Adaptive planning of stormwater management measures to mitigate pluvial flooding under climatic and socio-economic uncertainties

by

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in partial fulfillment of the requirements for the degree of Master of Science
in Hydraulic Engineering and Water Resource Management (DDP),
at the Delft University of Technology and the National University of Singapore,
to be defended publicly on Wednesday May 15, 2019 at 10:30 AM (UTC+2).

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Project duration:	September 1, 2018 – April 30, 2019	
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This thesis is confidential and cannot be made public until May 15, 2019.

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Deltares Enabling Delta Life

Preface

This master thesis has been accomplished to meet the final requirement for the completion of the Double Degree Program in Hydraulic Engineering and Water Resources Management, which is offered in collaboration between the National University of Singapore (NUS) and the Delft University of Technology (TUD). The research mainly focuses on the adaptive planning of stormwater management measures to cope with the urban pluvial flooding in a changing environment characterized by various uncertainties. This document not only is a MSc thesis report but also marks the ending of my 2 years and 8 months of the graduate education abroad. This experience is a treasure in my life that I will remember forever.

During my involvement in the final graduation journey, I have received so much support from all people around me, without which I would never have been able to go this far. First, I would like to thank Prof. Frans van de Ven for his generously offering me the internship opportunity at Deltares, which triggered the entire journey, and for his kind mentoring, continuous encouragement, and constructive guidance, which saw me through all the difficulties along the journey. Second, I am deeply grateful to my daily supervisor Toine Vergroesen. I have been sitting face to face with him on many working days in the past year, during which I have learned a lot from his expertise in water and his passion for work and life. I cannot thank him enough for his kindly imparting the knowledge to me, patiently resolving my doubts, constantly offering me supportive help, and everything else he has done for me. Third, I would like to express my gratitude to Prof. Vladan Babovic for pointing me in the bright research direction, and for his crucial instructions on my work which cleared up my doubts and made the final completion of the project possible. Next, I would like to say thanks to Prof. Marie-Claire ten Veldhuis for her valuable and insightful comments on the thesis work, which helped improve the content a lot. Then, I would like to thank Erik van Berchum for his patient explanations and valuable advice on the drawbacks of my work. Moreover, many thanks to Luxemburg, Yuniar, and Cecilia for always patiently helping me with the formalities and the requirements of this program. Furthermore, I also want to thank my friends Simo, Yundan, Kaixuan, and Weichen for their kind encouragement, help, and support. Last but not least, I must express my greatest gratitude to my parents for their unconditional love and unfailing support at every stage throughout my life.

Not everything went smoothly when I was studying for a master degree in a country which is 8584 km away from my hometown. But finally, I made it! I did all that I had to do and saw through all the obstacles. This experience gives me great confidence to seek for the next challenging journey in my life.

Wenxing Zhang
Delft, May 2019

Abstract

The undertaken thesis work conducts a research study based on the study area — Laakhaven, The Hague, to develop an implementation example of the Adaptation Pathway approach, in order to support long-term adaptive stormwater management planning on urban adaptation measures to mitigate pluvial flooding under the climatic and socio-economic uncertainties.

The methodology is presented in the stepwise procedure to develop adaptation pathways. The core part of this method is expressed as the risk-based approach, which considers the flood risk from the aspects of the probability and the consequence. Different climate and socio-economic scenarios are developed to represent the uncertain environment for policymaking resulting from long-term changes. An urban water balance model is applied to produce the novel empirical performance indicator for the effectiveness of adaptation measures as the critical input to this assessment. Sell-by dates of adaptation actions are computed based on the assumption that, once a policy action reaches the perspective-based socially acceptable risk, it is said to encounter an adaptation tipping point thus requiring additional interventions. With the computed sell-by dates, the adaptation pathways maps are assembled under certain rules that exclude illogical sequences. Robust adaptation pathways that can succeed over various future scenarios are outlined from the pool of pathways. The developed adaptation pathways map provides the policymakers with a range of possible options. The results indicate the significance of investing in the modular rainwater harvesting devices on private space since it is effective and flexible action that supports the development of dynamic robust strategies for the long-term adaptive stormwater management planning. The implementation methodology of this case study is theoretically viable and its potential to make a more comprehensive study has been proven. Therefore, it is recommended to take the undertaken study as a starting point and further improve it to find the ultimate answer through sub-selecting preferred pathways.

Summary

The undertaken study aims to develop an implementation example of the Adaptation Pathway approach to support the adaptive planning of stormwater management measures to mitigate urban pluvial flooding under climatic and socio-economic uncertainties. It is based on a case study of Laakhaven, The Hague.

Pluvial flooding is damaging especially to strongly urbanized areas. Extreme flood events are expected to occur more frequently due to climate change. Besides, the potential consequences of flooding may be intensified as a result of the socio-economic development. Both climatic and socio-economic uncertainties make it a challenging task for policymakers to develop long-term stormwater management plans. Designs made with the traditional planning approach sometimes fail to meet the preset objectives since the future often unfolds differently from initially-assumed future scenarios. The thing is people don't know exactly what the climate and the society will look like in the future. Therefore, there has been a shift in the mindset that, given the inability to predict the uncertain future with precision, people began to think which adaptable actions can they take now to best prepare for the future. This argues for making adaptive plans that incorporate flexibility in engineering, which can avoid future lock-ins, reduce potential regrets, and profit from adaptation opportunities.

The undertaken study selects Adaptation Pathway approach as the decision-making model to develop long-term adaptive stormwater management plans. The study follows the stepwise procedure for developing adaptation pathways. The entire procedure contains six steps. The first step is to define and describe the study area. Laakhaven is chosen as the study area mainly for two reasons — It is a neighborhood-scale strongly built-up area that is vulnerable to rising pluvial flooding risks; The area is confronting continuous densification of its socio-economic activities, therefore, the potential consequence of floods is increasing. The second step is to define the package of adaptation measures. We classify 24 pluvial flooding mitigation measures presented in the Adaptation Support Tool under different dimensions and finally outline 6 adaptation measures out of them — three measures on the rooftops (private space) namely rain barrel, extensive green roof, and green roof with drainage delay; and three measures on the ground (public space) namely porous pavement, bioswale, and water square. Each adaptation measure has small and large specifications.

The third to the fifth step is the core part of the implementation methodology, which views the problem from the risk-based perspective: *Risk* = *Probability* × *Consequence*. The third step is to develop scenarios. Synthetic time series of precipitation and evaporation are made on the basis of the 30-year hourly time series of precipitation and evaporation for Laakhaven as the transient climate scenarios representing the four KNMI'14 climate scenarios. Three growth rates of socio-economic development were defined based on the

WLO-study. Therefore, the potential consequence of hazardous events is intensified with the continuous growth in the economic value of the study area. The fourth step is to run the assessment model. *Runoff frequency reduction factor* is the performance indicator for the effectiveness of measures, which are applied in the assessment model. It tells how the probability of the runoff event is changed by an adaptation measure. It is obtained by a lumped conceptual hydrological model — Urbanwb model. This factor is an empirical relationship observed by analyzing the model's outcomes with the empirical graphic method. The validity of this factor is confirmed with numerous simulations of various measure under different climate scenarios. Therefore, it is taken as the performance indicator for the effectiveness of adaptation measures and thus used as the crucial input to the assessment model. With the probability and the consequence, the risk is computed as an increasing function of time. Socially acceptable risk is taken as the adaptation tipping point above which the current strategy fails to meet the objective thus requiring additional inventions. Three perspectives are introduced from the Cultural Theory, namely *Hierarchist*, *Individualist*, and *Egalitarian* to represent three different people's perceptions on risks. With the risk formula, the sell-by dates of all the adaptive actions are computed. The data are thus used in the last step to assemble these adaptation actions in a reasonable manner to make adaptation pathways maps.

After analyzing the results of the computed sell-by dates and final adaptation pathways, several conclusions are drawn as the answers to the research questions. We formulate the the problem of developing adaptive stormwater management planning to mitigate pluvial flooding in the following way. The implementation methodology of the adaptation pathway approach is based on the risk-based approach. In terms of the probability of flooding, we apply the urban water balance model to produce reliable performance indicators for the effectiveness of measures *i.e. runoff frequency reduction factor*. Consequence of flooding is expressed as an increasing function of time due to the continuous socio-economic growth. The acceptable threshold for the risk is set as the adaptation tipping point of adaptation actions, which is dependent on people's perspectives. With the risk formula, sell-by dates of adaptation actions are computed, which are later used to make adaptation pathways (maps) following certain rules. The results show the difference in the socio-economic scenarios and the societal risk perception can have a greater influence on the durability of adaptation policies. The resulting adaptation pathways map provides the policymakers with a wide range of possible strategies into the uncertain future. Analyzing these pathways sheds light on the general directions for the development of urban stormwater management measures. It is recommended to make investments in modular rainwater harvesting devices on private spaces. This is because this action is not only flexible action that allows easy adaptation and avoids future lock-ins, but also no-regret action that brings additional benefits and prevents some dormant problems of centralized measures. It brings both the effectiveness and the flexibility into the management strategy thus supporting developing dynamic robust strategies that can succeed over various future scenarios. The case study is an implementation example of the adaptation pathway approach on adaptive urban stormwater management planning. Its limitations are attributed to all the assumptions and simplifications made. However, the entire implementation methodology is theoretically viable. It is recommended to put more efforts to improve the current work in order to make a more comprehensive study in future researches.

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Chapter 1

Introduction

1.1 Background and motivation

Climate change presents immense challenges to both the environment and the human society. Adaptation to climate change to alleviate its potential adverse impacts is getting increasing recognition around the world. Pluvial flooding hazard is one big theme of climate change adaptation. Pluvial flooding is damaging especially to strongly urbanized areas. Extreme flood events are expected to occur more frequently due to climate change. Besides, their potential consequences may be intensified as a result of the population growth, the continuous urbanization, and the economic development. Therefore, this dynamically changing environment characterized by uncertainties in both the climatic and socio-economic changes makes it a challenging task for policymakers to develop long-term plans on stormwater management infrastructures that can perform effectively and accomplish their intended goals of pluvial flooding mitigation within its design life-cycle.

The traditional approach of designing stormwater management strategies can be summarized as the "Predict then build" approach (Manocha and Babovic, 2017). First, water managers outline the "best estimates" of the "most likely" future based on central estimates of climate change and extrapolations of current socio-economic trends (Haasnoot et al., 2012). Then, based on a handful of selected potential future projections, water managers develop a series of possible designs. Later, they perform the economic evaluation and the optimization between costs and benefits to determine the best optimal designs. Strong dependence on the estimated climate scenarios is the main limitation of the traditional approach since these requirements are unrealistically deterministic (Medellín-Azuara et al., 2007). Real experience has shown that future conditions do often turn out to be incompatible with the initially assumed scenarios and therefore bring unindented impacts (sometimes failures) to the designed strategies (Swanson and Bhadwal, 2009). This is simply because people do not know exactly what the climate and the society will look like in the future. Inability to precisely predict the uncertain future is the biggest challenge in the traditional planning approach (Haasnoot et al., 2012).

In order to develop strategies that can succeed over various future scenarios rather than only a handful of selected future projections, people can take either robust action or flexible action. Robust action usually indicates an infrastructure with large system capacity and high protection standards so that it is insensitive to changing conditions and thus can succeed under many possible futures. However, robust action is often quite expensive and designed to be long-lived. Therefore, it is difficult to be adapted or changed once built in the ground. Besides, strategies considered feasible today may not be preferable in the future. Consequently, robust but irreversible long-term strategies can potentially be a hindrance especially when it comes to spatial planning (Haasnoot et al., 2012). In contrast to robust action, flexible action incorporates flexibility into the strategy as it can be easily adapted to the changed situations because of its lower associated costs, relatively short design lifetime, and minor consequences to the society.

As the future unfolds, people will get more information and develop more knowledge which would help them resolve uncertainties. Engineering flexibility enables them to update their strategies to cope with newly emerged circumstances, therefore, it has been increasingly advocated to develop flexible strategies that can be easily adapted and changed over time in response to uncertain climatic and socio-economic changes (Buurman and Babovic, 2016; Haasnoot et al., 2012, 2013). In this sense, a well-designed flexible strategy is also a (dynamic) robust strategy. Hence, there is a gradual change in the water managers' way of thinking on the long-term planning — instead of asking which future is most likely to happen in the view of the traditional approach, they begin to ask, given that the future cannot be perfectly predicted, which action can they take now to best prepare for the uncertain future (Manocha and Babovic, 2017)? The shift in their mindset argues for taking adaptive small-step interventions to meet near-term objectives in order to avoid future lock-ins, to reduce potential regrets, and to seize advantage of adaptation opportunities (Dessai and Hulme, 2007; Haasnoot et al., 2012; Manocha and Babovic, 2017).

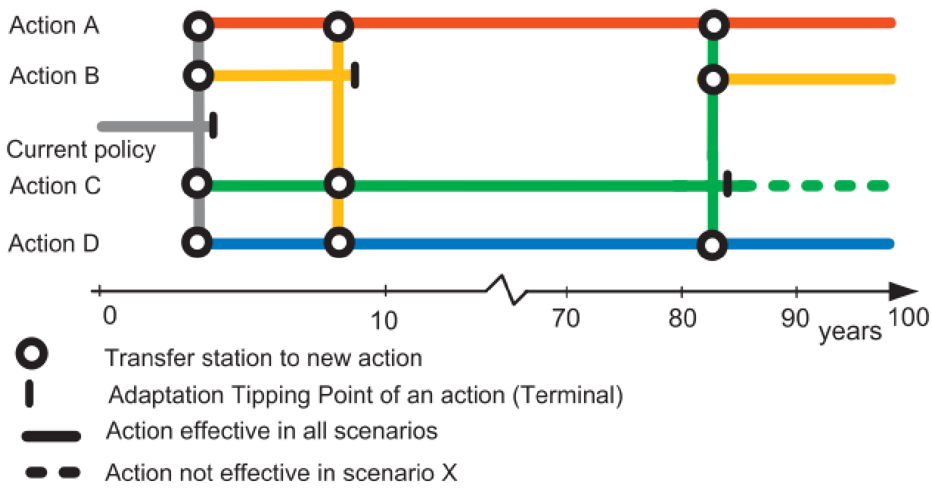


Figure 1.1: Illustration of an Adaptation Pathways map from Adaptation Pathway Approach, reprinted from Haasnoot et al. (2013)

In the context of developing adaptive strategies for climate change adaptation, many relevant policymaking frameworks and decision-making approaches have been proposed throughout the years. Thereinto, Haasnoot et al. (2012) developed a novel adaptive planning approach called Adaptation Pathway approach with the aim of supporting the decision-making on adaptive water policies in the face of uncertainties about the future. As shown in Figure 1.1 above, the Adaptation Pathways map is similar to a metro map. It presents multiple possible routes (*i.e.* adaptation pathways) into a desired point in the future (*e.g.* 100 years). Each adaptation pathway consists of a series of adaptation actions. In case the action fails to meet the predefined objective thus reaching the terminal, it is said to reach the adaptation tipping point (*abbr.* ATP). Therefore, if the terminal of this action is not the intended destination, it becomes necessary to transfer to another more effective action or combine with other action in order to successfully manage the system over the entire planning time horizon. Adaptation pathways differ from each other in the actions to take, the moment the action is taken, the associated costs, and the resulting benefits. Some adaptation pathways are robust, while some are flexible. An Adaptation Pathways map provides the decision-makers with a range of possible choices. But the sub-selection of preferred pathways is subject to the stakeholders' preferences, the availability of the resources, and the optimization between costs and benefits. Anyway, each of the resulting adaptation pathways indicates a possible long-term planning strategy that is successful at any point in time between now and the desired point in the future.

Long-term stormwater management planning on adaptation measures to mitigate urban pluvial flooding is made against various uncertainties in both climate change and socio-economic change. Both the climatic and anthropogenic factors, *e.g.*, potential climate change, continuous urbanization, ongoing economic development, *etc.*, are the stressing factors to the flood risks. Moreover, the spatial configuration and the spatial planning of an intensely built-up area, especially the complementary and conflicting relationships between public space and private space, make the situations even more complicated for the decision-makers to develop long-term stormwater management plans in the urban context. Hence, it becomes increasingly significant to make adaptive stormwater management plans, which can response more strategically than traditional planning strategies in the face of the deeply uncertain nature. This gives us the motivation to study how it is possible to formulate the above-stated problems into a decision-making model such as the Adaptation Pathway approach in order to provide at least some first-level insights on the long-term adaptive planning of stormwater management measures. Therefore, the main research objective of this undertaken study is to develop adaptation pathways to support the long-term adaptive stormwater management planning of urban adaptation measures to mitigate pluvial flooding under climatic and socio-economic uncertainties, through implementing the concept of the Adaptation Pathway approach on a case study of Laakhaven.

Within the implementation of the Adaptation Pathway approach, it is mostly the case that the timing of adaptation tipping points of policy options is determined by the assessment models (sometimes by expert judgment). Therefore, setting up an appropriate assessment model to evaluate the effectiveness and durability of adaptation actions is the critical part of the methodology. The assessment model applied in this research is associated with a dynamic urban water balance model. This hydrological model was initially developed by Deltares in Excel spreadsheet, and it has recently been converted to a Python-based model and further developed. One of the performance indicators of adaptation measures generated by this model is called runoff frequency reduction factor, which is quite a novel concept. Previously, due to the limitations of the excel model, this finding was only validated for a few adaptation measures with short-term time series. Therefore, another research objective of the undertaken study is to try to validate this performance indicator with numerous simulations of long-term time series for various measure cases. After confirming the validity of this empirical factor, we can apply this outcome as an important input to the assessment model. With the assessment model, the sell-by dates (*i.e.* the timing of adaptation tipping points) of adaptation actions can be determined, with which the final adaptation pathways (maps) can be assembled under certain rules. Analyzing these Adaptation Pathways maps can help decision-makers outline possible water management road-maps into the future, through identifying opportunities, threats, no-regret actions, potential lock-in, and the timing and sequence of actions (Haasnoot et al., 2012, 2013)

1.2 Research objectives

(i) Develop adaptation pathways to support the long-term adaptive planning of stormwater management measures to mitigate urban pluvial flooding at neighborhood scale in the face of climatic and socio-economic uncertainties, through applying the Adaptation Pathway approach to a case study in the Netherlands — Laakhaven, on the basis of the outcomes of the dynamic urban water balance modeling and the risk-based approach. Therefore, in the end, a theoretically sound methodology should be proposed as a worthwhile prototypical implementation example for future studies.

(ii) Develop adaptation pathways maps to provide the policymakers with an extensive comparison of numerous optional long-term stormwater management strategies into the future. Analyze these developed adaptation pathways to shed some light on the general directions in which the development of pluvial flooding adaptation measures in a strongly built-up area should be focused.

(iii) Validate the urban water balance model and its associated empirical performance indicators, which are applied as a critical input to the assessment model within the implementation of the Adaptation Pathway approach. Study the effectiveness of various adaptation measures and the factors that potentially influence their efficacy.

1.3 Research questions

The undertaken thesis aims to present a viable and reliable implementation example of the Adaptation Pathway approach so as to support the long-term adaptive stormwater management planning of urban adaptation measures to mitigate pluvial flooding, based on a case study of Laakhaven. Encompassing this main research objective, the main research questions (*i.e.* research objectives) and sub-questions are formulated as follows:

- In relation to the research objective (iii):
  - Given the numerous types of urban adaptation measures, how to categorize and conceptualize these structural adaptation measures and later formulate them into the dynamic urban water balance model?
  - With the massive simulation runs of various measures using long-term time series, can we confirm the validity of the empirical performance indicator (*i.e.* runoff frequency reduction factor) and the validity of this hydrological model?
  - What are the distinctions in the effectiveness of different adaptation measures, what factors potentially influence their efficacy, and what lessons can we learn from it regarding the operations and maintenance of adaptation measures?

- In relation to the research objectives (i) and (ii):
  - How to formulate the urban pluvial flooding problem and implement the Adaptation Pathway approach to develop adaptation pathways for the long-term adaptive planning of stormwater management measures for urbanized areas?
  - Based on the resulting adaptation pathways generated with this first-level assessment, what lessons can we learn regarding the general directions in which the adaptation development should be focused?
  - Is this methodology theoretically sound? What are the advantages and limitations of the proposed methodology? Which parts are recommended to be improved for future studies?

