2010 |
| Stadscentrum | Bui 50, <2,5% | 0,02 | Bui 50 | 3 | 0% | 2010 | 2010 |
| complete project area | Bui 100, <5% | 0,01 | Bui 100 | 3 | 0% | 2010 | 2010 |
| Benedenstad | Bui 100, <5% | 0,01 | Bui 100 | 3 | 0% | 2010 | 2010 |
| Biezen | Bui 100, <5% | 0,01 | Bui 100 | 3 | 0% | 2010 | 2010 |
| Stadscentrum | Bui 100, <5% | 0,01 | Bui 100 | 3 | 15% | 2038 | 2036 |

**Table 50 Timings of ATPs at doorstep of 15cm**

| Area | Threshold | Return period (year) | Rainfall event | Doorstep (cm) | Headroom | KNMI G | KNMI W |
|---|---|---|---|---|---|---|---|
| | | | | | | | |
| complete project area | Bui 8, <1% | 0,5 | Bui 8 | 15 | 55% | 2318 | 2199 |
| Benedenstad | Bui 8, <1% | 0,5 | Bui 8 | 15 | 55% | 2318 | 2199 |
| Biezen | Bui 8, <1% | 0,5 | Bui 8 | 15 | 55% | 2318 | 2199 |
| Stadscentrum | Bui 8, <1% | 0,5 | Bui 8 | 15 | 55% | 2318 | 2199 |
| complete project area | Bui 50, <2,5% | 0,02 | Bui 50 | 15 | 55% | 2113 | 2105 |
| Benedenstad | Bui 50, <2,5% | 0,02 | Bui 50 | 15 | 0% | 2010 | 2010 |
| Biezen | Bui 50, <2,5% | 0,02 | Bui 50 | 15 | 55% | 2113 | 2105 |
| Stadscentrum | Bui 50, <2,5% | 0,02 | Bui 50 | 15 | 35% | 2075 | 2070 |
| complete project area | Bui 100, <5% | 0,01 | Bui 100 | 15 | 55% | 2113 | 2105 |
| Benedenstad | Bui 100, <5% | 0,01 | Bui 100 | 15 | 0% | 2010 | 2010 |
| Biezen | Bui 100, <5% | 0,01 | Bui 100 | 15 | 55% | 2113 | 2105 |
| Stadscentrum | Bui 100, <5% | 0,01 | Bui 100 | 15 | 35% | 2075 | 2070 |

# Appendix 8 Municipal vulnerability assessment

*Suitability of the Adaptation Tipping Point method for municipalities*

Various studies indicate that the frequency and intensity of pluvial flooding, groundwater flooding, drought and heat stress will increase in The Netherlands. This is why it is important for Dutch municipalities to have a method for the assessment of vulnerability. However, vulnerability is not directly measurable. Methods to assess the vulnerability of urban areas to climate change are either qualitative and not informative enough or too costly, specific, or complex, and therefore they are not often applied by municipalities. The Adaptation Tipping Point method is a promising method that helps municipalities to determine the urgency of climate change adaptation. It comprises assessment of ATPs: "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). In this article, the ATP-method is pre-tested as a method for vulnerability assessment in Rotterdam-Noord and a part of Nijmegen. These case studies, together with past experiences based on literature research, suggest that the method is - in principle - suitable for use as a way of assessing vulnerability by municipalities. It provides useful information in addition to traditional top-down impact and damage assessments. However, more research into improving the feasibility of the ATP-method, for example through estimation of ATPs on the basis of either rules of thumb or expert judgement, is necessary to make the method practically feasible. In addition, the application of the method to the theme of pluvial flooding is a proof of principle; it needs to be applied to the themes of groundwater flooding, drought and heat stress on municipal level as well.