1.4 Research methodology

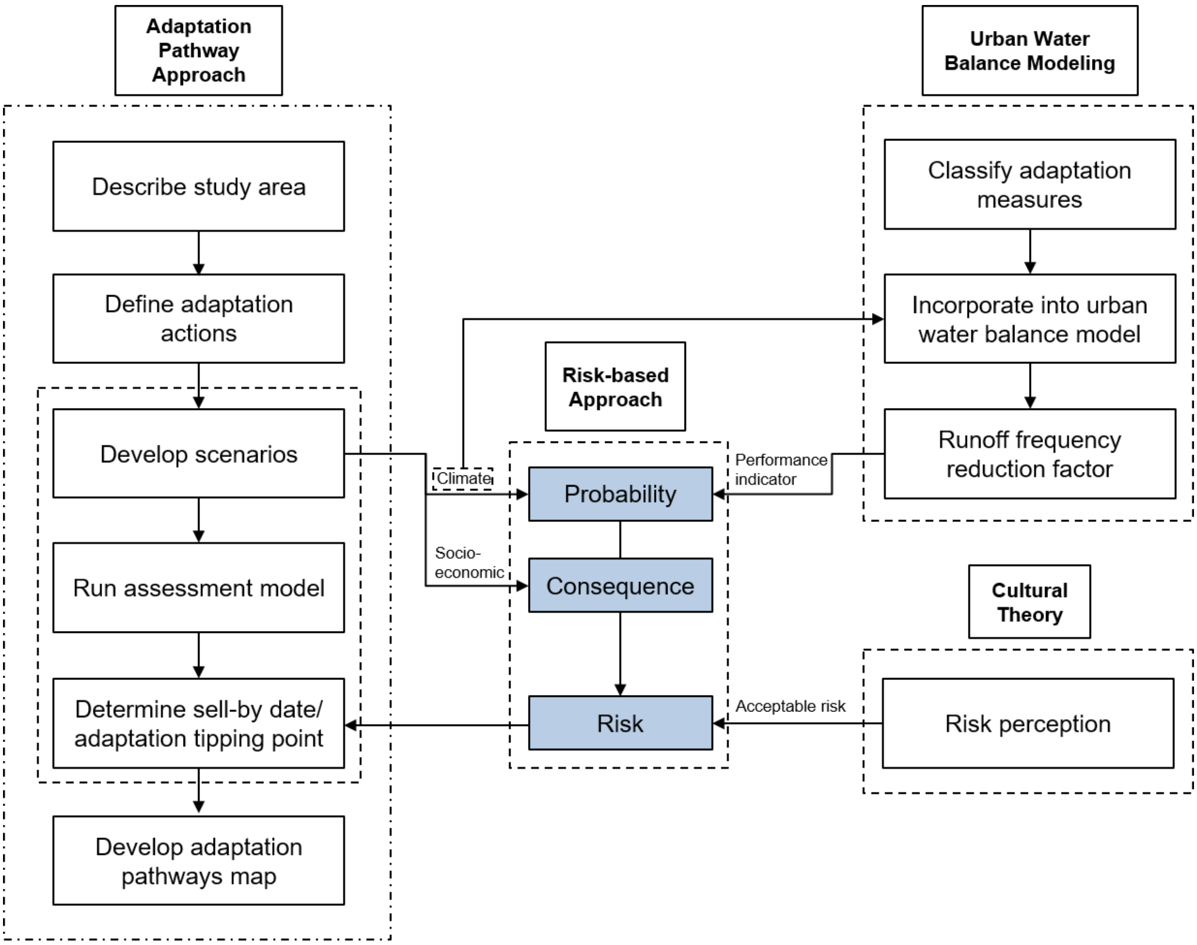


Figure 1.2: Research methodology of the implementation of the Adaptation Pathway approach in the undertaken study, the core of which is based on the risk-based approach, which integrates the urban water balance modeling and the Cultural theory

Since the thesis work covers two main parts — ***a.*** the hydrological part, where the dynamic urban water balance model is set up to produce reliable performance matrices of various adaptation measures, and ***b.*** the adaptation pathways development part, where the implementation methodology is proposed, which formulates the problem of interest based on the risk-based approach. Both two parts can be separate topics on their own, however, they are organized in an integral manner. Therefore, in order to give readers a clear idea about the entire layout of the undertaken study, the general approach is presented in Figure 1.2 above.

The research methodology follows the procedural sequence of the Adaptation Pathway approach, as shown in the left panel of the figure. The core part of this methodology — to determine the sell-by date of adaptation actions, is based on the risk-based approach. The risk-based approach focuses on the probability of flooding and its corresponding consequences. The flood probability is mainly determined by the developed climate scenarios but can be altered through implementing adaptation actions. The effectiveness of adaptation measures is computed with the dynamic urban water balance model. The potential damage of the flooding is a function of the developed socio-economic scenarios. When the computed risk exceeds the perspective-based socially acceptable risk, the adaption action is said to reach an adaptation tipping point, therefore, its sell-by date is calculated. The resulting sell-by dates of all adaptation actions are later used to assemble the adaptation pathways and make adaptation pathways maps under certain rules. Once Adaptation Pathways maps are crafted, the analysis is performed to get some first-level knowledge regarding the adaptive planning of stormwater management measures to mitigate pluvial flooding at a neighborhood-scale urbanized area.

1.5 Thesis outline

This thesis is organized into five chapters as follows:

- Chapter 1 briefly introduces the motivation, research objectives, research questions, and general methodology of the undertaken study.
- Chapter 2 contains the literature review on climate change adaptation, uncertainties, and Adaptation Pathway approach as the necessary background information and the supplementary introduction to Chapter 1.
- Chapter 3 gives a detailed description of the entire research methodology. It proceeds with the implementation procedure of developing adaptation pathways and contains additional information specific to the section content.
- Chapter 4 presents the analysis of the results and the discussions to answer the research questions.
- Chapter 5 closes the undertaken study with the final conclusions and several recommendations for future studies.

Chapter 2

Literature review

This chapter provides more detailed background information as the supplementary information to Chapter 1. In section 2.1, climate change adaptation and its significance are introduced. Section 2.2 discusses the uncertainties faced by policymakers who make climate adaptation decisions. In section 2.3, detailed information on the Adaptation Pathway approach is presented. The last section 2.4 briefly discusses some applications of the Adaptation Pathway approach.

2.1 Adaptation to climate change

2.1.1 Climate change

Before talking about climate change, it is important to differentiate climate variability and climate change. Selvaraju and Baas (2007) gave definitions of several relevant terms as follows: Weather is the current atmospheric condition and its short-term (usually from hours to weeks) variations in a given locality. Climate is the long-term (usually at least 30 years) average pattern of the weather for a particular place. Climate variability usually refers to fluctuations around the mean state and variations in other statistics (*e.g.* standard deviations, the occurrence of extremes) of the climate at different spatial and temporal scale without changing the long-term average. Climate variability that results from only internal variability of the climate system is referred to as natural climate variability. Climate change refers to any change in the climate over a long time span, whether it is caused by natural variability or human activities. But climate change is nowadays more commonly used as the term for the human-induced change in the climate.

Climate change affects nearly every aspect of the environment and the society, therefore, it has emerged as one of the most pressing defining issues of our time (IPCC, 2014). It has been confirmed by recent studies that the imprint of the anthropogenic influences on the climate change can be recognized in observed events (Carter et al., 2015; Min et al., 2011). Therefore, the awareness for increased human-induced climate change is rapidly increasing (van Lohuizen, 2018). Observation records like increasing heavy precipitation events show a possible intensifying trend over the 21st century (IPCC, 2014). The increase in the number of extreme weather and climate events is expected to bring significant risks to both ecosystems and societies (Field et al., 2012). In terms of climate change in the Netherlands, the Netherlands Environmental Assessment Agency (*abbr.* MNP) has confirmed the observed changes in the climate of the Netherlands which have already impacted various natural and human systems (Bresser et al., 2005). Research studies from the Dutch Meteorological Institute (KNMI) have also demonstrated the scientific evidence that sea level rise, heavy precipitation events, increased drought and heat stress in the Netherlands can be more extreme and happen more frequently in the future (Klein Tank et al., 2014).

2.1.2 Climate change adaptation

There are two major strategies to deal with climate change — mitigation and adaptation. Despite the extensive consensus amongst scientists and policymakers that mitigating climate change with global efforts is effective and thus should be put the prime focus on, it is increasingly recognized that adapting to climate change has become unavoidable (Dessai and van der Sluijs, 2007; IPCC, 2014). The necessity for climate change adaptation is especially pressing when it comes to the regional scale. This is simply because "climate change is a case of the 'tragedy of the commons' [1]; Mitigation is a public good" (IPCC, 2014). It indicates that the effective mitigation to climate change cannot be achieved if individual agents (individuals, organizations or countries) act self-seekingly instead of contributing to common interest and international collaboration. On the other hand, adaptation can be deemed as a private good since it can directly take effect on individual regions that undertake adaptation actions in the face of climate change.

Climate change adaptation has been defined as "an adjustment in ecological, social, or economic systems in response to actual or expected climatic stimuli and their effects or impacts" by IPCC (Smit and Pilifosova, 2003), "in order to alleviate adverse impacts of change or take advantage of new opportunities" (Carter et al., 2015). Climate change adaptation is a very broad concept including many aspects, therefore, one needs to specify what to adapt, who/what adapts and how adaptation occurs (Smit et al., 2000). In response to climate change, a system needs to reduce its vulnerability by enhancing the adaptive capacity, which is defined as "the ability of a system to adjust to climate change ... to moderate potential damage, take advantage of opportunities or to cope with the consequences" (Fischlin et al., 2007). However, several experiences have suggested that higher generic adaptive capacity does not necessarily bring reduced vulnerability (Adger et al., 2005; Pachauri and Reisinger, 2008). Therefore, to reflect the indirect link between adaptive capacity and reduced vulnerability, adaptation measures are subdivided into following two dimensions: building adaptive capacity, *i.e.* increasing the ability of climate change adaptation; and implementing adaptive decisions, *i.e.* transforming the capacity into action (Adger et al., 2005; Füssel and Klein, 2006). Both dimensions of adaptation measures are important and indispensable, and their success requires manifold actions by individuals, organizations, and government throughout the entire society (Adger et al., 2005).

[1] The tragedy of the commons is an economic theory of a situation within a shared-resource system where individual users acting independently and rationally according to their own self-interest behave contrary to the common good of all users by depleting that resource (Wikipedia contributors, 2019c).

2.1.3 Dutch adaptation history of flood control and water management

The Netherlands, corresponding to its literal meaning "low countries", is situated in the low-lying delta formed by three major rivers — the Rhine, the Meuse, and the Scheldt. In accordance with the famous saying "God created the world, but the Dutch created the Netherlands", a large part of the land called "polders" had been reclaimed from dry seas, lakes, swamps, and marshes from the 14th century onwards. Approximately one-third of the Netherlands is below the sea level, and two-thirds are vulnerable to flooding. Low elevation together with dense population makes the flood control and water management everlastingly critical issues for the Netherlands. The Dutch therefore has developed prowess and expertise in the field of water through the long adaptation history and tradition of continuously creating innovative techniques and technologies in relation to the flood control and water management. Thousands of polders and iconic water-pumping windmills are symbols of their early mastery of the water, which had kept the Netherlands safe from flooding for centuries. However, the catastrophic North Sea flood of 1953 sharply eroded this sense of safety and thus provided the impetus for the First Delta Act and the start of the enormous flood-control infrastructure project — "Delta Works", which has been considered as one of the modern engineering marvels. After the 1970s, with the rising awareness of the importance of nature conservation, water management approaches had become more adaptive and participatory (Van der Brugge et al., 2005). For instance, the concept of integrated water resource management (IWRM) was proposed in the 1980s and subsequently become a national policy (Mostert, 2006). Moreover, The Dutch water policies began to synchronize with international policies like the EU Water Framework Directive. As a result of the intensifying impacts of climate change and sea-level rise, Dutch water experts have seen the limitations to the traditional "hard engineering" approach in this changing environment characterized by uncertainties. Therefore, they have begun to evolve their mindset and approach to fit into a more adaptive and sustainable manner. Room for the river project from 2006 onwards is a good example of the vigorous new mindset that considers the flooding problems related to the changing climate from a long-term and holistic perspective.

Dessai and van der Sluijs (2007) summarized the continuous adaptation history of flood protection and water management in the Netherlands as a paradigm shift from curative reactive adaptation triggered by disasters (*e.g.* extreme flood events) towards planned precautionary adaptation in response to anticipated climate change. As a result of the raised awareness of the significance of climate change adaptation, since 2005, European Union member states have started to develop National Adaptation Strategies (NAS) to timely meet the challenge to the national development induced by climate change and its corresponding impacts. Under this framework, the Netherlands has made a series of progress. In 2006, the national government worked in collaboration with local governments to initialize a national program on spatial planning and climate adaptation (Adaptatieprogramma Ruimte en Klimaat, *abbr.* ARK), marking the commencement of developing more climate-proofing and water-resilient strategies nationwide in the Netherlands. In the same year, the Netherlands Scientific Council for Government Policy (Wetenschappelijke Raad voor het Regeringsbeleid, *abbr.* WRR) recommended high priority should be given to adaptation, especially in water policies related to flood protection. Under this background, the annual Delta Program (Deltaprogramma) has come into practice from 2010 onwards to develop strategic decisions that ensure freshwater availability and enhance flood protection in response to climate change. In 2012, the Court of Audit stated that the Delta Program alone could not sufficiently prepare the Netherlands for climate-associated risks. Therefore, the National Climate Adaptation Strategy (Nationale klimaatadaptatiestrategie, *abbr.* NAS) was first drawn up in 2016 as a supplement to the Delta Program. The Delta Program has proposed five Delta Decisions covering three main fields — flood risk management, freshwater availability, and water-resilient spatial planning and the program is now in the transition from the proposal phase to the elaboration and implementation phase (Deltacommissioner, 2017a, 2018).

Four primary hazards have been framed and selected as the major themes of climate change adaptation especially for Dutch urban areas (Van de Ven et al., 2011, 2014):

- Fluvial & coastal flooding
- Pluvial flooding
- Droughts
- Heat stress

It can be foreseen that large investments and many relevant policies are expected in the upcoming decades to address the above-mentioned issues and make the cities in the Netherlands more "climate-proof" in the face of anticipated impacts and possible surprises in relation to climate change (Dessai and van der Sluijs, 2007). Due to the paradigm shift in the Dutch flood management style from event-trigged reactive style to precautionary proactive style, the way of thinking is changing to the risk-based approach — weighing the costs of reinforcements against the expected flood risk reduction. The risk-based approach is essential to the Delta Program, especially in terms of flood protection adaptation. The stringency of the new flood protection standards is not only linked to the probability of flooding but also dependent on the scope of its potential consequence (Deltacommissioner, 2017b).

Generally speaking, the aim of making bundles of investments and policies on climate change adaptation is to cope with rising risks faced by individuals and societies as a result of more extremes and the corresponding potential impacts induced by climate change (Buurman and Babovic, 2016; IPCC, 2014). Therefore, climate change adaptation should not be a goal on its own (Agrawal and Lemos, 2015), but is part of the sustainable development that requires the policymakers to make trade-offs between cost-benefits of adaptation measures, societal risk perception, and other development objectives (Buurman and Babovic, 2016).

2.1.4 Climate adaptation decisions

Climate change is a slow-onset process, of which the trend is observed over many decades. Adaptation to climate change often implies dealing with extremes and shocks, therefore, climate change adaptation is partially similar to deal with existing climate variability although the variability may not be stationary due to climate change (Buurman and Babovic, 2016).

Resilience is the ability of a system to withstand extremes and shocks and maintain normal functioning. Likewise, adaptation refers to adjustment to alleviate the adverse impacts of change or take advantage of the positive effects of climate change. Therefore, the concept of resilience is frequently mentioned in the context of climate change adaptation.

Resilience requires the system to be flexible and easily adaptable to cope with expected and unexpected changes (Linkov et al., 2014).

Traditional approach makes designs and plans based on an array of selected "best estimates" of future projections, however, the future often unfold differently from the initially assumed scenarios because of the uncertainties resulting from the long-term changes (De Neufville and Scholtes, 2011; Manocha and Babovic, 2017; Swanson and Bhadwal, 2009). Therefore, since the future cannot be predicted with certainty, the designs and plans should not be simply based on a limited number of possible scenarios but should allow for flexibility to adapt to newly emerged situations (Buurman and Babovic, 2016; Deng et al., 2013). Uncertainties unknown at the designing stage do reduce over time (Haasnoot et al., 2013). As the future unfolds, previously incomplete and uncertain information and knowledge may be resolved by people. Besides, the actual circumstance may differ from what is anticipated initially. Therefore, flexibility in engineering makes it possible for policymakers to adapt their old management strategies to new conditions. A system with flexibility is easily adaptable to actual futures thus greatly increases the expected value by eliminating future downside risks and profiting from upside opportunities (De Neufville and Scholtes, 2011).

2.2 Uncertainties

Climate adaptation decisions need to be made in an environment characterized by uncertainties (Buurman and Babovic, 2016). In the context of policymaking for climate change adaptation, there are plenty of uncertainties arising from various aspects and therefore it is of great significance to differentiate and classify different dimensions and types of uncertainties (Buurman and Babovic, 2016).

Inspired by the interpretations of probability as epistemic and aleatoric types (Gillies et al., 2000), Van Asselt and Rotmans (2002) classified uncertainties in terms of the dimension of the source where they are derived, as either epistemic uncertainties (*i.e.* uncertainties due to incomplete knowledge) or aleatoric uncertainties (*i.e.* uncertainties inherent in the system due to the variability of nature). Epistemic uncertainties include, for instance, deficiency of observations and measurements, inexactness and conflicting evidence, while aleatoric uncertainties contain variability in human behavior, value diversity, socio-economic dynamics and the inherent randomness of nature (Roeser et al., 2012).

In order to develop a systematic typology of uncertainties to support model-based decisionmaking from modelers' view, Walker et al. (2003) included two more dimensions in the classification than merely the dimension of source. They distinguished three dimensions of uncertainty as the location, level, and nature of uncertainty as shown in Figure 2.1.

- ***The location of uncertainty*** is identified by the generic locations of the model formulation and are therefore subdivided between context, model, input, parameters, and model outcome uncertainty. The Location of uncertainty answers "where uncertainty manifests itself within the whole model complex".

- ***The level of uncertainty*** answers the question "where the uncertainty manifests itself along the spectrum between deterministic knowledge and total ignorance". They described it as a progression from complete determinism to total ignorance within four levels — determinism, statistical uncertainty, scenario uncertainty, recognized ignorance

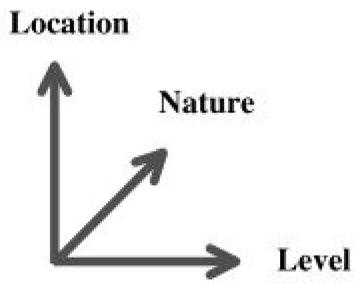


Figure 2.1: Uncertainty: A three-dimensional concept, reprinted from Walker et al. (2003)

and total ignorance. Figure 2.2 below illustrates the uncertainty space as a continuum, in which imprecision or statistical uncertainty may be addressed through addressing lack of data and implementing a series of currently available tools and approaches like statistical analysis, probabilistic approaches and scenario analysis (Buurman and Babovic, 2016), whereas deep uncertainties are much more problematic to deal with since they are unknowable at present and data may simply not exist, but deep uncertainties can reduce over time as future unfolds (Buurman and Babovic, 2016; Haasnoot et al., 2013; Walker et al., 2003, 2010).

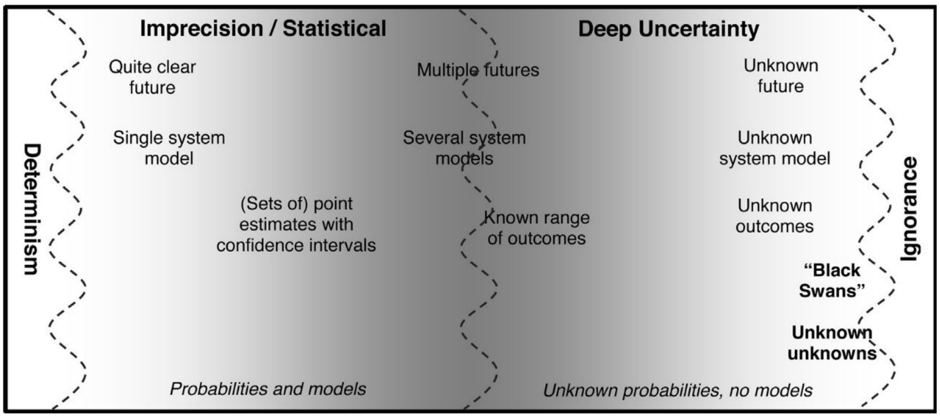


Figure 2.2: Different types of uncertainties (based on Walker et al. (2003)), reprinted from Buurman and Babovic (2016)

- ***The nature of uncertainty*** mainly talks about the source of uncertainty, and therefore answers the question "Whether the uncertainty is due to the imperfection of our knowledge or is due to the inherent variability of the phenomena being described". Just like the definition of source dimension by Van Asselt and Rotmans (2002), they differentiate uncertainties by the nature as epistemic uncertainty, which is due to lack of knowledge and may be reduced by additional research, and variability uncertainty, which is due to inherent variability like behavioural variability, societal variability and natural randomness.