*Key-words:* Adaptation Tipping Point Vulnerability, Vulnerability assessment, Pluvial floods, Climate change

## 1. Introduction

Urban areas are affected by climate change in a number of ways. An increase in the frequency and severity of extreme rainfall events causes increased vulnerability to pluvial floods (water nuisance). The association of insurers calculated that the insurance claims due to extreme rainfall events will increase from 6% to 22% between 2010 and 2050, if no adaptation measures are taken (Ririassa and Hoen, 2010). Pluvial floods do not lead to structural collapse, injuries and casualties. However, if all relatively small damages are cumulated over time, the damage is similar to the damages due to a reasonably big fluvial flooding (Ten Veldhuis, 2010). More frequent and longer periods of drought cause damage to wooden foundation pillars, deterioration of urban vegetation and water quality problems. A higher average rainfall increases the problems with groundwater floods. Finally, more frequent and longer heat waves lead to higher hospitalization and mortality, as well as a decreased productivity. Daanen et al. (2010) calculated that the current annual number of 36 premature deaths in Rotterdam could be doubled by 2050.These impacts are only a selection of the consequences of climate change (Bosch Slabbers Landschapsarchitecten, 2010, Planbureau voor de Leefomgeving, 2011). Increased vulnerability to climate change is not only caused by the changing climate itself; socio-economic developments are equally contributing to increased vulnerability to climate change.

Despite the increasing vulnerability of urban areas to climate change, interviews with representatives of 7 municipalities , in combination with findings from Runhaar et al. (2012) showed that it is difficult for municipalities to assess their vulnerability and its implications for the urgency of pro-active adaptation policies and measures. This makes it not only difficult for municipalities to justify adaptation measures and strategies to themselves, but it also makes it difficult to convince other parties of the necessity of adaptation measures in urban projects.

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)..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). Although local vulnerability assessments are not often applied, 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 (interviews, Vrolijks et al., 2011, Ministerie van Infrastructuur en Milieu, 2011).

Many methods have been developed to assess climate change impacts, vulnerability and adaptation: 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. Quantitative methods that are particularly suitable for relatively simple assessment of vulnerability for long-term climate change adaptation policymaking are scarce. A relatively new method in the field of quantitative vulnerability assessments is the Adaptation Tipping Point (ATP) method (e.g. Kwadijk et al., 2008a, Asselman et al., 2008, Kwadijk et al., 2010, Jeuken and te Linden, 2011).

This article describes the pre-testing of the suitability of the ATP-method as quantitative method for the assessment of vulnerability to climate change in urban areas, with a focus on pluvial flooding. This research comprises literature research as well as interviews with Rotterdam, Amsterdam Nieuw-West and Amsterdam Watergraafsmeer, Den Haag, Utrecht, Nijmegen and Arnhem. In addition, modelling is applied in order to apply the ATP-method in Rotterdam-Noord and Nijmegen. Also, a limited amount of field work has been performed within these areas. Section 2 defines vulnerability in the context of this article. Section 3 introduces the Adaptation Tipping Point Method. Since the ATP-method has not primarily been designed as a method for vulnerability assessment, section 4 describes the relation of the ATP-method with vulnerability. The case study approach has been described in section 5. The results of the case studies in Rotterdam-Noord and Nijmegen have been described in section 6 and 7. Finally, , section 8 describes the conclusions and recommendations.

## 2. Definitions of vulnerability

Vulnerability is not directly measureable. 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 accord different meanings to it. In other instances, they use different words for the same concept (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).

(Füssel and Klein, 2006) states that there are three models for the conceptualisation and assessment of vulnerability: the risk-hazard framework, the social constructivist framework and the integrated framework, which is in line with the IPCC definition. The risk-hazard framework considers vulnerability as a dose-response relationship between an external stressor and its consequences on a system (e.g. Downing and Patwardhan, 2004). The social constructivist framework sees vulnerability mainly in terms of a set of socio-economic and political factors that cause differential exposure and sensitivity of different groups of people. The integrated framework considers vulnerability as a function of exposure, sensitivity and adaptive capacity (McCarthy et al., 2001). Vulnerability in the risk-hazard framework can be seen as sensitivity under the integrated framework (Füssel and Klein, 2006).

The ATP-method does not prescribe a certain vulnerability definition, as long as vulnerability is expressed in terms of impacts, with or without adaptation. This excludes the social constructivist framework. A choice has been made for the integrated framework definition of vulnerability, since it provides a better basis for comprehensive vulnerability assessment than the risk-hazard framework:

*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)

In this article the system under consideration is a geographical area, e.g. a neighbourhood or a city.

## 3. The 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 circumstance and when, in time, 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).

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, referring 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. 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 (Jeuken and te Linden, 2011).

The steps of the ATP-method are as follows (Jeuken and te Linden, 2011, p.9):

5. Define scope: This step includes an initial delineation of the assessment regarding the themes, functions, sectors as well as the most important climate impacts.
6. Identify indicators and threshold values: This step includes defining the performance criteria and threshold values on the basis of existing norms, natural boundary conditions, stakeholder involvement or statistics. The indicator needs to be defined on a functional basis. If it is based on a solution, it prescribes the measures for vulnerability reduction beforehand.
7. Determine ATPs: ATPs are determined on the basis of modelling or simpler means of calculation.
8. Translate ATPs to time: Timings of ATPs can be calculated on the basis of climate scenarios.

The last step of the original method, in which step 3 and 4 are repeated with adaptation measures, is not taken into account in this article.

The ATP-method in the Netherlands has been applied before (e.g. Kwadijk et al., 2008a, Kwadijk et al., 2010, Kwadijk et al., 2008b, Passchier et al., 2010, Hoogvliet et al., 2010, Franssen et al., 2011). Nasruddin (2010) applied the method in Wielwijk, a neighbourhood in Dordrecht. He assessed the robustness of the minor and the major drainage system for climate change and calculated the effect of certain measures on the timing of ATPs. The ATP-method has not yet been applied on municipal scale for groundwater flooding, drought and heat stress. In this article the ATP-method will be further explored for pluvial flooding.

## 4. Is the ATP-method a method for vulnerability assessment?

The Adaptation Tipping Point method is a method for assessment of outcome vulnerability, which means that vulnerability is measured in terms of residual impacts, impacts minus potential adaptation (O'Brien et al., 2007). The method can be used as an extension to physical modelling and presents the outcomes of this modelling in terms of the timing of ATPs (Jeuken and te Linden, 2011), which, in turn, are based on vulnerability indicators. The method does not directly assess potential adaptation, but it is possible to calculate the effect of adaptation measures on the timing of ATPs. The measure that leads to the longest extension of the timing of the ATP would in principle be an indication for potential adaptation. Vulnerability is not only determined by the size of impacts, but also by the graduality and spatial distribution of impacts. These characteristics of vulnerability are not reflected in the timing of ATPs.

## 5. Assessing vulnerability to pluvial floods – Case study approach

The ATP-method has been pre-tested in two case studies, one covering Rotterdam-Noord and one covering three complete neighbourhoods and parts of a number of other neighbourhoods in Nijmegen. It will be described very briefly how these case studies have been performed. A more extensive description of the application of the case studies is included in Husson (2012)Although modelling was part of the case studies, their primary focus was on the application of the method, rather than on assessing the vulnerability of the case study areas.

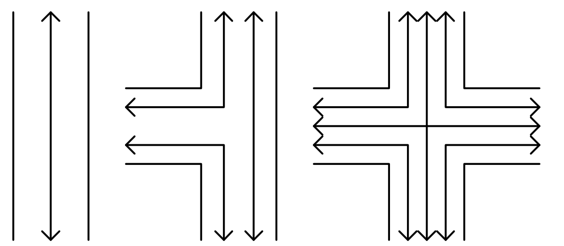
The case studies addressed pluvial flooding of buildings and major roads in Rotterdam-Noord and pluvial flooding of buildings in Nijmegen.

The ATP-method is most attractive when the vulnerability indicator is easy to understand (Jeuken and te Linden, 2011). Because of this, the concept of proportional vulnerability (Adger, 2006, p.279) has been applied in the case study for the flooding of buildings. For specific rainfall events with a known return period it has been calculated what the percentage of flooded buildings is. The results of the case study indicated very few flooded buildings. This is why the threshold values have been set very strictly.

For traffic nuisance, which has only been addressed in Rotterdam-Noord, an index has been made that is based on the number of blocked road segments and the number of road segments in which water causes nuisance. The Road Importance (RI) is based on the number of driving directions of a specific road segment (see Table 51). The Depth Classes (DC) are based on the maximum water level on a certain road segment. They make sure that traffic nuisance on a road segment is considered as half as important as road blockage. The index is easy to understand because of the fixed range of the index. A value of 1 represents a situation in which all of the roads are blocked and a value of 0 represents a situation of no nuisance at all.