Integrating three dimensions of uncertainty on the basis of the location dimension of uncertainty, a more inclusive categorization of uncertainty was proposed by Roeser et al.

(2012), which differentiates five levels of uncertainty as following — three levels of uncertainty within the modeling process, and the other two levels of uncertainty outside the modeling process:

- ***level 1*** — uncertainty about the outcome. In this level, although there is no absolute certainty, the model is known, the parameters are known, and therefore the outcome can be predicted with a certain probability. It corresponds with "model outcome uncertainty" in Walker et al. (2003)

- ***level 2*** — uncertainty about the parameters. In this level, the model is known but the parameters are not known. Uncertainty in parameters can be attributed to a variety of sources. It encompasses parameter uncertainty and input uncertainty in Walker et al. (2003) for reasons of simplicity and usefulness.

- ***level 3*** — uncertainty about the model. Models are simplified representations of the reality and there are usually multiple different perceptions and realizations of the world. In this level, we have several models as options and understand how likely each competing model is reflecting the real world. It is analogous with model uncertainty in Walker et al. (2003).

- ***level 4*** — uncertainty about acknowledged inadequacies and our implicitly made assumptions. A model can only reflect reality but cannot completely represent it. Even the best model has inevitable boundaries and limitations, which could be attributed to a host of possibilities like lack of data, inadequate assumptions, incomplete theories and *etc.* This level of uncertain is around indeterminacy section in the uncertainty spectrum.

- ***level 5*** — uncertainty about unknown inadequacies or "Deep uncertainty". This particular level of uncertainty refers to a deep level of uncertainty, to which extent we do not even know what we do not know — "unknown unknowns". It is difficult to formally or informally deal with these unknown inadequacies which are beyond our imaginations, simply because we do not know what they may be and what could possibly go wrong (Jasanoff, 2005).

Uncertainty related to climate change falls in the category of level 4 and level 5 uncertainties. Climatic adaptation decision is made under the environment characterized by deep uncertainties in climatic and socio-economic changes. Because these deep uncertainties have unknown probabilities and currently cannot be modeled due to inadequate knowledge, it is impossible to predict what exactly the future scenario will look like at the present time. However, these deep uncertainties can be diminished with the passage of time.

2.3 Adaptation pathway approach

2.3.1 Adaptive planning approaches

Uncertainties faced with decisionmakers are included with uncertainties in climate change, population growth, economic development, societal environment, *etc.* Deep uncertainties are unknowable at present but can be resolved as the future unfolds. In order to deal with these deep uncertainties, various planning approaches in the context of climate adaptation decision making, have been proposed throughout the years to support policymakers building long-term adaptive plans, which are flexible to be updated with the latest knowledge and are easily adaptable to the newly emerged situation in the changing environment.

According to the summarization by Manocha and Babovic (2018b), there are various adaptive planning approaches, including but not limited to, Assumption-based Planning (Dewar, 2002), Robust Decision Making (Lempert, 2003), Decision Tree Analysis (Ranger et al., 2013), Adaptive Policy Making (Walker et al., 2001), Adaptation Tipping Point (Kwadijk et al., 2010), Adaptation Pathways (Haasnoot et al., 2012), Dynamic Adaptation Policy Pathways (Haasnoot et al., 2013), Real Options Analysis (Zhang and Babovic, 2012), Info-Gap Robustness Pathway Method (Zischg et al., 2017), *etc.* These approaches have been implemented with other methodologies, tools, and techniques, like Monte Carlo Analysis (Zhang and Babovic, 2012), Info-gap decision theory (Zischg et al., 2017), *etc.*, to develop plans for the specific context of different case studies. As shown in Figure 2.3, these approaches deal with different levels of uncertainty with varied framing of the dynamic nature. Therefore, it is important to select appropriate approaches and implement it with proper methodologies and techniques to make long-term robust climate adaptation decisions.

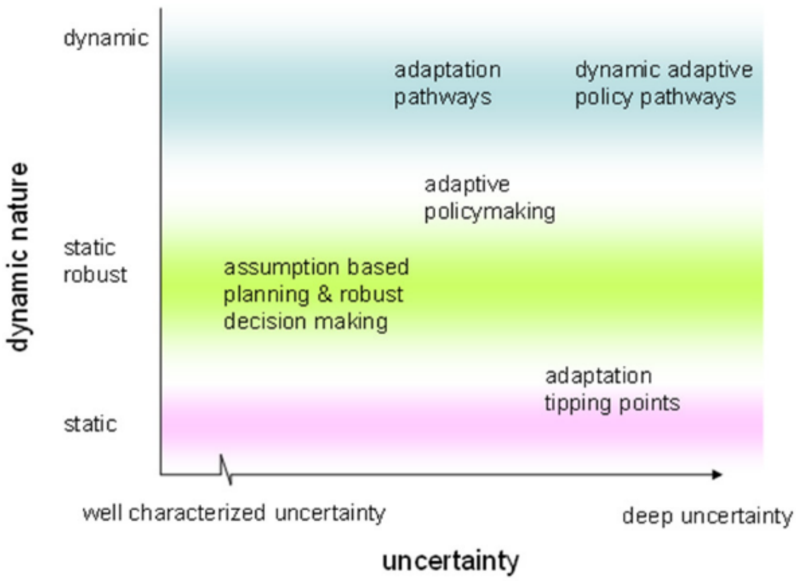


Figure 2.3: Adaptive planning approaches according to their dynamics and the framing of uncertainty, reprinted from Walker et al. (2013)

2.3.2 Steps to develop adaptation pathways

Among various adaptive planning approaches, the Adaptation Pathway approach (AP) proposed by Haasnoot et al. (2012) is getting increasingly popular with more and more applications to support dynamic adaptive climate adaptation decision making. The Dynamic Adaptation Policy Pathways approach (DAPP) proposed by Haasnoot et al. (2013)) can be deemed as its upgraded mode which integrates Adaptation Pathways with Adaptive Policymaking (Ranger et al., 2010).

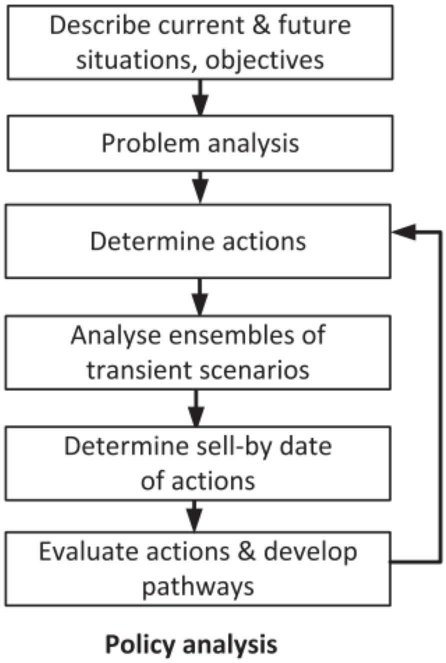


Figure 2.4: Stepwise procedure to construct Adaptation Pathways, reprinted from Haasnoot et al. (2013)

The stepwise procedure to develop adaptation pathways is summarized in Figure 2.4. According to the explanations from Haasnoot et al. (2013), a few basic concepts of Adaptation Pathway approach are presented below in brevity. Adaptation tipping point (ATP) is a key concept to Adaptation Pathway approach, which refers to the conditions under which an action fails to meet its predefined objectives (Kwadijk et al., 2010). The timing of the adaptation tipping point for a certain adaptive action is referred to as the sell-by date of the action, which is scenario-dependent. Once an action reaches an adaptation tipping point, it indicates additional actions are necessary, whether it is switching actions in sequence or adding actions in combination. Sell-by dates of actions are usually determined by the assessment model running a large ensemble of transient scenarios, of which the distribution can be summarized in box-whisker plots. The median values of sell-by dates are often used to assemble the adaptation pathways and make adaptation pathways maps.

2.3.3 Concepts in Adaptation Pathway approach

Several important terms associated with the Adaptation Pathway approach are introduced in this section. According to the glossary defined by Haasnoot (2013) and terminologies used by Haasnoot et al. (2012) and Manocha and Babovic (2017), the concepts of several relevant terms are provided as follows:

- **Action.** Adaptation/adaptive/policy + action/option is action to take. A strategy may be a single action or sequences of actions. An action can be switched to another action or be combined with another action when necessary.

- **Adaptation tipping point.** The condition under which the current management strategy performs unacceptably and can no longer meet its predefined objectives.

- **Sell-by date.** The timing of an adaptation tipping point for a policy option is the sell-by date of this action. Note that the exact timing of an adaptation tipping point for a certain action is unimportant, but the range and the moment should be roughly right.

- **Pathway**. Adaptation/policy + pathway is a sequence of adaptation/policy actions that is able to achieve the pre-specified objectives over the entire planning time frame. It is a possible and logical route/storyline into the desired point (*e.g.* 100year) in the future.

- **Lock-in.** A situation where some future actions in a pathway can only be implemented against major consequences like high associated costs or high societal impacts.

- **Flexible actions.** Actions which can be adapted (*i.e.* be leveled up or intensified), abandoned (*i.e.* be decommissioned and switch to a different action) or extended (*i.e.* be combined with other actions) without causing major consequences (high cost or high societal impacts). Flexible actions do not lead to future lock-ins. And, potential future action should be less limited by the anterior flexible actions.

- **No regret actions.** Actions that are robust or have additional benefits.

2.4 Case studies implementing Adaptation Pathway approach

Even though this adaptive planning approach — the Adaptation Pathway approach, is receiving increasing popularity in various disciplines, the number of research studies that have implemented this planning approach into water management issues is relatively small (Manocha and Babovic, 2017). And not to mention, despite the increasing number of applications per year, there have been only a few implementation cases of Adaptation Pathway approach and its modified mode in regard to flood management and urban drainage (Babovic and Mijic, 2019; Gersonius et al., 2014; Haasnoot et al., 2012, 2013; Ke et al., 2016; Manocha and Babovic, 2017, 2018a; Ranger et al., 2013).

Among these studies, due to the different context of study areas (*e.g.* situations, problems, objectives), the applicability of the assessment model, and other ad-hoc factors (*e.g.* simplifications, assumptions), researchers used different tailored methodologies to express and realize the fundamental principle of the Adaptation Pathway approach. Hence, it is important for this undertaken study to compare some existing typical examples in order to thoroughly learn not only the entire operational procedure but also the strength and weakness of different implementations of this approach. With a better understanding of the concept and framework, more comprehensive development of adaptation pathways can be realized. For this reason, two typical case studies are summarized for brevity and compared in Appendix G for reference, among which the Waas case is put more emphasis on as it is the primal case study where this approach was officially proposed and is a more complicated one. But the details are not dealt with here due to space limitations.

2.4.1 Top-down vs Bottom-up

It is important to differentiate two basic approaches people apply to support regional or local-scale climate adaptation planning — predictive top-down approach and resilience bottom-up approach (Carter et al., 2007; Dessai and van der Sluijs, 2007; Kwadijk et al., 2010). Two typical cases are introduced in detail in Appendix G as a comparison between the top-down implementation approach and the bottom-up implementation approach. Figure 2.5 is presented below as the contrast between the two approaches.

The predictive top-down approach is scenario-driven, using climate changing scenarios and social-economic scenarios as drivers in the assessment model to assess the impacts of adaptation actions and craft adaptation strategies (Dessai and van der Sluijs, 2007). Despite the deep dependence on the climate projections as one major limitation of this approach, the top-down approach has been most widely applied and thus has played a significant role in informing adaptation planning (Kwadijk et al., 2010). Waas case study by Haasnoot et al. (2012) is a typical example of the classic top-down implementation since thirty transient climate scenarios were used as the forcing to the assessment model. The resilience bottom-up approach can be deemed as a vulnerability assessment of the system which examines system's current adaptive capacity and necessary adaptation measures to increase system's resilience in response to climate change (Kwadijk et al., 2010). "Resilience is defined as the capacity of a system to tolerate disturbance without collapsing into a qualitatively different, usually undesired, state" (Dessai and van der Sluijs, 2007). In contrast to the top-down approach, the bottom-up approach is much less dependent on climate projections and can even be implemented without them (Kwadijk et al., 2010). Kent Ridge Catchment case study by Manocha and Babovic (2017) applied the adaptation tipping point approach using climate scenarios only to position the adaptation tipping points on the timeline, therefore, it is a typical implementation of the bottom-up approach.

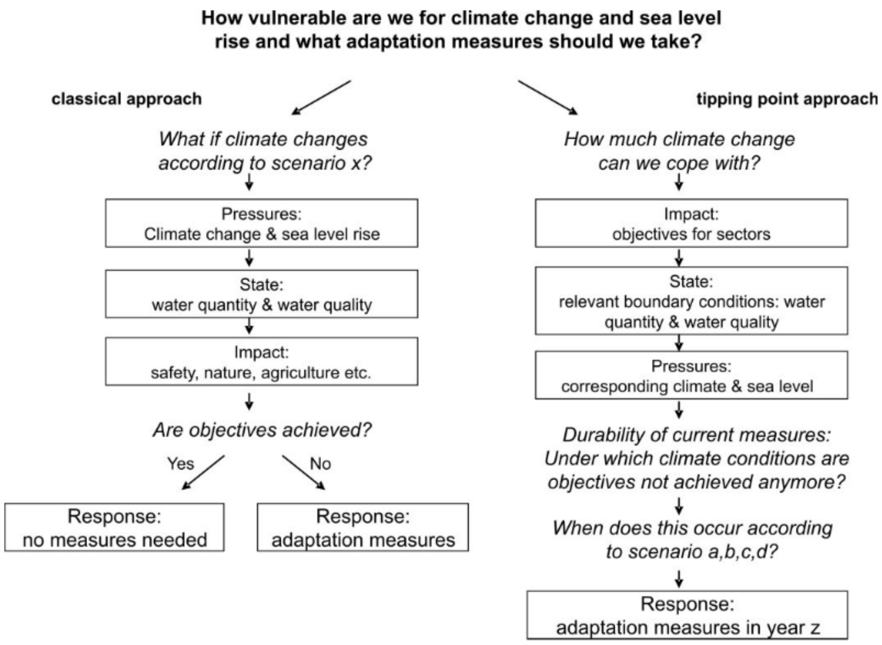


Figure 2.5: Classical top-down approach vs adaptation tipping point approach (resilience bottom-up approach), reprinted from Kwadijk et al. (2010)

Chapter 3

Methodology

Building adaptation pathways needs a series of stepwise actions. Based on the steps of the methodology of the original Waas case study carried out by Haasnoot et al. (2012) and its modified form put forward in IJsselmeer case study by Haasnoot et al. (2013), the methodology of developing adaptation pathways was refined and adjusted by Manocha and Babovic (2017) to make the adaptive planning of long-term urban drainage infrastructures for Kent Ridge Catchment in Singapore. Our Laakhaven case study has a similar objective as that of the Kent Ridge Catchment case study, aiming to provide policymakers with general directions on the long-term adaptive stormwater management planning of urban adaptation measures to mitigate neighborhood-scale pluvial flooding. Therefore, the stepwise procedure of the methodology of Kent Ridge Catchment case study is used as a reference mode and further adjusted in the undertaken study to develop adaptation pathways of pluvial flooding mitigation policies for Laakhaven-Oost. The procedure is shown in Figure 3.1 below.

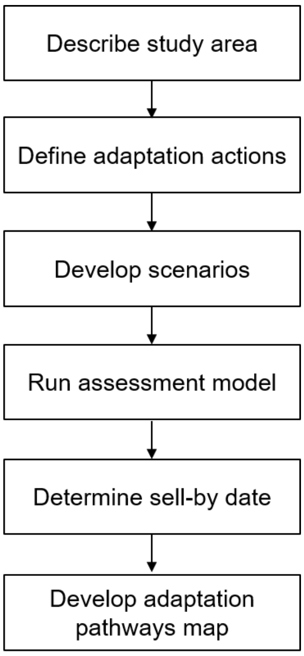


Figure 3.1: Stepwise procedure to develop adaptation pathways in the undertaken study

The methodology of this study consists of the following six steps:

1. The first step is to introduce the background information of the study area, including system characteristics, current problems, potential future constraints, and desired objectives.

2. The second step is to define an assortment of possible adaptation measures that may serve the objective and can be implemented with the assessment model. In practice, there could be nearly endless possibilities of adaptation actions to take. However, due to inevitable limitations and boundaries of both the model and the study, only a small number of options are incorporated and evaluated in the undertaken research.

3. The third step is to develop scenarios. Climate scenarios are essential to both the top-down and the bottom-up approach because the climate-associated uncertainties play the leading role in planning. However, climate scenarios are used quite differently by two approaches. Top-down approach uses transient climate scenarios as the forcing to drive the assessment model, for instance, in Waas case 30 transient climate scenarios are employed in the IAMM to encompass a bandwidth of possible future climates (Haasnoot et al., 2012). On the other hand, bottom-up approach, as a vulnerability assessment of the system, simply uses climate scenarios to project the adaptation tipping point in the timeline, a typical example of which is Kent Catchment Ridge case (Manocha and Babovic, 2017). This crucial distinction is elaborated in Appendix G. In this step, an array of climatic and social-economic scenarios is determined according to the requirements of the undertaken study.

4. The fourth step is to set up and run the assessment model. This step contains the hydrological part of the undertaken research, therefore, it has been put special emphasis on. The critical input to the assessment model — performance indicators of adaptation measures (*i.e.* runoff frequency reduction factor) is introduced in detail, including how the measures are formulated into the urban water balance model and whether the validity of this empirical relationship is confirmed. Therefore, careful explanations and illustrations on the assessment model are presented in this step.

5. The fifth step is to compute the sell-by dates of adaptation policies by timing the adaptation tipping point on the planning time horizon. The resulting sell-by dates are considered under three varied dimensions — climate scenarios, socio-economic scenarios, which have been developed in the third step, and the perspective-based socially acceptable risks.

6. The final step is to assemble the adaptation actions in rational sequences to make adaptation pathways (maps) following certain rules that exclude illogical pathways. Pathways are sequences of actions that meet the preset objective over the entire planning time frame (*i.e.* 100 years).

As shown in Figure 1.2 in section 1.4, except the initial steps in section 3.1 and 3.2, the core part in the implementation of the Adaptation Pathway approach is based on the risk-based approach. In the risk-based approach, the outcomes from the urban water balance modeling are applied as the critical input to the assessment model representing the effectiveness of adaptation actions, which are later put into the risk formula to determine the sell-by dates of adaptation policies. Figure 3.2 below shows three important elements in the risk formula in order to demonstrate the internal relationship between the steps of the methodology.