Traffic nuisance index: $V_{road} = \frac{1}{\sum DC_{ij}} \sum RI_i \times DC_{ij}$ , i = road segment and j=climate change factor.

**Table 51Road importance**



| Type of road | Road Importance (RI) |
|---|---|
| Straight road segments without crossings | 1 |
| T-crossings | 3 |
| Regular crossings | 6 |

Table 52 summarises the indicators and threshold values in the two case studies. These indicators and threshold values have not been discussed with stakeholders. Since the analysis of flooded buildings in Rotterdam-Noord showed that the number of flooded houses was very low, very strict thresholds have been chosen in this case study. In Nijmegen, more realistic threshold values have been applied. In reality it is likely that a municipality will accept more than one promille of flooded buildings for extreme rainfall events that occur once in a hundred years statistically.

**Table 52 Indicators and threshold values**

| Rainfall event | Return period | Thresholds Rotterdam Noord | Thresholds Nijmegen |
|---|---|---|---|
| Bui 8 | 2 years | % of flooded houses in neighbourhood < 0,1%<br>% of flooded commercial buildings < 0,1 %<br>Traffic nuisance index = 0.3 | % of flooded buildings < 1% |

| | | | |
|---|---|---|---|
| Bui 50 | 50 years | % of flooded houses in neighbourhood < 0,5%<br>% of flooded commercial buildings < 0,51%<br>Traffic nuisance index = 0,35 | % of e of flooded buildings < 2,5% |
| Bui 100 | 100 years | % of flooded houses in neighbourhood < 1%<br>% of flooded commercial buildings < 1%<br>Traffic nuisance index = 0,4 | % of flooded buildings < 5% |

In order to calculate the ATPs, a 2D Overland Flow Model (TUFLOW, 2011, AQUAVEO, 2012) has been applied in combination with ArcGIS. In Rotterdam the Digital Elevation Models AHN, with a grid size of five meter, is used and in Nijmegen, a Digital Terrain Model on the basis of LIDAR data with a spread of 1 meter that has been interpolated using Inverse Weighted interpolation to a three meter grid size. Application of the ATP-method required flood modelling of three standard rainfall events (bui 8, bui 50 and bui 100) in combination with uplifts between 0% and 55%. It was not feasible to model all climate change factors between 0% and 55% with 5% intervals. This is why interpolation of the outcomes of a smaller number of modelled scenarios has been applied.

The outcomes of the flood models, which comprised grids with water levels, were attributed to buildings on the basis of the lowest flood values of surrounding grid cells. Manual validation has not been performed. In order to determine which houses would be flooded, it was necessary to carry out research into the doorsteps of buildings. In Rotterdam, all residential buildings were manually investigated that had a water level of 10 cm or more, and all shops with a water level of 5 cm or more under the most extreme modelled rainfall scenario. The doorsteps of these buildings have been estimated on the basis of Google Streetview by the author, counting the number of stair steps, assuming that stair steps have a similar height. Onsite visit showed that the height of doorsteps was 10-18 cm. It was assumed that all stair steps had a height of 10 cm. In Nijmegen, a standard doorstep height of 10 cm was assumed. The doorstep heights in a number of streets in the shopping area of the city centre have been investigated manually by the municipality of Nijmegen.

For traffic nuisance, the outcomes of the flood models have been used to assess the water depth at the road segments. These values could directly be implemented in the traffic nuisance index..

For each of the indicators it was manually assessed at which climate change factor the threshold value was exceeded. The conversion from the climate change factor to timing of ATPs has been done with the use of linear interpolation on the basis of the KNMI climate scenarios.

## 6. Results and discussion Rotterdam-Noord

The case studies served as a proof of principle of the application of the ATP-method to assess the vulnerability of urban areas to pluvial flooding. Hence, the discussion will only address the methodological aspects of the case study. First the results of the case study will be presented.

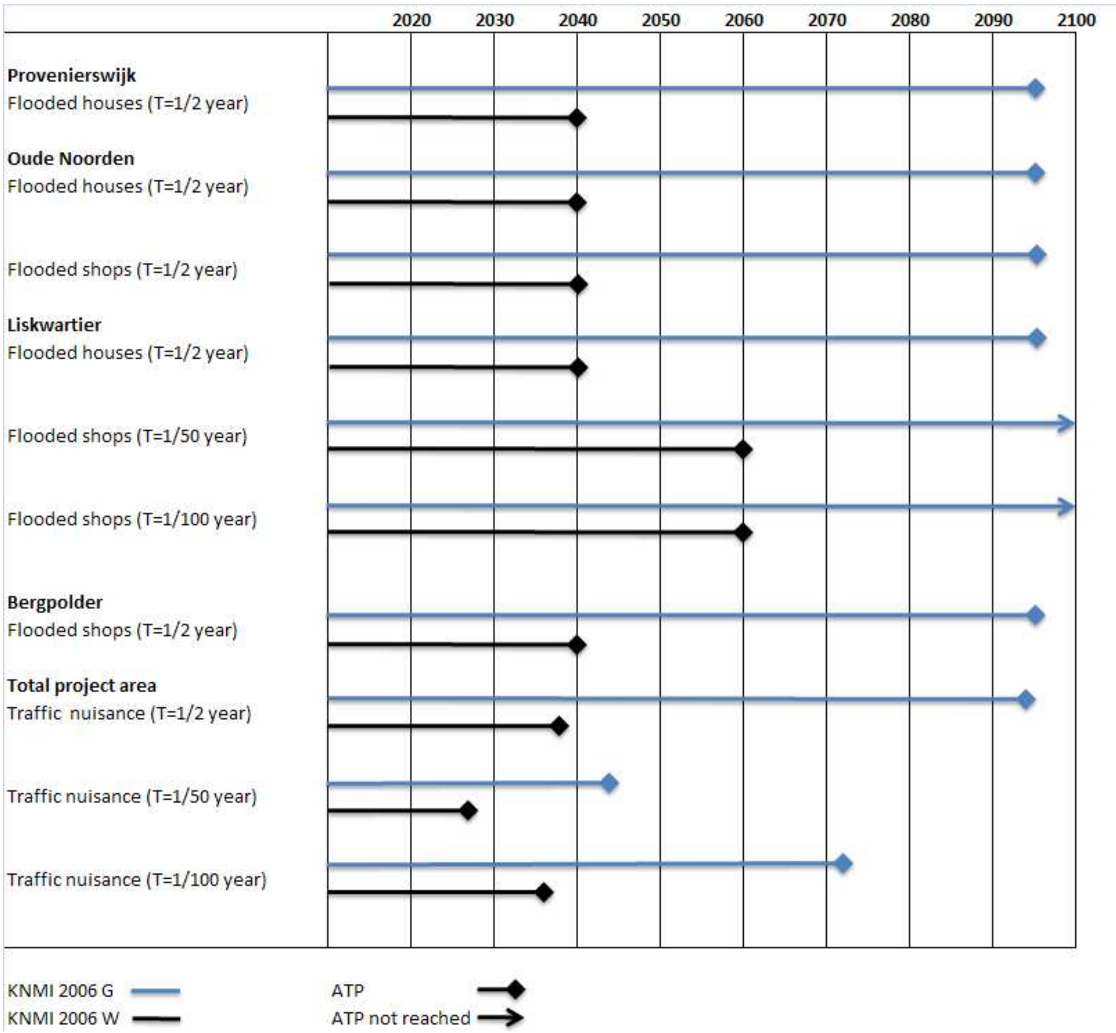



**Figure 42 Results of ATP-analysis in Rotterdam. ATPs are not modelled to be reached before 2100 are not included.**

**Error! Reference source not found.** shows the outcomes of the analysis for Rotterdam. The length of each bar indicates the timing of ATPs, and consequently the time until the neighbourhoods and the submunicipality become too vulnerable. The first bars indicate that the ATP with regard to flooded residential buildings in the neighbourhood Provenierswijk is exceeded in 2095 under the KNMI G scenario and in 2040 under the KNMI W scenario. In general, it can be seen that the threshold value for flooding under bui8, corresponding to a return period of 2 years, will be exceeded before 2100 in many neighbourhoods. For other rainfall events, only the neighbourhood Liskwartier reaches its ATP before 2100. It should be noted that the threshold values are very strict. Because of this, the timings of realistic ATPs will be later.