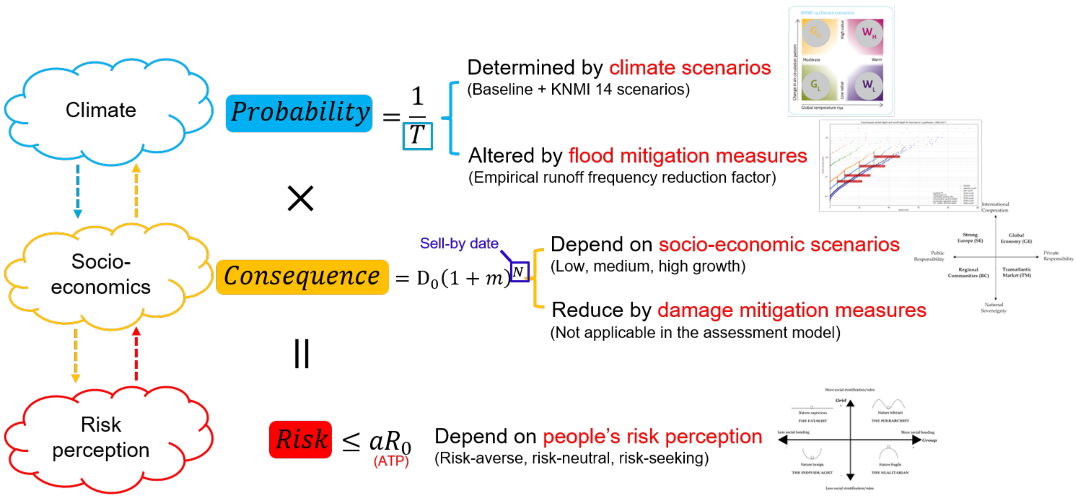


Figure 3.2: Risk-based approach as the core part in the implementation of Adaptation Pathway approach in the undertaken study

Below is the risk formula of the risk-based approach:

$$\text{Risk} = \text{Probability} \times \text{Consequence}$$

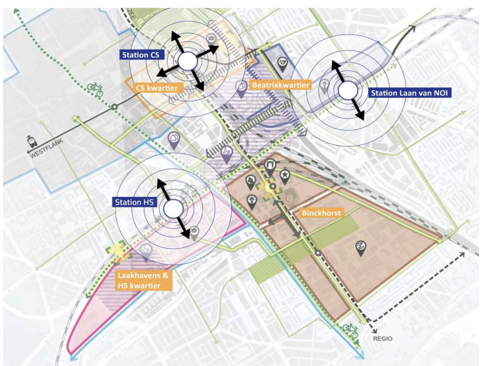
, in which the *Probability* corresponds with the climatic uncertainties. The probability of a flood (runoff) event is mainly determined by the rainfall of a climate scenario. Therefore, apart from the baseline climate scenario, we include another four KNMI'14 climate scenarios in section 3.3 to represent the uncertain climate change. However, the probability of the flood can be altered by the implementation of urban adaptation measures. In order to understand how these measures influence the flooding probability, a dynamic urban water balance model is employed to simulate these measures in section 3.4. A novel performance indicator of these adaptation measures, called runoff frequency reduction factor, is obtained from analyzing the empirical relationship in the model outcomes. The validity of this empirical performance indicator is proven by numerous runs and thus is used as the critical input to the assessment model. Another element in the risk formula is the *Consequence*, which is expressed as the potential damage of a certain flood event compounded over years due to the continuous socio-economic development. Therefore, three growth rates are introduced in section 3.3 to represent the socio-economic uncertainties.

With the probability and the consequence, the risk is computed as an increasing function of time. People with different world-views have different attitudes towards the risks, so the socially acceptable risk is considered as the adaptation tipping point, above which the current policy is said to fail to meet the target. Therefore, if a policy reaches this threshold at a certain time in the planning time horizon, it then becomes necessary to involve additional interventions to make the management under control again. We introduce three different risk perceptions as *Hierarchist*, *Individualist*, and *Egalitarian* from the Cultural Theory, each of which has a tolerable threshold for the risk. Based on the risk-based approach, the sell-by dates of all the adaptive actions are calculated in section 3.5, which are later used to assemble adaptation pathways maps in section 3.6 under certain rules.

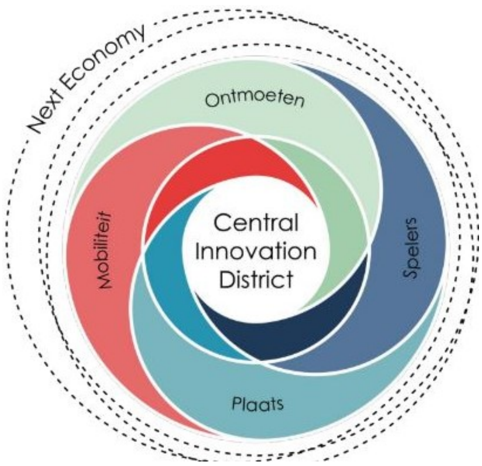
3.1 Description of the case study

Many urbanized areas are running towards the limit of urbanization expansion due to less and less available space for urban development, and as a result of this, people begin to opt for further concentration and densification of housing, work, and facilities on the basis of existing built-up contours (Haaland and van den Bosch, 2015). Nowadays, in the face of this challenge, an increasing number of municipalities in the Netherlands have been implementing the concept of the compact city to limit the suburban sprawl and to foster sustainable development (Broitman and Koomen, 2015; Nabielek, 2012). In the next few years, substantial improvements may have to be made to meet the rising demands. However, every new brick indicates a piece of green is under threat of disappearance. As commonly known, urban green space is an important element to the urban environment because it can help with evaporative cooling and flooding mitigation, bring environmental and ecologic benefits and enhance attractiveness and livability (Anguluri and Narayanan, 2017; Haaland and van den Bosch, 2015). Consequently, in The Hague, the Netherlands, current and future urban spatial developments will be centered around densification and greening as much as possible, which ask for urban developing in a resilient and sustainable manner. Above-mentioned anticipations and ambitions have been anchored in different policy documents such as the Agenda — Room for the City (2016), the Memorandum — high-rise buildings in the Hague: Eyeline and Skyline (2017) and the Covenant — Climate adaptive Building (2018). Anyway, the negative effects of compacting urban development approach on urban water management should be prevented or at least mitigated.

The Netherlands is a country that values innovation. According to the Global Innovation Index (GII) report (Dutta et al., 2018), in 2018 the Netherlands has climbed to the 2nd spot among 126 countries with significant advantages in terms of Business sophistication, Knowledge and technology outputs and Creative outputs. As a test site for innovative "city of the future", the Central Innovation District (CID) in The Hague, which is triangulated by three railway stations — The Hague Central, Hollands Spoor and Laan van NOT (North-East Indies) (see in Figure 3.3a), has been considered as one of the most important current and future economic pillars of Rotterdam–The Hague metropolitan area.



(a) The planning diagram of CID



(b) An integral view of CID

Figure 3.3: Central Innovation District (CID) — Economic heart of The Hague, reprinted from Pol (2018)

In the coming years, under the collaboration of all stakeholders, this area is planned to be developed into an attractive, multifaceted, and internationally competitive innovation district. Therefore, the CID is confronted with both opportunities and challenges since various values and objectives such as housing, transportation, and public design have to be integrally realized in a creative way to prepare for the next economy as shown in Figure 3.3b.

Under the CID framework, regional agendas have already been drawn up to depict the vision of the "education quarter" of the CID — Laakhaven-Oost, the area around Station Holland Spoor and The Hague University, as a sustainable green city campus. A previous study has shown that the Laakhaven-Oost is vulnerable to a greater chance of extreme precipitation and temperature events due to climate change (Brolsma, 2018). This evidence reveals that it is of vital importance for the municipality and all relevant stakeholders to take note of the impacts and consequences of climate change and make allowance for corresponding adaptation strategies. The planning task is not solely linked to engineering and technologies, but is strongly associated with socio-economic elements and requires intensive collaboration and information sharing between stakeholders from different public and private sectors (McEvoy et al., 2018; Voskamp and Van de Ven, 2015). Thanks to the Adaptation Support Tool (AST), a workshop-based preliminary urban planning dialogue is made easier (van de Ven et al., 2016). The AST is not a detailed analysis tool, but a tool built to support exploration of resilient and climate-proof urban planning strategies, which integrates quantifying adaptation objective and identifying possible solutions into a workshop to provide participants with a shared picture on how certain adaptation measures can contribute to the climate resilience, the urban attractiveness, the life quality, and the social cohesion in the neighborhood of interest (van de Ven et al., 2016). Two workshops have been successfully conducted to discuss possible solutions to corresponding flooding and heat problems in Laakhaven-Oost (Brolsma, 2018). Taking these as a starting point, we think that Laakhaven-Oost is a good example to study urban adaptation strategy for a strongly urbanized neighborhood suffering pluvial flooding risk.

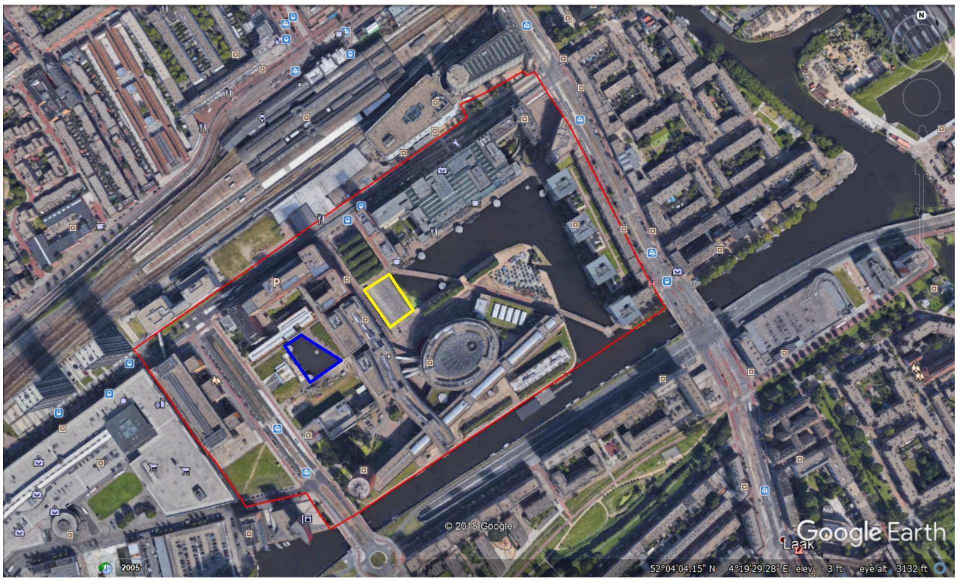


Figure 3.4: Aerial view of the study area located in Laakhaven-Oost, retrieved from Google Earth Pro

The study area is the area around Haagse Hogeschool opposite to Station HS, located in the western part of Buurt 19 Laakhaven-Oost intersected by Rijswijkseweg. Figure 3.4 shows its contour. Laakhaven-Oost neighborhood lies within Wijk 38 Laakkwartier en Spoorwijk in the municipality of 's-Gravenhage (*i.e.* The Hague). According to a yearly statistical report by Statistics Netherlands (Centraal Bureau voor de Statistiek, *abbr.* CBS) (CBS, 2018), a Dutch governmental institution that gathers and publishes reliable consistent statistical information about the Netherlands, Laakhaven-Oost has a total surface area of 34 hectares, of which 29 are land and 5 are water, and it is one of the most densely populated territories with a population density of 14048 inhabitants per km^2, which is around 28 times greater than the average population density of the Netherlands (510 inhabitants per km^2). This crowded area is filled with large companies and organizations. There are enterprises like the Consumentenbond Holding B.V., UWV-kantoren en Werkpleinen and T-Mobile Hoofdkantoor, and universities and schools like De Haagse Hogeschool and ROCMondriaan.

Figure 3.5: Land cover map of Laakhaven-Oost, made using QGIS

As shown in Figure 3.4, the entire surface covers 16.4 hectares. The area of the surface water is 1.9 ha, including water beneath the platform (yellow polygon) but excluding the pond (blue polygon). An urban water balance model was applied to dynamically simulate the hydrological processes in the water system of the study area. This model is introduced in detail in section 3.4. The surface water is considered as an external exchange to the model, while the pond is considered as the internal open water component of the model. Open water drains the excessive water above the target water level to the outside water at the predefined pumping capacity and lets water in to compensate for the water shortage. During heavy rainfall events, the storage capacity over the surface water could be exhausted, so the backwater from the open water together with the incoming stormwater runoff fills the sewer system leading to sewer overflows onto the streets — pluvial flooding. Therefore, adaptation measures are necessary to cope with the excessive water to alleviate the overloading to the drainage system. Extracting the 1.9 ha surface water from the total area, the project area to model thus came to 14.5 ha. Figure 3.5 below shows the land cover map of Laakhaven-Oost plotted using QGIS. Based on the land cover map together with observations and measurements from Google Earth Pro, the land cover proportions were determined, the results of which are shown in table 3.1 below. One thing to note here is that approximately 0.2 ha of the buildings are covered with a green roof, however, it was not taken into account because the properties of these installations were unknown.

Table 3.1: Land cover fractions and related parameters of Laakhaven-Oost. Estimations of interception capacity and infiltration capacity were based on the findings [1] from van de Ven (1989) and expert judgment.

Code	**Type**	**Percentage**	**Acreage** (ha)	**Interception capacity** (mm)	**Infiltration capacity** (mm/d)
PR	Building	32.60%	4.727	1.6	–
CP	Closed paved	11.00%	1.595	1.6	–
OP	Open paved	41.60%	6.032	1.6	10.9
UP	Unpaved	13.80%	2.001	20	480
OW	Open water	1.00%	0.145	–	–

Some other model parameters are included with the follows:

- Target open water level (NAP -0.43 m) is 1.03 m below the ground level (NAP +0.6m).
- There is no combined sewer system. Storage of the stormwater drainage system is 2 mm over the connected area. 100% of the paved area is connected to the sewer system.
- Water overflow onto the street is designed to occur once every 2 years (T = 2 year) under 16.8 mm/hr rainfall.
- Seepage from shallow groundwater to deep groundwater is preset as 0.25mm/d.
- Soil type is podzol and crop type is grass.
- Other parameter setups are summarized in Table C.1 in section C.3.

[1] On annual basis, rainfall falling on a roof or closed pavement is on average partitioned into 20% evaporation and 80% runoff; rainfall falling on open pavement is on average partitioned into 20% evaporation, 30% infiltration and 50% runoff.

3.2 Definition of adaptive actions

3.2.1 Pluvial flooding adaptation measures

Urban flooding can be categorized into three types according to the cause: pluvial flooding, fluvial flooding, and coastal flooding. Our research focuses on the pluvial flooding only. Pluvial flooding occurs usually when an extremely intense or prolonged rainfall event saturates the storage capacity and drainage capacity of the urban water system so that the excess water can no longer be absorbed resulting in overland flow on streets and ponding in local depressions and topographic lows, and pluvial flooding often leads to significant environmental impacts and huge socio-economic losses (Houston et al., 2011; ten Veldhuis, 2010). Pluvial flooding can also be associated with lower intensity rainfall or snow melting given a near-saturation antecedent condition or if the ground is highly impervious due to paved or frozen land surface (Houston et al., 2011). It is a direct, quick and localized consequence of rainfall that virtually can happen anywhere (Simões et al., 2015). In strongly urbanized areas where the density of the population, buildings, critical infrastructures, and socio-economic activities is high, the hazard of the pluvial flooding is the most pronounced and damaging, and its potential impact is likely to be exacerbated by critical stress factors like the rapid urbanization and the changing climate (Houston et al., 2011; Simões et al., 2015; ten Veldhuis, 2010). In the Netherlands, pluvial flooding is further differentiated into three categories as water hindrance, severe water hindrance, and water nuisance according to the severity of potential impacts (Riel, 2011; RIONED, 2006) and the potential impacts can be classified as material impacts, economic impacts, health impacts, emergency assistance impacts, and discomfort (Riel, 2011). Figure 3.6a depicts a flood event in Copenhagen, Denmark, which disrupted the traffic in city center thus interrupting ordinary course of business. Figure 3.6b shows an inundation in a residential area in the Rivierenbuurt neighborhood in Amsterdam, The Netherlands, which was likely to negatively affect people's mood and health.

(a) Urban floods, Copenhagen, July 2011, reprinted from Landa Mendez (2014)

(b) Waterlogging, Amsterdam, July 2014, reprinted from Parool (2014), copyright Ruben Steeman

Figure 3.6: Urban pluvial flooding brings damage to the environment, the infrastructure, and people, resulting in social-economic losses. This issue is accentuated by climate change and urbanization.

To deal with this serious and evolving challenge of urban flooding, it is of vital significance to manage the existing and future flood risks through a series of actions (Jha et al., 2012). Urban flood management measures can be divided into structural measures and non-structural measures and an integrated strategy requires balancing the use of both measures (Dawson et al., 2011; Jha et al., 2012). Structural flood risk management measures are physical constructions that intervene in urban runoff and storage to alter the probability of flooding; on the other hand, non-structural measures generally have no physical presence but use knowledge, practice or agreement to mitigate potential damage, examples of which are land use regulations, people's preparedness, risk financing instrument, *etc.* (Dawson et al., 2011; Jongman, 2018; UNISDR, 2009).

Pluvial flooding adaptation measures in question for the undertaken study are limited to structural measures in the broad sense [2]. Structural measures can be divided into gray measures, blue measures and green measures, the latter of which have the latest jargon "nature-based solutions (NBS)" (Depietri and McPhearson, 2017). In contrast to traditional gray measures that mainly use concrete and steel, in recent years, blue-green measures (GI or BGI), which mimic natural processes, have been giving increasing considerations and implementations for their multi-functionalities and ecosystem-related co-benefits (Demuzere et al., 2014; Dhakal and Chevalier, 2017; Kazmierczak and Carter, 2010).

In the Adaptation Support Tool (AST), there is a long list of more than 60 blue, green and gray adaptation measures for mitigating the issues of urban pluvial flooding, drought and heat stress (van de Ven et al., 2016). Among them, 24 adaptation measure options are directly related to pluvial flooding mitigation, thus are used as the scope of selection. An overview of these adaptation measures is in Table 3.2 below. For more detailed information like the descriptions and conceptualizations of these measures, please refer to Appendix A.

AST ID	Measure	AST ID	Measure
3	Adding trees to streetscape	29	Rain barrel
4	Urban wetland	32	Storage by creating extra freeboard
6	Bioswale (with drainage)	33	Infiltration boxes
10	Deep groundwater infiltration	40	Water roof
11	Ditches	41	Water square
14	Green facade	42	Green roof (with drainage delay)
16	Green roof (extensive)	46	Underground storage tank
19	Create extra surface water	71	Wet pond
20	Driange-Infiltration-Transport (DIT) drain	82	Gravel layers
22	Infiltration fields and strips with surface storage	90	Permeable pavement (storage)
25	Urban forest	91	Remove pavement to plant green
26	Permeable pavement systems (infiltration)	45 (&97)	Hollow roads

Table 3.2: 24 urban adaptation measures outlined in the Adaptation Support Tool (AST) that help mitigate pluvial flooding risk. Their corresponding IDs in the AST are used as indexes for subsequent classifications.

3.2.2 Classification of adaptation measures

Fundamentally speaking, in spite of various types and terminologies of these structural flood management measures, they all can be categorized into specific classifications in light of different metrics like functionality, location, degree of centralization. Appropriate

[2] Here, structural measure means any measure with physical presence. In civil engineering, structural measure often narrowly refers to constructions made of concrete and steel (Gray Infrastructure).

classification of these adaptation measures not only helps with sub-selection of representative ones to increase the trackability of the subsequent study but also contributes to a better understanding of urban stormwater management. To ensure a good classification of measures, one should understand why, what and where these measures are applied, which is not possible without the basic understanding of urban water systems.

3.2.2.1 Urban "Watersystem"

Urban water systems have to deal with five types of water namely precipitation, drinking water, surface water, groundwater, and wastewater (Van de Ven, 2016). As shown in Figure 3.7, an urban water system is partitioned into two interrelated parts based on the source of water — *"Waterchain"* on the upper part of the figure, which includes external drinking water supply, sanitary sewer, and wastewater treatment; and *"Watersystem"* on the lower part, which requires a comprehensive management on the quantity and quality of precipitation (rainwater and stormwater), groundwater, and urban surface water (De Graaf, 2009). *"Waterchain"* is more of sanitary engineers' concern, whereas *"Watersystem"* is the study field for urban water management engineers (De Graaf, 2009) thus the focus of this thesis.

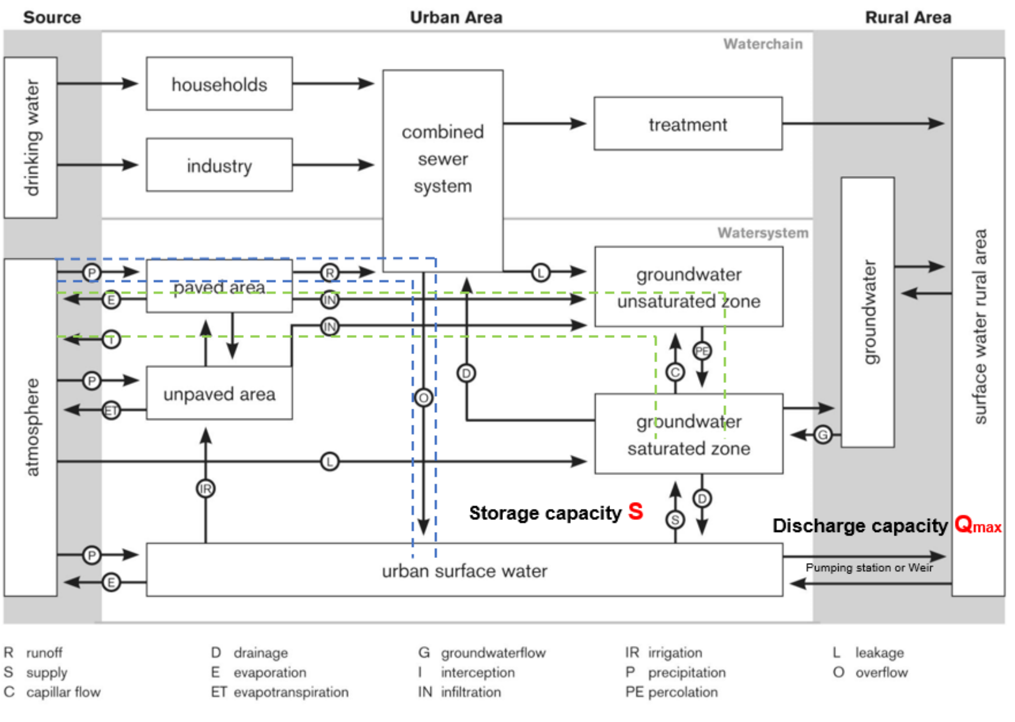


Figure 3.7: Schematic overview of an urban water system (with only combined sewer system), adapted from De Graaf (2009)

3.2.2.2 Source-Pathway-Receptor Approach

An urban water system is separated from the surrounding rural (regional) water system by a weir or a pumping station for a multitude of reasons (Van de Ven, 2016). ten Veldhuis et al.