Case study Rotterdam-Noord led to the following insights into the application and suitability of the ATP-method:

- Modelling of the impacts of pluvial flooding with regard to flooding of buildings is difficult. Flood levels are very low, which makes small details in the urban space significant. Accurate, well-validated modelling of entire municipalities, which also includes sewers, is not feasible. This can only be done on a smaller scale. The results of the modelling showed implausible results, which makes it difficult to indicate the vulnerability of the area.

- If the results would be considered as sufficiently reliable, the method provides an interesting insight into the urgency of managing climate change uncertainty in addition to the traditional impact models.
- Since the extent of flooding was very limited, it was decided to make the vulnerability threshold very strict. This did not require any additional (flood) modelling. Although this could be seen as a weakness and an invitation to opportunistic behaviour, in reality norms can change over time. The ATP-method is flexible to accommodate these changes. This also extends to updates of climate change scenarios.
- The concept of ATPs is easy to communicate. When they need to be further analysed, more difficulties arise. For example, does the percentage of flooded buildings really indicate the urgency of adaptation measures? What is the spatial distribution of the flooded buildings?

# 7. Results and discussion Nijmegen

Figure 18 shows the results of Nijmegen. It can be seen that especially Benedenstad is vulnerable to flooding of buildings. In the modelling of the current rainfall events that occur once in fifty and a hundred years, the percentage of buildings that floods is higher than the threshold value, which implies that immediate measures are required.

Deeper reflection on the results of the ATP-analysis gave the following insights:

- The results of the flood modelling in Nijmegen lead to more plausible results than in Rotterdam-Noord. This might be related to the larger relief in the area.
- The results of the case study seem to be highly sensitive to a decrease of the standard doorstep. The change of timing of ATPs amounts up to more than 100 years when the standard doorstep height is decreased from 10 cm to 3 cm. Also the spatial distribution of the flooded buildings changes. At a doorstep height of 10 cm, there are only three locations where a number of buildings get flooded. At a doorstep height of 3 cm, the locations of the flooded buildings are highly spread over the area. This strongly affects the policy recommendations that should be made to the municipality.
- The vulnerability indicator addresses the percentage of buildings within a neighbourhood. In reality this can cause that buildings in the same street belong to different neighbourhoods. The ATP-analysis could suggest that buildings on one side of the street require measures, while buildings on the other side of the same street don’t need to be made less vulnerable.
- This high sensitivity to doorstep heights confirms that it is of high importance that it is assessed what the confidence level in the results is.