(2011) used the concept of source-pathway-receptor [3] to describe internal components of an urban drainage system for a typical polder system. Here, the concept is adapted to suit the study context and presented as follows:

- **Source**

  Water on the urban unpaved and paved surface is considered as the source. It mainly comes from precipitation.

- **Pathway**

  Two pathways are defined as the fast runoff pathway and the slow runoff pathway. The fast runoff pathway is "a fast surface and piped runoff component", whereas the slow runoff pathway is "a slow runoff component through the soil/subsurface drainage system" (Van de Ven, 2016).

  – Fast runoff pathway (marked as blue dashed line in Figure 3.7) is that stormwater mainly takes sewer systems as routes to the surface water receptor. There are two types of sewer systems. Combined sewer systems were commonly applied in the past. It transports wastewater together with rainwater to the wastewater treatment plant (WWTP) under dry weather and light rainfall condition. During heavy rainfall events, combined sewer overflows (CSOs) occur discharging excessive water directly to recipient watercourses. In case of extreme events, sewer overflows on the street through manholes may occur due to the system overloading of the sewer system and watercourses. Combined sewer system brings pollution to both the surface water and the streets. Separate sewer systems were later introduced in the 1970s. It consists of two separate sewer pipelines — a sanitary sewer discharging wastewater to WWTP and a storm sewer discharging stormwater directly to surface water. Therefore it overcomes the main drawback of combined sewer systems. Given a heavy rainfall, pluvial flooding can arise in both sewer systems due to the system overloading or the pathway interruption as a result of the failing system component (ten Veldhuis et al., 2011; ten Veldhuis, 2010). Stormwater runoff through sewer systems is a relatively fast process. In a separate sewer system, stormwater drains pretty fast from roofs and streets via storm sewers to the surface water usually with the delay of no more than 5-15 minutes (Van de Ven, 2016). A combined sewer system is different since it needs to be filled up to the weir level before overflows to the watercourse. However, the hydrological response in a sewer drainage system is considered much faster than a natural drainage system.

  – Slow runoff pathway (marked as green dashed line in Figure 3.7) refers to that stormwater either directly infiltrates to the groundwater receptor or drains via groundwater (in many cases a subsurface drainage system) to the surface water receptor. Stormwater drains at a much delayed pace through the slow runoff pathway. Compared to the fast runoff pathway, the delay of stormwater runoff

[3] Singapore PUB also uses Source-Pathway-Receptor approach to provide holistic solutions that cover every spectrum of the drainage system (PUB, 2013). However, two concepts are different, especially in the definition of receptor. In Singapore context, receptor means infrastructures exposed to flooding thus requiring damage mitigation measures.

through natural drainage and subsurface drainage to receptors would be the hundreds or even thousands larger (Van de Ven, 2016).

- **Receptor**

  Urban surface water and groundwater are the final receptors. Urban surface water includes, but is not limited to ponds, canals, and watercourses that serve as recipient water bodies of the runoff coming from above mentioned fast and slow tracks. They are maintained at the target water level by pumping excessive water out to rural surface water, limited by a discharge capacity of the polder (Q_{max} in Figure 3.7). Water from outside is also let into the polder to maintain the correct level in the watercourses by compensating for the water loss due to *e.g* evaporation. During heavy rainfall events, the runoff input to the surface water receptor is greater than the discharge capacity thus resulting in the water level rise. Target water level, freeboard and maximum acceptable increase in water level dH_{max} are three significant design factors that influence not only the storage capacity (S in Figure 3.7) and hydrological processes but also the dynamics of the entire system. During heavy storms, when the storage capacity over the surface water receptor is completely exhausted, the backwater from the watercourse and the still incoming stormwater runoff will saturate the drainage system thus causing sewer overflows on the street, *i.e.* pluvial flooding. Therefore, adaptation measures are necessary to cope with the water surplus in these cases. Groundwater is another receptor dynamically interacting with the surface water. Large amounts of water from pervious and semi-pervious surface replenishes the groundwater through infiltration.

3.2.2.3 Storage capacity - Discharge capacity

System capacity of an urban water system to cope with extreme storms is composed of discharge capacity and storage capacity, and they are exchangeable (Van de Ven, 2016). Figure 3.8 below shows the Storage-Discharge-Frequency curve for Laakhaven, which is made through analyzing the outcomes from the urban water balance model. As can be seen from the figure, a system with large pump and small storage could fail once every 2 years, just as a system with small pump and large storage. A suitable combination of the discharge capacity and the corresponding required storage capacity can be determined by water managers based on this SDF-curve.
To level up the system, one can either increase the pumping capacity or add more storage volume based on the local context and cost-effectiveness analysis. However, nowadays in the Netherlands, due to a series of hydrological, geotechnical and aesthetical reasons, the discharge capacity of an urban water system to outside water is much more limited than previously, reduced from 15-25 mm/d to 12-14 mm/d (Hooimeijer and van der Toorn Vrijthoff, 2014; Van de Ven, 2016). Therefore, it requires larger storage capacity to handle extreme rainfall events, indicating much more stormwater shall be buffered in the urban surface water and the groundwater. However, the storage capacity of the receptors cannot be unlimitedly increased. Therefore, here comes a third solution to the Storage-Discharge problem — reducing the runoff input (*i.e.* runoff intensity and runoff volume) to the receptors (Van de Ven, 2016).

As mentioned above, the water is drained much faster through the fast runoff pathway than through the slow runoff pathway. Hence, if the stormwater on the urban paved

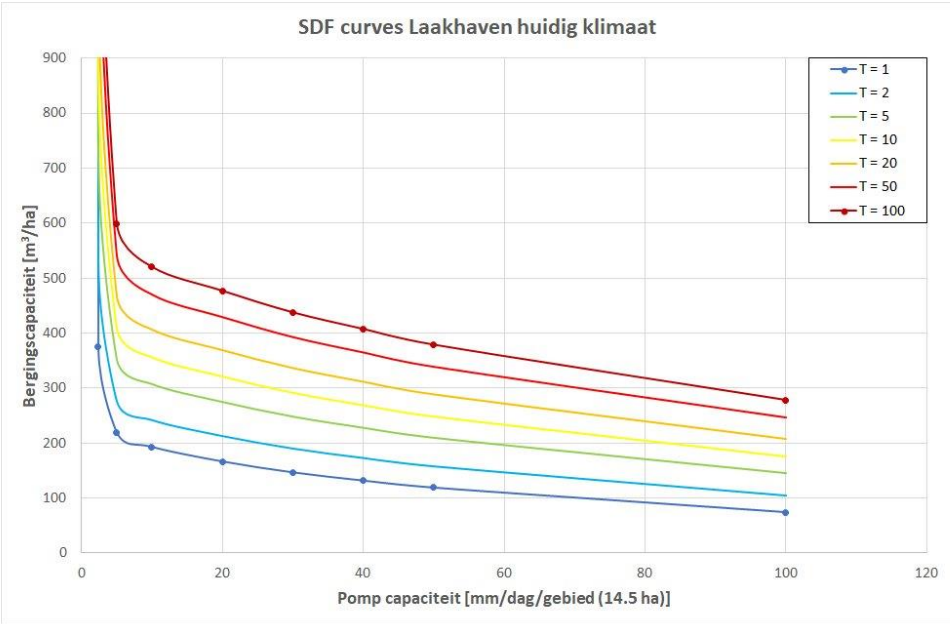


Figure 3.8: Storage-Discharge-Frequency (SDF) Curve for Laakhaven under the current climate, made with results from Urbanwb model

surface is diverted to the slow runoff pathway where it infiltrates into the groundwater or drains through the subsurface drainage system to surface water instead of directly entering the sewer system, the runoff process is delayed and thus the loading to the sewer system is relieved. Or, the stormwater can be temporarily stored in a retention or a detention basin [4] before entering the sewer system, in this way, system overloading of the drainage system can be alleviated thus reducing the probability of pluvial flooding. Figure 3.9 below shows above-mentioned two ways of reducing the runoff input to the receptor. Furthermore, there are additional benefits brought by this method. For instance, stormwater quality is improved through filtration and retention, the heat stress is reduced through evapotranspirative cooling, and the groundwater is replenished which helps alleviate droughts and land subsidence.

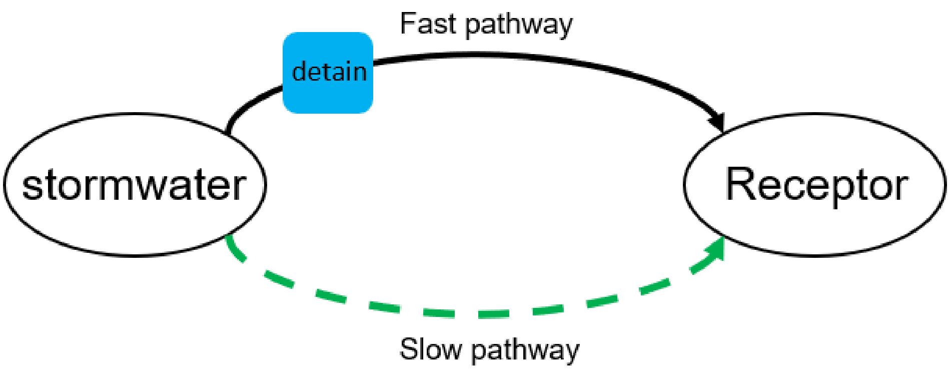


Figure 3.9: 3rd solution to the storage-discharge problem — reducing runoff input to the receptor

[4] Detention and retention are often used interchangeably. More precisely, a detention pond is a dry pond while a retention pond is a wet pond that remains permanent pool.

Numerous measures exist to achieve the purpose of reducing runoff input to the surface water and these measures are the so-called Sustainable Drainage Systems (SuDS) components. Various concepts akin to SuDS are used in different countries. SuDS was a popular concept originated in the United Kingdoms (Ashley et al., 2015). Similarly, Green Infrastructure (GI) (Gill et al., 2007), Best Management Practices (BMPs) (Barrett, 2005) and Low Impact Development (LID) (Dietz, 2007) have been frequently used in North America. These new terminologies were developed and adopted over time, reflecting the evolution of the urban drainage profession and its transition to an increasingly sustainable and integrated pattern (Fletcher et al., 2015).

Sustainable drainage systems (SuDS) manage stormwater runoff as close to its source as possible and mimic natural drainage pattern, and they can be designed to encourage infiltration, increase evapotranspiration, attenuate stormwater runoff and support passive treatment (Griffiths, 2017). Griffiths (2017) classified components of SuDS as following: ***a.*** Source control component manages rainfall locally at where it falls thus reducing runoff in the downstream direction. Examples are rain barrels, green roofs, permeable pavements, *etc.* ***b.*** Conveyance component slows down the transfer of stormwater runoff across the site between different components. Examples are vegetated swales, Drainage-Infiltration-Transport (DIT) drain, *etc.* ***c.*** Treatment and attenuation component creates relatively large storage volume to retain water. It mainly provides stormwater runoff attenuation. Sometimes, treatment through sedimentation is possible if given enough residence time. Examples are wet ponds, detention basins, water squares, and underground off-line tank. Plenty of adaptation measures can be applied as the SuSD components in an urbanized catchment to cover the entire Source-Pathway-Receptor chain for the purpose of enhancing an urban water system's resilience to more extremes induced by the climate change.

3.2.2.4 Classification and sub-selection of adaptation measures

For now, we have already listed 24 adaptation measures shown in Table 3.2, of which the detailed explanations and conceptualizations are presented in Appendix A. Classification of these measures and further sub-selection is necessary for the subsequent study.

In terms of the Storage-Discharge relationship, the measures can be classified as shown in Figure 3.10 below. Design discharge capacity Q, target water level, freeboard, and maximum acceptable increase in water level dH_{max} make up a package of interlinked parameters, which is the results of thorough iterative considerations on various aspects like hydraulic, hydrological, urban architecture (Van de Ven, 2016). Increasing pumping capacity is a straightforward way to increase the Q enabling urban surface water drain the surplus water more rapidly to the outside. However, as such, problems are then shifted to the downstream neighborhoods. Deep groundwater infiltration (AST 10) can be seen as a different way to increase the discharge capacity. Increasing storage capacity on the urban surface water receptor can be realized in two ways — increase water level fluctuations or create more surface water area. Real-time-control preventive pumping before a rainstorm coming is an easy and the least expensive way to allow more pre-event storage capacity without any spatial intervention, but it is not always reliable. Having more watercourses as the surface water is often constrained by the urban spatial planning. Creating runoff retention measures like ditches and wet ponds can be considered as creating extra surface water in the system. Other measures are thus categorized as "reducing runoff input" measures.

Based on the SuDS component representation (Source control — Conveyance — At-

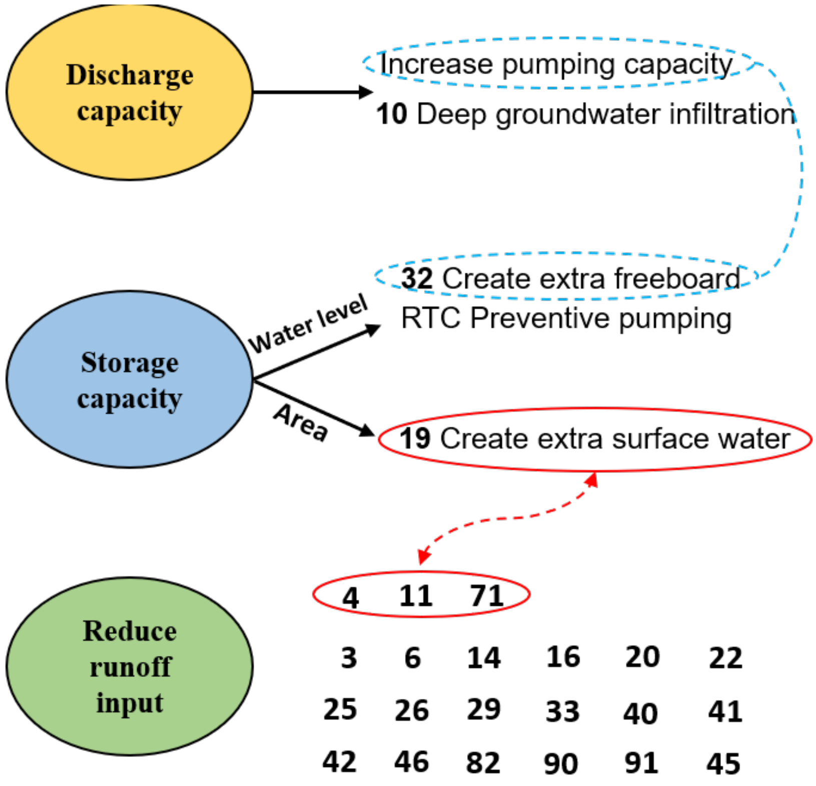


Figure 3.10: Classification of 24 adaptation measures based on Storage-Discharge relationship

tenuation), 21 "reducing runoff input" measures are further categorized as in Figure 3.11 below. These measures have at least a certain amount of storage volume. The emptying mechanisms of these measures are differentiated according to their design functionalities – evapotranspiration, infiltration, attenuation, and combinations of these functionalities. Referring to the emptying regimes mentioned by Vergroesen et al. (2013), we here define the measures' emptying mechanisms as three ways — through evapotranspiration, through infiltration, and through regulated discharge. Thereinto, regulated discharge is further defined into two simple kinds — fast pumping, which represents periodic/regular pumping; and delayed drainage, which involves a discharge level (head difference) and drainage resistance. Actually, the regulated emptying regime in reality is much more complicated and is sometimes almost impossible to model. The emptying mechanism of measures is important since it determines how much room for storage is available again when the next rainfall event comes. The classification of adaptation measures in terms of emptying mechanisms is presented in Figure 3.12 below. An urban paved area can be divided into the paved area at the ground level (impervious paved surface and semi-pervious paved surface), which we call the paved land surface, and the paved area above the ground level (building roofs), which we call the paved roofs. Therefore, measures are installed on either the ground or the rooftops. A rain barrel is usually installed in a private garden collecting runoff from roofs, but here it is also considered as a measure on roofs. Based on the installation location and the source of runoff, the classification of adaptation measures in terms of locations is presented in Figure 3.13 below.

In terms of different dimensions mentioned above — Storage-Discharge relationship, SuDS component representation, emptying mechanisms, and installation locations, 24 measures have been classified in a clear manner. 6 out of 24 measures are further sub-selected as the adaptation measures in question, which are later used in the subsequent study. Please note that 24 measures are all simulated and evaluated, of which the results are in Appendix D for the readers' reference. The out-selected 6 measures are 3 measures applied to collect the runoff from private roofs — rain barrel, green roof (extensive), and green roof (with drainage delay), and 3 measures constructed on the ground — porous pavement, bioswale, and water square. Then here comes the question — what are the specifications of these measures? They can be basically designed in any reasonable form and size. To answer this question, we introduce the concept of effective depth, which is carefully talked about in section 3.4. Adaptation measures in isolation or in combination make up the whole package of adaptation actions, which is presented in detail in section 3.5.

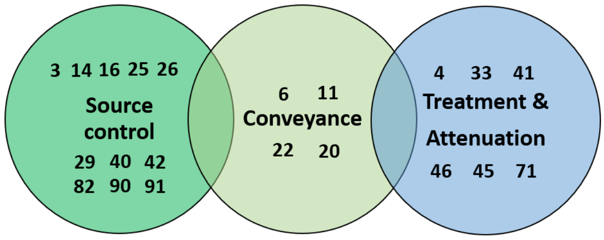


Figure 3.11: Classification of adaptation measures in terms of SuDS component representation

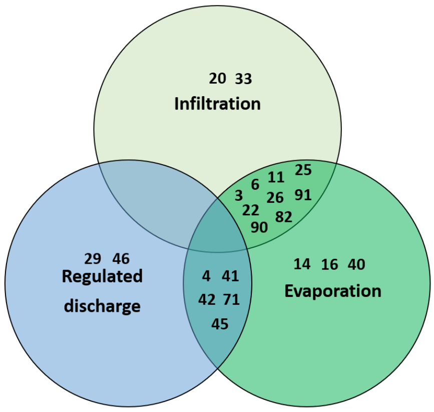


Figure 3.12: Classification of adaptation measures in terms of emptying mechanisms

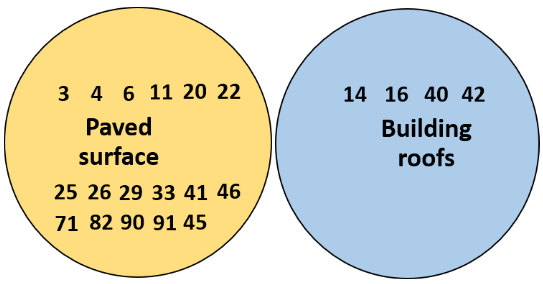


Figure 3.13: Classification of adaptation measures in terms of installation locations

3.3 Development of scenarios

A collection of different climate scenarios and socio-economic scenarios were developed in this section to study the coupled impacts of climatic and anthropogenic factors on the timing of the adaptation tipping point — sell-by date of adaptation actions. A range of possible futures is covered by these developed scenarios to support the development of the adaptive planning of pluvial flooding mitigation measures.

3.3.1 Climate scenarios

The Royal Dutch Meteorological Institute (KNMI), as the national data and knowledge institute for climate science, is constantly adapting and publishing updated results with the latest insights to support professionals from various disciplines with enormous climate information (Van den Hurk et al., 2007). KNMI develops climate scenarios in step with the Intergovernmental Panel on Climate Change (IPCC)'s scenarios on a regular basis. The newest version of KNMI future climate scenarios is KNMI'14 scenarios, which updated previous KNMI'6 scenarios based on recent scientific evidence (Klein Tank et al., 2014). Four new scenarios were proposed in KNMI'14 scenario, namely G_L, G_H, W_L, and W_H. A summary table of the predicted temperature rise and the mean amount of seasonal precipitation and evaporation change in 2085 is shown in Table 3.3 below:

Table 3.3: KNMI'14 climate scenario change values for the climate around 2085 (2071-2100)

Season	**Variable**	**Indicator**	G_L	G_H	W_L	W_H
Global temperature rise			+1.5°	+1.5°	+3.5°	+3.5°
Change in air circulation pattern			Low value	High value	Low value	High value
Year	Precipitation	Mean amount	+5%	+5%	+7%	+7%
	Evaporation	Potential evaporation (Makkink)	+2.5%	+5.5%	+6%	+10%
Winter	Precipitation	Mean amount	+4.5%	+12%	+13%	+30%
Spring	Precipitation	Mean amount	+8%	+7.5%	+15%	+12%
Summer	Precipitation	Mean amount	+1%	−8%	−5%	−23%
		Maximum hourly intensity per year	+8 to +16%	+9 to +19%	+22 to +45%	+22 to +45%
	Evaporation	Potential evaporation (Makkink)	+3.5%	+8.5%	+9%	+15%
Autumn	precipitation	Mean amount	+7.5%	+9%	+6.5%	+12%

The baseline climate scenario is well represented with the 30-year hourly time series of precipitation and evaporation for Laakhaven (from 1988-01-01 to 2018-01-01). Taking the predicted change values of KNMI'14 scenarios as a guideline, we developed four synthetic time series representing four KNMI climate scenarios based on the reference time series by changing the precipitation and evaporation amount at predefined proportions for each season period. Details on how these synthetic transient climate time series were produced can be found in the Appendix B. In contrast to 30 transient climate scenarios of different realizations of precipitation and evaporation generated by the weather generator applied in Haasnoot et al. (2012)'s research, we only used 5 scenarios as the collection of climate scenarios. To make this analysis trackable is not the only reason for that. Weather and climate predicting is intrinsically uncertain due to the chaotic nature of climate and natural variability at all timescales (Slingo and Palmer, 2011). Contemporary knowledge level cannot predict the weather a few days later with absolute certainty, let along to foresee when exactly an extreme event of a certain level will occur within a long time span. "The only thing certain about predicting the future climate is that nothing can be predicted with certainty" (Manocha, 2018). For the above reasons, we argue that these five transient climate scenarios already has an acceptable level of coverage of possible future climates' bandwidth to support first-level analysis at the preliminary planning stage. However, it is recommended in the future research to explore numerous transient climate scenarios synthesized by weather generator like the Waas case (Haasnoot et al., 2012) for a more comprehensive study purpose.

3.3.2 Socio-economic scenarios

The anthropogenic factor is considered in the undertaken study as the other significant driving factor to the timing of the adaptation tipping point. Different from the land-use scenarios used in Kent Ridge Catchment case by Manocha and Babovic (2017), we here considered socio-economic scenarios as scenarios with different growth rates of the economic value of the study area. We reason that, for a strongly built-up neighborhood-scale area like Laakhaven where the hard paved surface (including rooftops and paved land surface) percentage has already reached to a certain high level (85% in total), the land cover fraction is hard to be changed too much for the sustainability concern, but the economic value of the properties in this area can be continuously growing as a result of the constant densification of the area's economic functionality and the net growth in the productivity of this area. Note that inflation and deflation are not taken into account. Below provides some detailed explanations for this consideration.

Land use and land cover are often used interchangeably, but they are two separate terms and it is inaccurate to conflate them arbitrarily (Rawat and Kumar, 2015). Land cover represents the observed biophysical manifestation of earth's surface, included with *e.g* vegetation, pavement, open water, and other biophysical features of the land, which are attributed to (the combination of and interactions between) natural and anthropogenic factors; Whereas land use refers in particular to humans' usage pattern of the land, especially on the economical functionality aspect (Rozenstein and Karnieli, 2011). When it comes to the urban context, land cover is a concrete concept because it is directly observable, while land use is an abstraction since sometimes its classification is hard to tell even being closely observed (Zhan, 2003). For instance, a satellite image can show you here is a building (land cover), but it does not tell you what is inside the building (land use), whether there are residential apartments, shops and markets or banks and companies. Therefore we made a distinct differentiation between these two concepts. The consequences of urban flooding contain not merely the direct damages to the assets and infrastructures, but also the economic losses as a result of business disruption, welfare effects, and supply chain shocks, the latter of which can often equal or exceed direct damages on occasions (Hallegatte, 2008; Jongman, 2018). Therefore, with the continuous densification of the economic functionality of this area, for instance, a residential building being gradually converted to an office building, the potential damage caused by the same flood event is expected to increase. Besides city compacting, the economic value of this region is also growing with the gross domestic product (GDP) as the result of productivity growth.

It is commonly acknowledged that indefinite development of an urban environment is impossible and there is always a limit for urbanization beyond which the negative impacts like instability, environment degradation, social-economic and ecological deterioration, and irreversible damage could merge (Oh et al., 2005; Wei et al., 2015). Currently, more than 85% area of the Laakhaven—Oost has been paved, which is a relatively high built-up percentage. Besides, the population density in this area is 28 times the average population density of the nation. Since over-development and over-density might result in a reduction in overall living quality, in consideration of the actual physical and demographic conditions of Laakhaven-Oost as well as the sustainability and resilience requirement, it is thus assumed by the undertaken study that the land cover fractions (the percentages of buildings, closed paved, open paved, unpaved and surface water) remain unchanged within the simulation time frame, but the economic value of this urban area is getting more and more expensive over time due to the productivity growth and the continuous urban densification with an increasing accent on its economic functionality. Assuming a constant growth rate of economic value m (%), then after N years, the economic value of the study area is therefore increased by $(1+m)^N$.

Consequences of climate change largely depend on the societal and economic developments in the following decades (Van de Ven et al., 2010). According to the WLO-study ('Prosperity, Wellbeing and quality of the living environment', Welvaart en Leefomgeving) conducted by three Dutch planning agencies CPB (2006), four socio-economic scenarios had been outlined particularly for The Netherlands, namely Global Economy (GE), Strong Europe (SE), Transatlantic Market (TM) and Regional communities (RC), as shown in Figure 3.14 below.

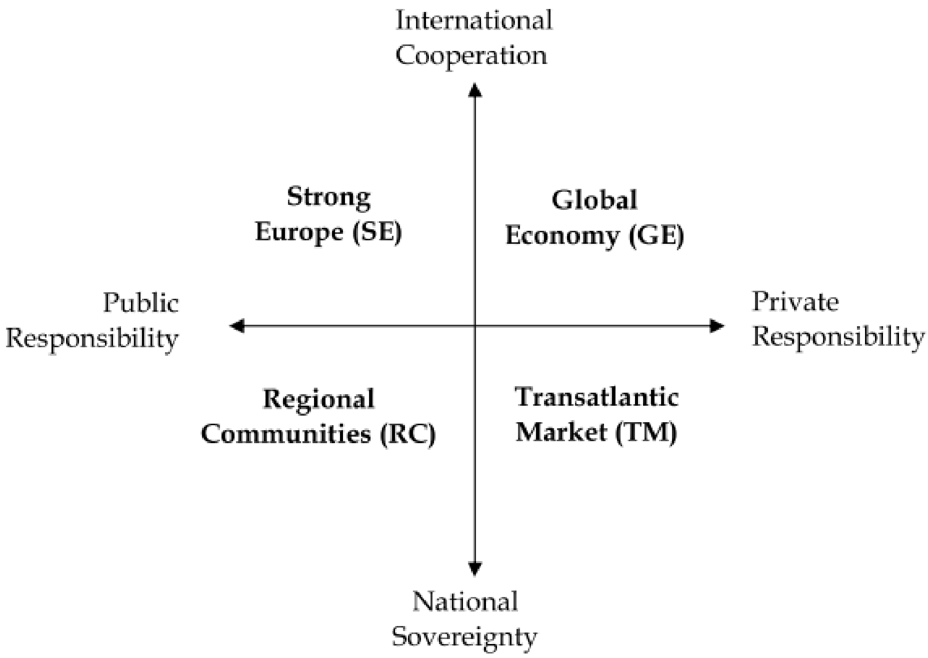


Figure 3.14: Socio-economic growth scenarios for the Netherlands, reprinted from Riedijk et al. (2007)

Table 3.4 below shows some selected macro-economic indicators of these scenarios. As shown in the table, economic growth is expressed in the yearly growth in Gross Domestic Product (GDP)[5] and it varies considerably with different scenarios. Therefore, to represent different levels of social-economic development, considering the net GDP growth rate

[5]The real economic growth, or real GDP growth rate, measures economic growth as it relates to the gross domestic product (GDP) from one period to another, adjusted for inflation, and expressed in real terms as opposed to nominal terms (Wikipedia contributors, 2019a).

Table 3.4: Selected macro-economic indicators for the WLO scenarios, adapted from Riedijk et al. (2007)

Mutations per year in %	1971-2001	GE 2002-2040	SE 2002-2040	TM 2002-2040	RC 2002-2040
Population growth	0.7	0.5	0.4	0.2	0
Labour supply growth	1.1	0.4	0.1	0.0	-0.4
Labour productivity growth	1.9	2.1	1.5	1.9	1.2
GDP growth	2.6	2.6	1.6	1.9	0.7
GDP per capita growth	1.9	2.1	1.2	1.7	0.7

together with the densification of the economic functionality of Laakhaven, three annual growth rates are simply assumed in the undertaken study, as a low growth rate of 1%, a medium growth rate of 2%, and a high growth rate of 3%.

With the continuous growth in the economic value of the study area, the potential consequence of the same flood event is also increased if no damage mitigation intervention is applied. Here, for simplicity, we assume that the increase in the potential damage is directly associated with the growth rate of the area's economic value. Potential damage (consequence) is expressed in economic losses in the monetary term (euros). Therefore, given the initial potential consequence of a flood event with the considered magnitude being D_0 (€) and growth rate being m (%), after N years, the potential consequence becomes $D_0 \cdot (1+m)^N$ (€).

Table 3.5: Three different growth rate of the potential consequence of a certain flood event for three socio-economic scenarios

Low growth	1%
Medium growth	2%
High growth	3%

Since the climate scenarios are important factors in the derivation of socio-economic scenarios, they are actually not independent from each other. However, for simplicity, we ignore their internal links and assume they can be combined in random pairs. It is recommended in the future studies to consider these probabilities. In this section, both climate and socio-economic scenarios have been determined to reflect the uncertainties in the climatic and socio-economic aspects for the later use in subsequent studies.

3.4 Setup of the assessment model

To assess the impacts and effectiveness of various adaptation measures, an urban water balance model called Urbanwb model is applied as the main body of the assessment model. A lot of emphases is put on this section because this part is the hydrological part of the main content of the thesis. It is thus necessary to carefully illustrate the innovative architecture of the model with which the measure is simulated and assessed and how the empirical relationship obtained through analyzing the model' outcome is used as the performance indicator of adaptation measures.

3.4.1 Overview of Urbanwb model

Urbanwb model is a dynamic urban water balance model initially developed by Toine Vergroesen [6] in Excel spreadsheet in 2013 for rapidly modeling dominant dynamics in an urban water system at the neighborhood level. The model also supports producing Storage-Discharge-Frequency (SDF) Curve and testing the effectiveness of various adaptation measures. It is a lumped hydrological model. The model has been checked for the internal consistency and the output plausibility by expert judgment and has been successfully applied in multiple projects around the world. In 2018, the model was converted from scratch and further developed into a Python-based model by Martijn Visser [7] and Wenxing Zhang [8] to cope with its increasing complexity due to continuous evolution.

Urbanwb model, as a conceptual lumped multi-reservoir model for urban water balance modeling, dynamically simulates dominant hydrological processes in an urban water system. Rainfall-runoff processes, shallow groundwater (unsaturated and saturated zone), surface water, and sewer system are all incorporated in this model. Three external water exchanges are included with atmosphere, deep groundwater, outside water, and the wastewater treatment plant (WWTP). Figure 3.15 below provides a schematic overview of Urbanwb model with its fundamental elements. Under this conceptual framework, major hydrological dynamics in an urban water system over a long time span can be quickly modeled to give modelers a general indicative idea of the system's behaviors under predefined settings and given circumstances. Some fundamental points about Urbanwb model are briefly explained below for readers' preliminary understanding of the underlying concepts of the model:

- Forcing

  The forcing to the Urbanwb model is hourly (or daily) time series of precipitation, potential open water evaporation or reference crop evapotranspiration.

- Elements

  Urbanwb model has 9 internal elements, namely paved roof (PR, *e.g.* buildings), closed paved (CP, *e.g.* roads and asphalt street), open paved (OP, *e.g.* porous asphalt and interlocking pavement), unpaved (UP, *e.g.* gardens and grassland), vadose zone (UZ), groundwater (GW), open water (OW), combined sewer system (MSS), storm

[6] Senior researcher, Deltares
[7] Researcher, Deltares
[8] MSc student, TU Delft

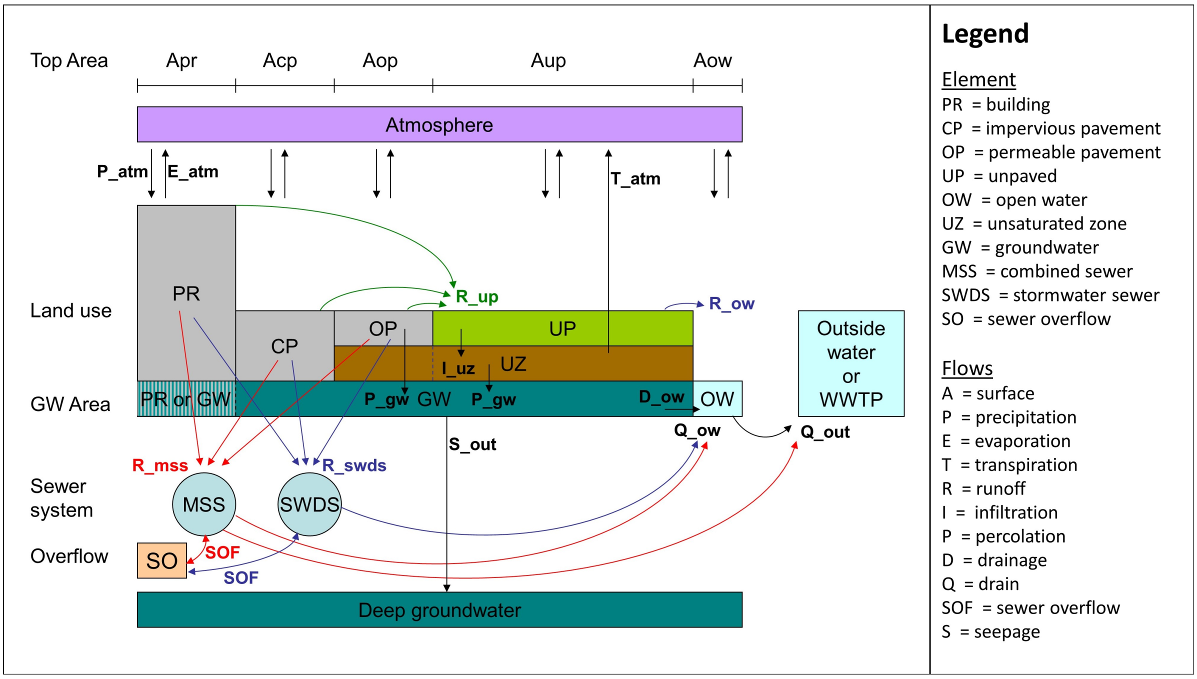


Figure 3.15: Schematic overview of Urbanwb model, modified from Excel-based model by Toine Vergroesen

water drainage system (SWDS). Urbanwb model is a lumped model but has the potential to be further integrated as a node into a (semi-)distributed model. Routing between internal elements is irrelevant in the model. It does not take time for the water to "travel" between interconnected reservoirs. For instance, during the same time step, the runoff from paved roof goes into the combined sewer system and from there it is pumped to the wastewater treatment plant (WWTP); disconnected fraction of the runoff from paved roof by assumption flows to the unpaved area where infiltration to unsaturated zone is allowed; Overland flow on the unpaved area is assumed to flow to the surface water where the excess water above the target water level is pumped outside. It is reasonable for a small-to-intermediate neighborhood-scale urbanized area where the hydrological response of the drainage system and water routing is relatively fast. Water balance is strictly closed for both the individual element and the whole model at every time step and throughout the entire simulation. Urbanwb model is capable of modeling a neighborhood-level urban water system. However, use at a larger spatial scale is questionable and the outcomes may be misleading.

- Output

  Time series of states and fluxes of all components of the model.

A brief documentation about this model is provided in Appendix C. For the access to the detailed documentation on the Urbanwb model and a stable version of this package, please consult Deltares [9]. The validation of the model is not within the undertaken study due to

[9] https://publicwiki.deltares.nl/display/AST

the lack of observations in Laakhaven to compare with modeled results. By the way, a predecessor of this urban water balance model — HDSM model was validated and calibrated by Kuijk (2015) with detailed information and observations in a case study of Lelystad. The Urbanwb model can be applied as a useful modeling tool that provides first-level accurate dynamic simulations of hydrological processes in neighborhood-level catchments.

3.4.2 Measure module

Apart from the basic elements mentioned above, another significant individual module can be incorporated into the Urbanwb model to establish interactions with other model components thus enabling modelers to assess the effectiveness of various adaptation measures under a generalized framework in an innovative manner. An interesting empirical relationship on how the measure alters the return time of event-based runoff depth is found through analyzing the model's outcomes of long-term time series. We call this factor "*runoff frequency reduction factor*". After proving the validity of this factor with numerous simulations, this factor is later used as the performance indicator of measures to support the subsequent research. In this section, the fundamental architecture of the Measure module and the runoff frequency reduction factor are explained.

3.4.2.1 Adaptive generalized framework of measures

To effectively adapt to the rising pluvial flooding risk, a combination of structural and non-structural intervention strategies is required. The Urbanwb model is capable of modeling a multitude of structural adaptation measures, including gray, blue, and green measures. In fact, apart from the Measure module, the Urbanwb model presents flooding indicators for the entire modeled domain through two aspects — occurrence of sewer overflow onto the street and the required storage height above the surface water. But the Measure module is especially useful to evaluate the impacts of adaptation measures on runoff reduction over the runoff inflow area to the measure.

As stated in section 3.2, structural adaptation measures mitigate pluvial flooding by intervening stormwater runoff thus altering the probability of flooding. Measures could create extra buffering storage, encourage evapotranspiration, facilitate infiltration, regulate drainage regime, or realize a combination of these functionalities. Therefore, in spite of various terms of these pluvial flooding adaptation measures, they all can be conceptualized, categorized, and modeled under a generalized architecture but with different specific settings. It is the underlying idea of the Measure module to propose such a generalized but adaptive framework that supports representing measures' physical dimensions and mimicking their predominant functionalities. In this way, the mechanisms behind these measures are simulated and can then be incorporated into the main body of the model to dynamically interacts with other model components of the urban water system. The measure can be defined freely according to the user's perceptions on the measure as 1-layer, 2-layer, or 3-layer structure. The generalized framework is illustrated in Figure 3.16 below:

- 1-layer structure contains only an interception layer, representing the type of measures that simply creates extra storage (and allows evaporation). A typical example would be a blue roof for evaporative cooling only without drainage delay.