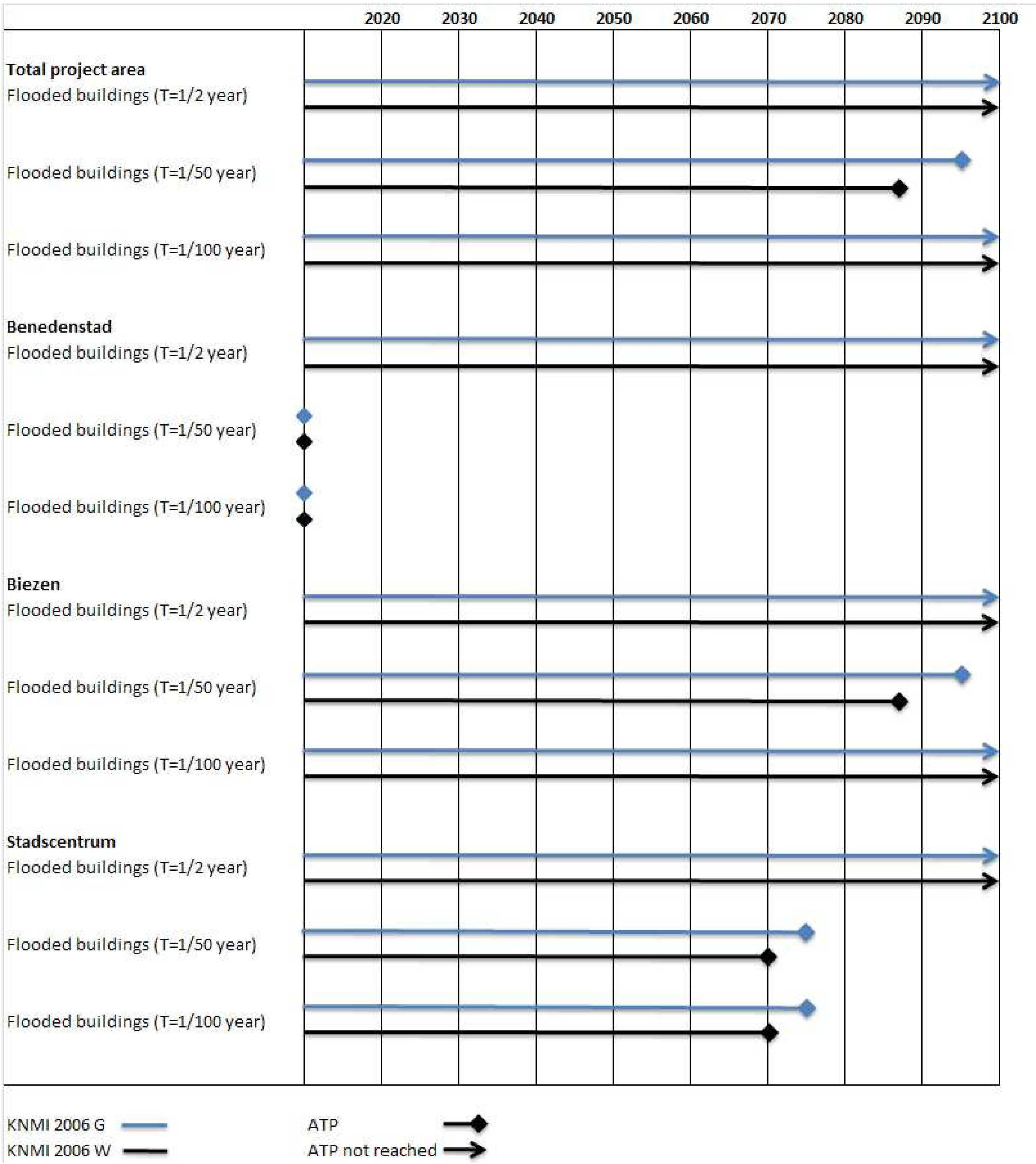



**Figure 43 Timings of ATPs in total project area and in the neighbourhoods Benedenstad, Stadscentrum and Biezen.**

## 8. Conclusions and discussion

This article described the usefulness and limitations of the Adaptation Tipping Point (ATP)- method for assessment of vulnerability to pluvial flooding, groundwater flooding, drought and heat stress.

The ATP-method is applicable as vulnerability assessment method. Timing of moments when a strategy does not comply with a threshold of acceptability anymore provides usable information about the need for adaptation measures and adaptive strategies in different areas. The method is flexible with regard to the (vulnerability) indicator, which allows measuring vulnerability in terms of, for example, numbers and percentages of affected objects or persons or monetary values.

The ATP-method clearly shows when action by the municipality and/or other stakeholders is necessary. It leaves normative elements of vulnerability to the decision makers and other stakeholders. It leads to results that can be easily communicated with decision makers and other stakeholders. The ATP-method is relatively independent of climate change scenarios. The timings of ATPs change, but the impact analyses, which constitute most of the work, do not need to be changed. Another important advantage of the ATP method is that the vulnerability threshold can be based on any physical modelling method, as long as future impacts under influence of climate change can be included.

Weaknesses relate to the feasibility of the method. Impact and damage modelling yet is difficult and precise modelling is not feasible for application to entire municipalities. This weakness is further amplified by the need for calculation of many scenarios. In addition, social factors of vulnerability are not taken into account.

It is recommended to perform further research into:

- Options for determination of ATPs on the basis of expert judgments, such as in Gemeentewerken Rotterdam (2011) and Asselman et al. (2008)
- Application of the method in detail for a number of standard neighbourhoods with comparable characteristics in combination with an extensive sensitivity analysis. Possibly, the results can then be used to estimate the timing of ATPs in comparable neighbourhoods.
- Application of the method to the themes of heat stress, groundwater flooding and drought on municipal scale.

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