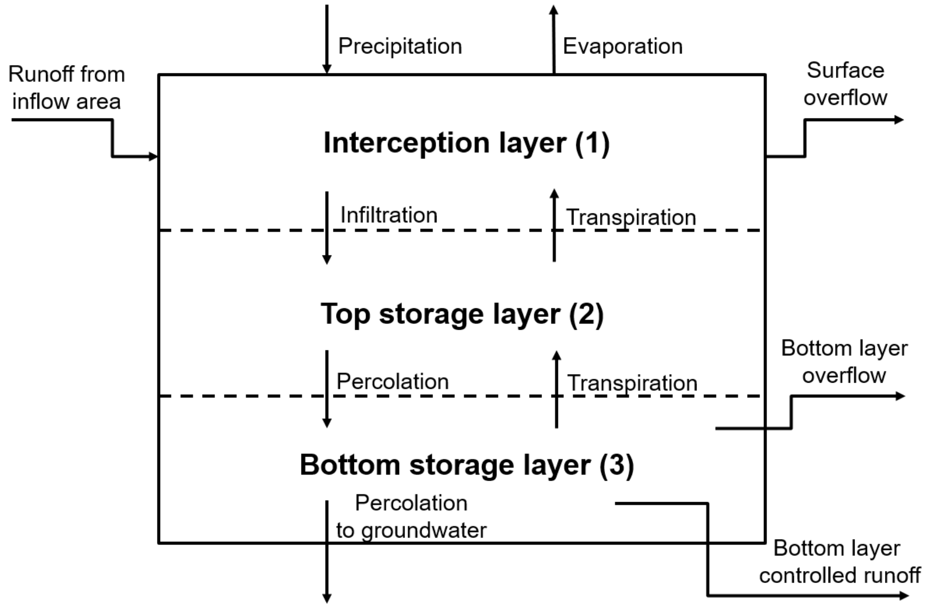


Figure 3.16: A generalized adaptive framework that supports modeling various types of adaptation measures

- 2-layer structure consists of an interception layer and a bottom storage layer. Most of the shortlisted measures with intermediate complexity in Table A.1 can be modeled as 2-layer structure. The bottom storage layer is the most complex part of the Measure framework where the evapotranspiration, the percolation to groundwater, and the controlled runoff can be defined by the users. As mentioned previously, adaptation measures reduce the runoff input (intensity and volume) to the surface water by directing the runoff to the slower and more natural pathway (*e.g.* infiltration) or temporarily detaining the runoff to relieve loading to the drainage system (*e.g.* water square). This part of stormwater runoff is said to be controlled by the measure — controlled runoff. Controlled runoff means that runoff coming from inflow area to a normally functioning measure is under the measure's control routines, *e.g.*, detention, retention, evapotranspiration, infiltration and regulated discharge. Hence, in terms of the inflow area to the measure, controlled runoff is no longer a problem whereas the uncontrolled runoff in the forms of overflows is the problem remaining unsolved by the measure. In the Measure module, controlled runoff is defined either as a constant flux to represent periodic emptying or as a dynamic flux that depends on the drainage level and resistance to simulate delayed drainage. Though the Urbanwb model trades accuracy with efficiency for the purpose of rapidly modeling long-term time series, it is good enough to produce useful results if applied properly. Hence, a good setup of measures and the basic model involves the empirical knowledge and expert judgment. Examples of 2-layer-structure measures are rain barrel, wet pond, infiltration box, *etc.*.

- 3-layer structure is composed of interception layer, top storage layer, and bottom storage layer. 3-layer structure is specially designed to model measures like bioswale and green roof which have an intermediate growing medium layer that encourages evapotranspiration and a drainage layer beneath the soil layer. Calculation formulas for measures akin to green roofs are specifically modified because a normally functioning green roof is designed to be free from surface submergence which may lead to plants suffocation. For example, an extensive green roof drains all the water surplus into a sewer regardless of its capacity. Examples of 3-layer structure are bioswale, green roof (extensive), and green roof (with drainage delay).

3.4.2.2 Examples of measures

Two examples are provided to illustrate how a measure is conceptualized and translated into this framework. Conceptualizations and setups of 24 measures are in Appendix A.

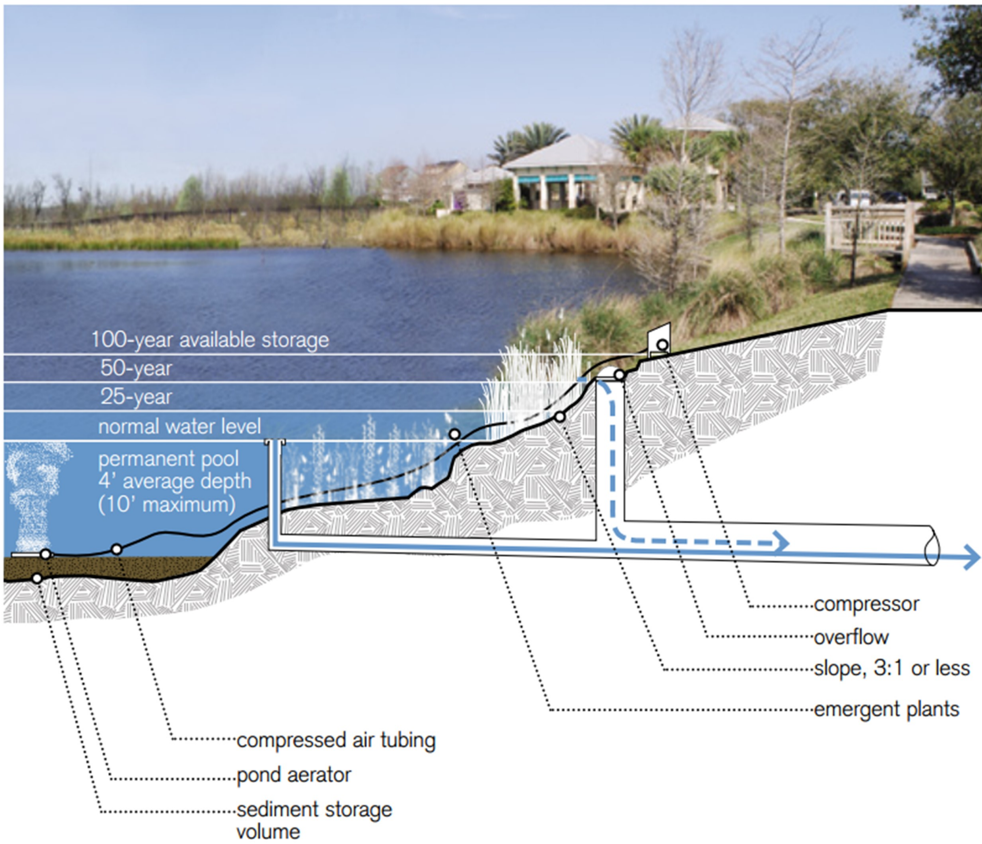
- **Wet pond**

Figure 3.17 below shows the conceptualization of a wet pond. A wet pond is a water retention basin for stormwater buffering with some minor treatment function. It can be thought of as a 2-layer-structure measure as shown in Figure 3.17b. The interception layer (marked with dashed line) is a pseudo layer that has no storage capacity and infinite infiltration capacity, so all the water including rainfall and runoff influx from inflow area directly goes into the bottom storage layer. Evaporation from the wet pond is limited by Penman evaporation. The bottom of a wet pond is sealed to ensure a permanent pool and no direct infiltration of polluted water. Therefore, direct percolation to groundwater is defined impossible. A reference water level is set as the drainage level above which the excessive water gradually drains to the surface water. This controlled runoff is regulated by a small pipe with an adjusting valve, therefore the discharge rate is determined by the head difference between the water level and drainage level and drainage resistance. Drainage level and drainage resistance are user-defined. Besides, initial storage of the wet pond can be set at the drainage level as the antecedent condition.

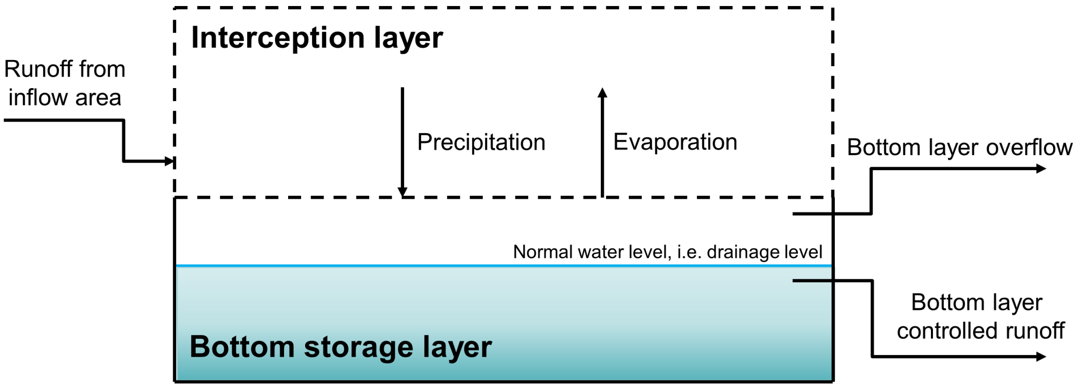
As shown in Figure 3.17a, above the normal water level, there are $T = 25yr$, $T = 50yr$, and $T = 100yr$ water levels. An overflow level is set as the $T = 50yr$ water level. This is represented by the storage capacity of the bottom layer. Given an extreme storm event, the inflow runoff to the measure can exceed the storage capacity of a wet pond thus resulting in overflows to the sewer system. The overflow runoff is considered as uncontrolled runoff because it is beyond the handling capacity of the measure and must be directed to the sewer system. So uncontrolled runoff still remains a loading to the drainage system.

Similar to a wet pond, a rain barrel can also be modeled as 2-layer-structure with a different setup. It may sound confusing, but with this generalized framework, a rain barrel should be modeled in a similar way. The main difference lies in how the controlled runoff is defined. As we know, people harvest rainwater using a rain barrel for watering gardens, washing cars, flushing toilets, or whatever they want in between or during rainfall events. However, since the real-world usage of a rain barrel is impossible to be totally simulated, simplifications and assumptions need to be made. Even though it is possible to add a Real-Time-Control feature to the measure that only empties the stock when it is dry, for the sake of KISS principle [10], we model the controlled runoff of a rain barrel as a regulated discharge limited by the pumping capacity that can empty the entire system stock within 2 days.

[10] Keep It Simple & Stupid. "The KISS principle states that most systems work best if they are kept simple rather than made complicated; therefore, simplicity should be a key goal in design, and unnecessary complexity should be avoided" (Wikipedia contributors, 2019b).



(a) Picture and sectional drawing of a wet pond, reprinted from Huber et al. (2010)



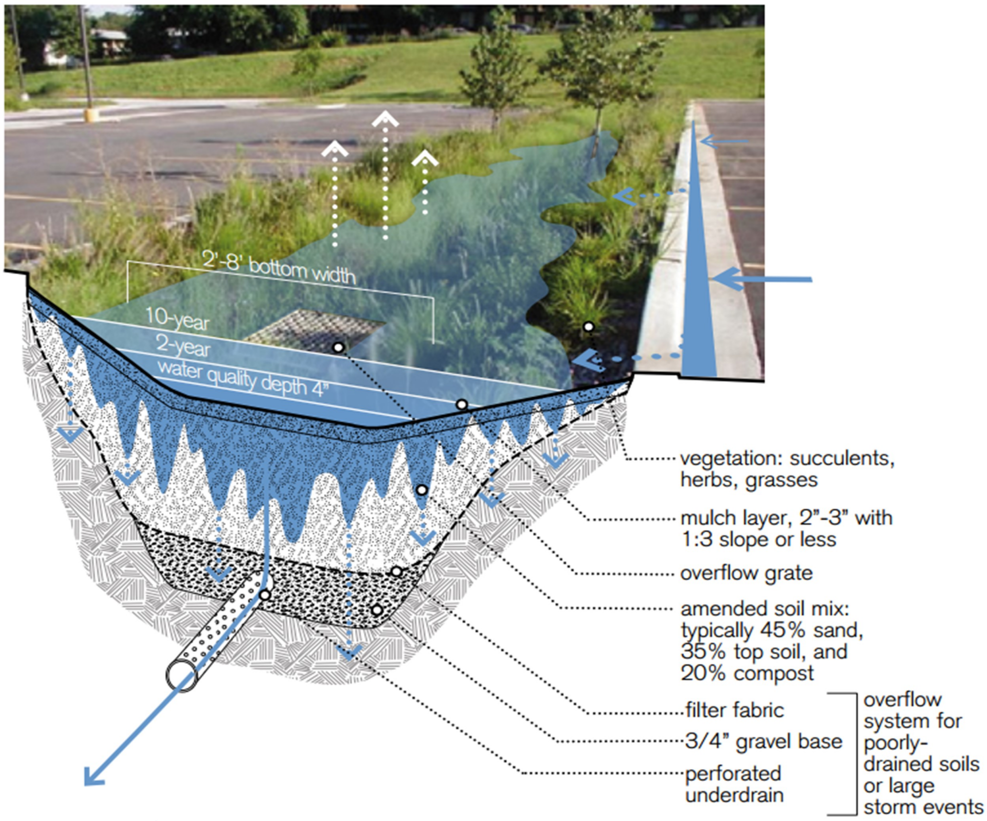
(b) Schematic drawing of a wet pond which is modeled as a 2-layer-structure measure

Figure 3.17: Example of a wet pond, modeled as a 2-layer-structure measure

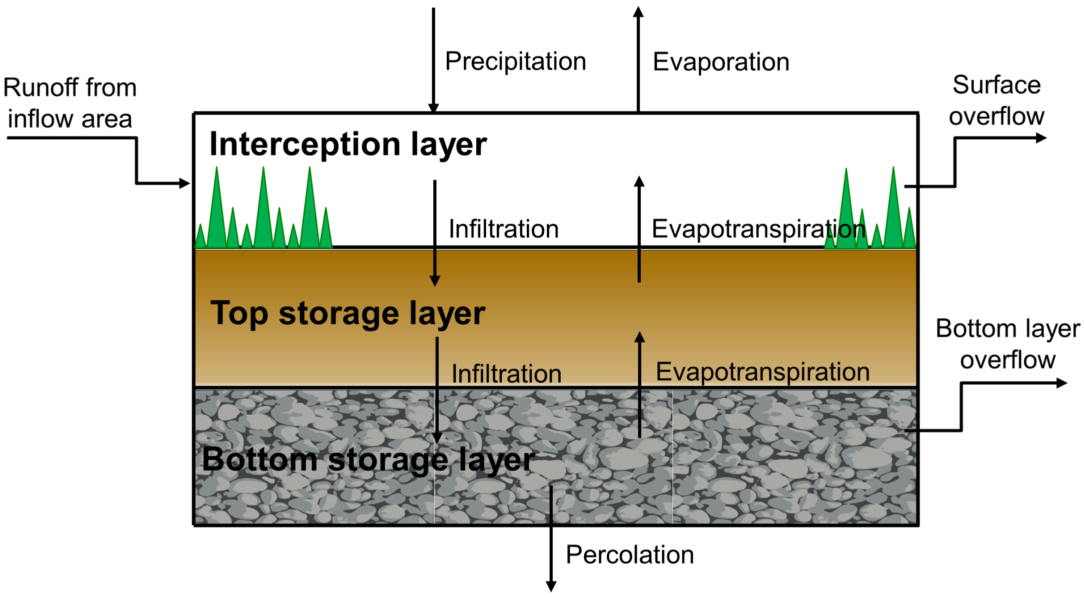
- **Bioswale**

Figure 3.18 below shows how a bioswale is conceptualized and simulated with the Measure module. A bioswale (Wadi) refers to a vegetated ditch on a porous bottom, which is used as an infiltration installation. Runoff from roofs and roads can be directed to the bioswale via above-ground gutters for further infiltration instead of entering the sewer system. Therefore, the stormwater runoff is directed to the slow drainage pathway thus alleviating the loading to the sewer system. Bioswale can be considered as a 3-layer-structure measure. Its vegetated surface is the interception layer which has minor interception storage capacity and facilitates infiltration to the subsurface layer. The subsurface layer is modeled as the top storage layer. It is made up of amended soil aggregate which serves as growing medium for the vegetation. Evaporation from soil and transpiration from plants are encouraged in this layer. After evapotranspiration, water exceeding the top layer storage capacity infiltrates downward to the bottom storage layer. Bottom storage layer is a gravel base that encourages further percolation to the groundwater. Evaporation from the bottom storage layer is possible when potential evapotranspiration rate exceeds the evapotranspiration from top storage layer because roots can uptake water from bottom drainage layer for further transpiration. In the gravel layer, a perforated plastic tube serves as an overflow underdrain that drains the water surplus to the sewer system. An overflow gate installed on the surface layer is also linked to this drainpipe to incorporate larger storm events. Given heavy storm events, overflows from the bottom storage layer and the interception layer will be drained through the overflow system into the sewer systems. If the percolation drainage to groundwater and the overflow system both are filled up, a bioswale is then turned into an above-ground conveyance system directly connected to the surface water, however, this is designed to occur only once every 25 years and is not taken into account in our model. In Urbanwb model, bioswale is considered as a measure for infiltration, in which the percolation to groundwater is the controlled runoff whereas the overflows through perforated drain pipes to the sewer system is the uncontrolled runoff.

3-layer-structure especially suits the type of measures that has a soil layer and a drainage layer beneath the soil layer. Another example would be an extensive green roof. Differences between a bioswale and an extensive green roof in terms of the model setup lie in the following two points: ***a.*** An extensive green roof is installed on the building rooftop, thus the controlled runoff is drained to the sewer system instead of the groundwater. ***b.*** A normally functioning green roof should have no water clogging, meaning water exceeding the storage capacity of the soil layer and drainage layer is directly drained to the sewer system regardless of its capacity. Therefore, the calculation formulas for measures akin to the green roof is specifically modified. Most of the out-listed measures in Table 3.2 are described and conceptualized into either 1-layer, 2-layer or 3-layer structure to be simulated with Urbanwb model. The contents are all presented in Appendix A. This appendix is highly informative and is recommended to the readers as a guideline to set up their own measures of concern. Their parameter setups come from the available information and expert judgment. Since in the undertaken study the measures are modeled in a generalized framework using some standardized parameter setups, it is sometimes the case that two different measures would have similar efficacy. Another thing to note is that one has to realize this lumped conceptual model is built for the quick assessment thus emphasizing on simplicity. For more sophisticated modeling purposes, other more advanced models are recommended under the constraints of *e.g.* the data availability and the computing power.



(a) Picture and sectional drawing of a bioswale, reprinted from Huber et al. (2010)



(b) Schematic drawing of a bioswale which is modeled as a 3-layer-structure measure

Figure 3.18: Example of a bioswale, modeled as a 3-layer-structure measure

3.4.3 Performance indicator of measures

3.4.3.1 Concept of effective depth

There are numerous kinds of adaptation measures and endless possibilities of options if the design, structure, dimensioning, and specifications are all taken into account. It is thus meaningless to ask how efficient is a rain barrel, or in terms of stormwater runoff buffering whether a wet pond is more efficient than a water square if no specific and detailed information is given. For a certain measure, larger its physical design dimension, larger the handling capacity it has. Besides the measure size, another important aspect is the runoff inflow area to this measure. A small rain barrel is useful to harvest stormwater runoff from a small roof, but the same device could have little effect if connected to a large-scale roof. In a realistic hydraulic modeling work, one has to specify the measure to model with certain suggested parameters. In our modeling, in order to assess measures with a range of specifications, the concept of (static) effective depth is introduced as follows:

$$\text{effective depth} = \frac{\text{measure depth} \times \text{measure area}}{\text{inflow area}}$$

,where measure depth = measure design depth × void ratio.

Figure 3.19: Aerial view of building roofs and rainwater harvesting devices. An example to illustrate the concept of (static) effective depth. The blue square is a roof; Small red squares are rain barrels; a medium orange square is a rainwater tank.

Figure 3.19 above shows the aerial view of paved roofs and rainwater harvesting devices. Blue squares are roofs, while small red squares and an orange square are rain barrels and a rainwater tank respectively. The roof is an $8m \times 8m$ square; a rain barrel has the dimension of $L \times W \times H = 1m \times 1m \times 1m$; a rainwater harvesting tank has the dimension of $L \times W \times H = 2m \times 2m \times 2m$. 100% of the roof is assumed connected to the rainwater harvesting device and overflows from the measure end in the sewer system. Measures are completely empty as initial conditions. Measure depth of a rain barrel is calculated as the product of the measure physical design depth ($1m$) and the void ratio (1.0), and thus is 1 meter. Therefore, the (static) effective depth of a rain barrel is calculated as $\frac{1\times1}{64} \times 1000 = 15.625mm$, which indicates rainfall falling on the roof above this threshold overflows to the sewer system. However, if we combine two identical rain barrels together as shown in the figure middle, then the effective depth of this holistic installation is doubled — $31.25mm$. A rainwater tank has the same mechanisms as a rain barrel but has a much larger storage capacity, and its effective depth is calculated as $\frac{2\times4}{64} \times 1000 = 125mm$. Hence, it can freely handle storm events with a rainfall depth below this threshold as long as it is completely emptied before the event coming. Here, effective depth only means the static effective depth. During consecutive events, the active or dynamic effective depth should be less than or equal to the (static) effective depth depending on the available room in the measure. If a rain barrel is well maintained and regularly emptied between storm events, more storage volume for the stormwater runoff is available. From this, one could somehow feel the importance of emptying mechanisms of a measure. In summary, by introducing the effective depth concept, measures of the same kind but with different dimensioning and specifications can be summarized into a unified framework.

3.4.3.2 Runoff frequency reduction factor

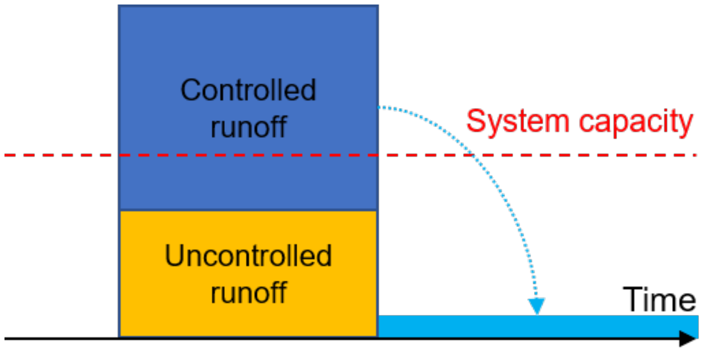


Figure 3.20: Concept of controlled runoff and uncontrolled runoff

Figure 3.20 above further illustrates the concept of the controlled runoff and the uncontrolled runoff. Stormwater runoff from grounds and roofs inflows to the measure and is handled by the measure up to its design capacity. From the measure, the water may infiltrate into the ground, get slowly released at the delayed pace, evaporate into the atmosphere, or whatever. Hence, instead of taking the fast pathway, this part of runoff either takes the slow pathway route (infiltration) or is temporarily detained before entering the sewer system. Therefore, the runoff loading to the drainage system is relieved and the flood risk is reduced. We call this fraction of runoff as the controlled runoff. However, due to the limited capacity of measures, part of the runoff cannot be handled by the measure as the controlled runoff. This runoff fraction is the so-called uncontrolled runoff. It is usually the overflow from the measure, which is assumed to still add loads to the sewer system. The calculation of runoff frequency reduction factor is based on the uncontrolled runoff.

As shown in Figure 3.21 below, previous studies on the effectiveness of measures, whatever it is a model-based study (marked in red) or an experiment-based study (marked in blue), commonly used performance indicators like *e.g.* peak discharge reduction, runoff volume reduction. Their analysis was usually based on the results of field measurements or computer simulation outcomes of selected standard design storms with a certain return period. Figure 3.22 shows such an example, in which Kong et al. (2017) used EPA's Storm Water Management Model (SWMM) to study the impacts of LID on the reduction of peak runoff rate and total runoff volume in a city-level catchment under a selected rainfall event. As commonly known, the results of a single-event simulation are strongly dependent on the antecedent conditions of the system. If both the drainage system and the measure are completely saturated, the measure may be not effective at all. Besides, more importantly, these results do not answer how the probability of flooding is changed by these LID measures, which can only be learned through long-term time series modeling.

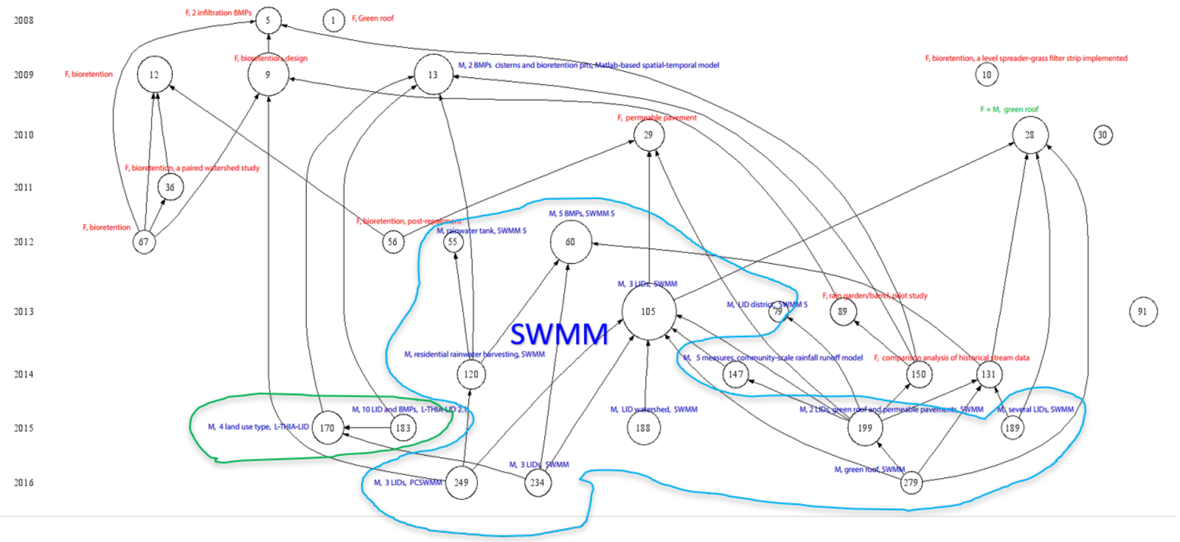


Figure 3.21: Top 30 most locally cited literature of previous studies on the effectiveness of adaptation measures, generated with retrievals from the Web of Science using Histcite. This figure also shows a trend from the field study to the modeling study and a preference for the SWMM model.

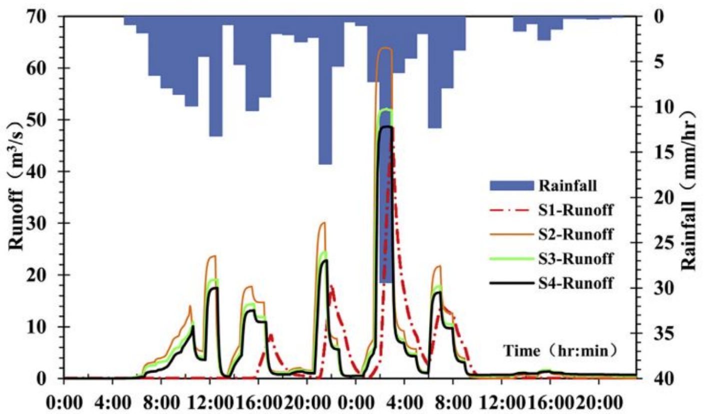


Figure 3.22: Hyetograph for a rainfall event and hydrograph for runoff under four scenarios modeled with SWMM, reprinted from Kong et al. (2017)

The long-term performance of these measures on the alteration of flood probability is lacking among all these studies. The Urbanwb model, because of its rather simplified architecture, can rapidly simulate the hydrological processes of a neighborhood-scale urban water system with a decades-long time series. Therefore, we could use it to study the measures long-term effectiveness that is not subject to the antecedent conditions. After performing extreme analysis of the outcomes of the model, an interesting empirical relationship is found regarding the flooding frequency reduction by the measures. Therefore, after being confirmed with numerous simulations of different cases, it can be used as a novel performance indicator of the effectiveness of measures. We call it runoff frequency reduction factor. Below are the steps to get these runoff frequency reduction factor:

1. 30-year hourly time series of the observed rainfall and the modeled runoff are used in the analysis. In a word, we use the simple empirical method —- plotting position method with Weibull formula to perform the frequency analysis on the data instead

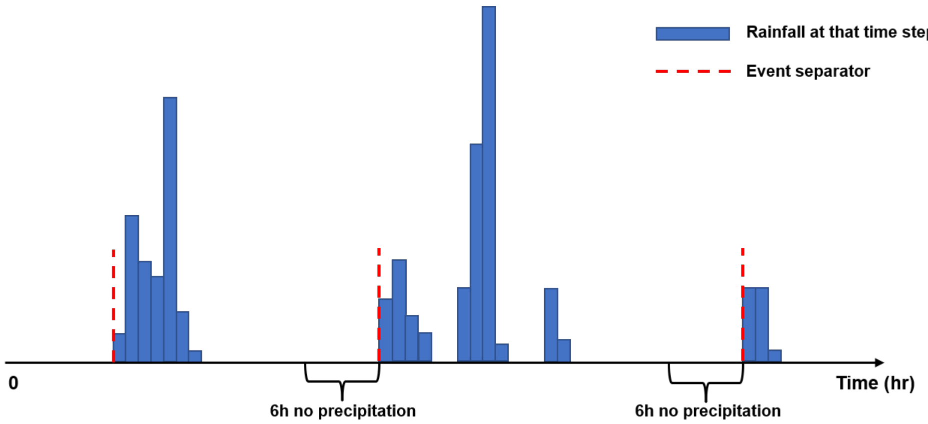


Figure 3.23: Event separation by 6 consecutive hours with no precipitation

of using analytic frequency factor method.

2. Separate rainfall events by six consecutive hours with no precipitation (see in Figure 3.23 above). The separators are fixed for the separation of runoff events.

3. Calculate event-based rainfall depth, event-based baseline runoff depth (current situation without measure), and event-based uncontrolled runoff depth (situation with applied measure).

4. Assign rank to the data after arranging them in descending order of magnitude. Calculate the probability of exceedance with Weibull formula $P = \frac{m}{N+1}$ (where m is rank assigned, N is number of records) and the corresponding return period T ($T = \frac{1}{P}$).

5. Plot runoff value against the corresponding return period for all the above results on a semi-logarithmic graph paper, where curves approximate straight lines which facilitate extrapolation (see an example in Figure 3.24). The empirical method gives relatively good results for small extrapolations, however larger extrapolation is questionable.

6. As shown in Figure 3.24 below, for a certain runoff depth, implementing a measure reduces its recurrence frequency and increases the return period by a factor, which is approximately constant within the lower to the intermediate range of the return value. In the example, installing a rain barrel with $10mm$ effective depth will increase the recurrence interval of a certain event-based runoff depth by a factor of around 4.6. This empirical relationship is found for most of the measures modeled under various climate scenarios, of which the results are documented in Appendix D.

7. Curves mostly approximate parallel within lower to medium range of the return value indicating a roughly constant frequency reduction factor, but they sometimes diverge for certain measures with a large effective depth or within the high range of the return value. Therefore, to have a unified computation of this factor, we take the average of the reduction factors for the runoff values (1,2,3,4,5,6,7,8,9,10,15,20,30,40,50mm). Please note that the runoff frequency reduction factor is not obtained from scientific derivation, but a physical, proven relationship observed from the empirical graphic

method. Its validity has been confirmed with numerous simulations and thus it can be used as a performance indicator of measures for first-level assessments.

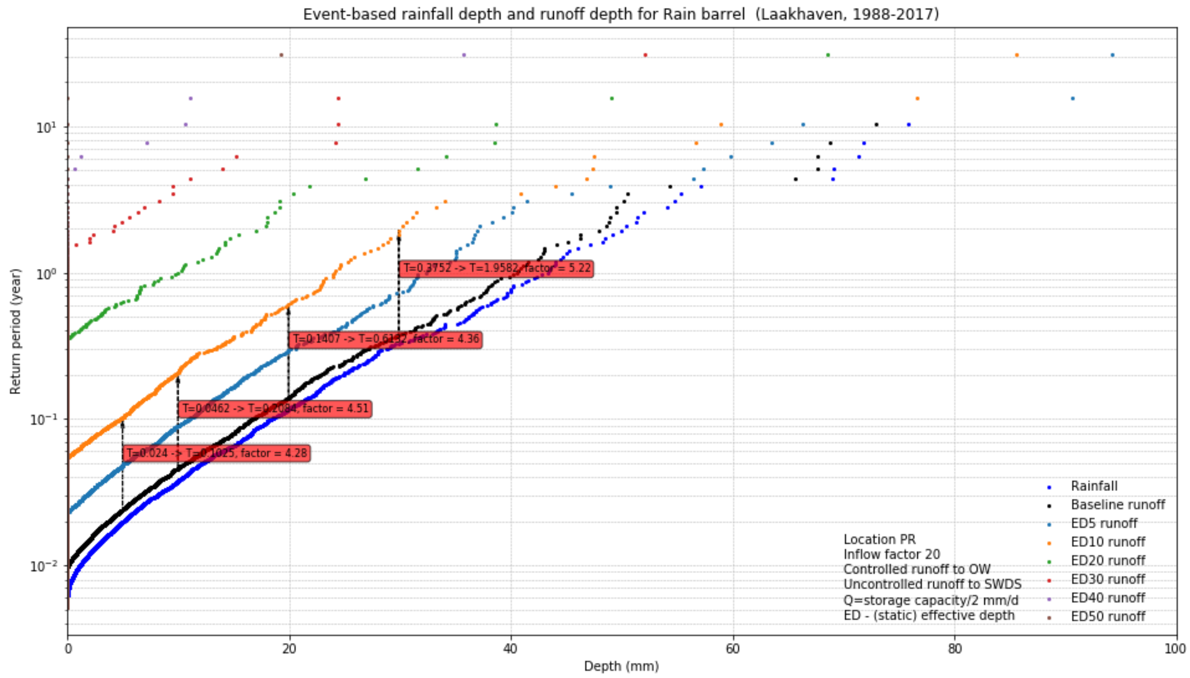


Figure 3.24: An example: Runoff frequency reduction factor for Rain barrel with 10 mm effective depth

3.4.3.3 Conversion of the empirical factor from runoff inflow area to total area

The runoff frequency reduction factor calculated above is actually based on the runoff inflow area to the measure. Therefore, a conversion is needed to convert this factor from the factor over only the measure inflow area to the entire study area. A new formula was proposed to make this conversion as shown below:

$$F_{tot} = \frac{A_p \cdot e^{\left(\frac{A_{mi} \cdot ln(F_{meas})}{A_p}\right)} + \frac{Perc_{RA}}{100} \cdot (A_{tot} - A_p)}{A_p + \frac{Perc_{RA}}{100} \cdot (A_{tot} - A_p)}$$

,where F_{tot} is the factor for total area, F_{meas} is the factor for measure inflow area, A_{tot} is the factor for total area, A_p is paved area, A_{mi} is measure inflow area, $Perc_{RA}$ is runoff from the rest of the area, estimated as a percentage from the runoff from paved area. The derivation is presented in Appendix D.1. This is another contribution made within the undertaken study. Another question to answer is how the effect of the combinations of measures is determined for the entire study area. This is important when there are one measure for the runoff from the rooftops and another measure for the runoff from the ground. For now, the combined effect of two measures (assuming no overlapping in the runoff inflow area thus being independent on each other) is temporarily computed as the product of the two performance indicators of the two measures over the entire area. It is recommended to investigate the reliability of this combined effect of measures in future studies.

3.5 Calculation of sell-by dates

In section 3.2, we have already classified numerous adaptation measures in different dimensions and selected six out of them for subsequent studies. In section 3.4, how structural adaptation measures are implemented in the hydrological model and how the runoff frequency reduction factor is used as the measures' performance indicators are illustrated in detail. In this section, the package of adaptive actions which involves single or the combination of adaptation measures are further defined and then the sell-by dates of these policy options are calculated for different climatic and socio-economic scenarios developed in section 3.3. Once the sell-by dates of all the adaptation actions are determined, they can be used to assemble the map of adaptation pathways in the following sections.

3.5.1 Risk-based approach

As mentioned in Chapter 2, the Delta Programme aims to ensure the flood risk management for the Netherlands being climate-proof and water resilient for the decades to come through implementing planned proactive actions rather than event-triggered reactive actions. This revolution in thinking on flood protection underpinned the new flood protection standards by weighing the costs of reinforcements against the reduction in flood risk they would achieve (Vergouwe, 2016). For this reason, new standards have been implemented and they are not only linked to the probability of flooding, but also to the corresponding impact. This new approach is called the risk-based approach. It has been applied in the Netherlands National Flood Risk Analysis (VNK) project to determine the statutory flood protection standards of levee systems. Here, we borrowed this risk-based approach idea into our case study to investigate the issue of urban pluvial flooding mitigation.

van Lohuizen (2018) combined multiple definitions of risk by IPCC, ISO, and Dutch policies, and summarized the basic definition of risk as a combination of a hazard and its consequence in several different forms. According to Dutch and international engineering practice, the risk is commonly defined as the product of the probability of a hazardous event occurring and the impact the event will have (Baan et al., 2003; E. Gloudemans and van Kruining, 2018), which is shown as below:

$$\text{Risk}[€/\text{year}] = \text{Probability}[1/\text{year}] \times \text{Consequence}[€]$$

Risk is the product of probability and consequence. Probability is the probability of occurrence of a flood event, which is often statistically described as once in every T year ($P = \frac{1}{T}$, T is return period or recurrence interval). Consequence is the potential damage of the flood event especially in terms of economic losses, which is expressed in the monetary term (€). This definition of risk is used in the present study. We use the (maximum) risk people are willing to take — acceptable risk as the adaptation tipping point (ATP). If the current strategy no longer meets the preset objective under certain conditions, in our case it means the resulting risk is above the acceptable threshold, it is said to reach an adaptation tipping point (ATP) and the moment when an ATP is reached is referred to as the sell-by date of a policy option (Haasnoot et al., 2012, 2013). People sharing the same perspective have the same acceptable risk. In contrast to the bottom-up Kent Ridge Catchment case (Manocha and Babovic, 2017) where the ATPs (maximum annual rainfall) vary with different adaptive actions with varied configuration, in our case study the ATP (acceptable risk) is a threshold set for all policy actions, which is akin to the Waas case (Haasnoot et al., 2012) where the ATP was expressed as the cumulative damage of 2500M euros. The difference in the (definition of) ATP is resulted from how the objective is set and it also makes an obvious distinction between the top-down and bottom-up approaches. Therefore, adaptation tipping point (ATP) is a weakened concept in this study. But the concept of sell-by date for adaptive actions, *i.e.* timing of the ATP, is more important and mentioned more frequently.

3.5.1.1 Factors that influence the risk

Because of the trade-offs between cost and benefits, many decades ago, the normative runoff was defined for many urban areas in the Netherlands that the protection standard of the current system allows water on the street once every two years. Therefore, the $T = 2$year runoff event is called the critical normative runoff event for the current system in the undertaken study. After modeling with Urbanwb model and performing statistic analysis, under the current baseline climate scenario, this normative runoff event has the event-based runoff depth of around $48mm$. This means the probability that a runoff event exceeding this considered magnitude ($48mm$) in a certain year is 50% for the current system under the current climate. However, climate change tends to make the extremes happen more frequently than before, therefore, the probability that an event which equals or exceeds $48mm$ event-based runoff depth in a given year is increased. After modeling the other four KNMI'14 climate scenarios with the Urbanwb model, it has been found out that this critical runoff event would occur more often thus has a shorter recurrence interval. The results are shown in Table 3.6 below.

Table 3.6: Return period of the runoff event with runoff depth ≥ 48 mm under five climate scenarios

Runoff depth	**Climate scenario**				
	Baseline	G_H	G_L	W_H	W_L
$\geq 48mm$	2yr	1.72yr	1.68yr	1.11yr	1.28yr

Apart from the increased probability of hazardous events due to climate change, due to the continuous growth in the economic value of the study area as stated in section 3.3, the impact of the same extreme event would be more damaging thus leads to more potential economic losses. We assume that, under the baseline climate scenario, an urban pluvial flooding event with runoff depth equal to or greater than 48mm will cause D_0 € losses [11] over the entire study area in the beginning year. Therefore, supposing the current climate scenario remains unchanged and no intervention is made: the risk people confront in the first year is $\text{Risk}_0 = \frac{1}{T_0} \times D_0 = \frac{1}{2} \times D_0 = 0.5D_0$(€/year). Since potential damage is continuously increasing with the socio-economic development (m (%) per year), therefore, after N years, the flood risk over the study area is calculated as $\text{Risk} = \frac{1}{T_0} \times D_0 = \frac{1}{2} \times D_0(1+m)^N = 0.5D_0(1+m)^N$(€/year).

However, risks do be altered by both climatic factors and humans' intervention. In terms of climate scenarios, as stated above in Table 3.6, under the four KNMI scenarios,

[11] There is no direct information on the economic losses induced by pluvial flooding in Laakhaven. Therefore, the value D_0 is used for simple illustration only. For a more accurate estimation of the flood-induced physical damage costs for different land use sectors, it is recommended to refer to Jonkman et al. (2008). It is especially important to have the real damage data to calculate the real risk reduction when it comes to the economic evaluation and the cost-benefit analysis. However, it is outside the scope of this study.

the return time of the critical runoff event is reduced. We denote the recurrence interval of the critical event under the baseline (current) climate as T_0 ($T_0 = 2yr$), therefore, the changed climate scenario alters the probability of the same event and results in the return time as $f_c T_0$ ($0 < f_c < 1$, f_c denotes the frequency increase factor by the changing climate). In terms of human interventions, people can change the flood risk from two aspects: altering the probability of flooding with flood mitigation measures and altering the potential damage with damage mitigation measures.

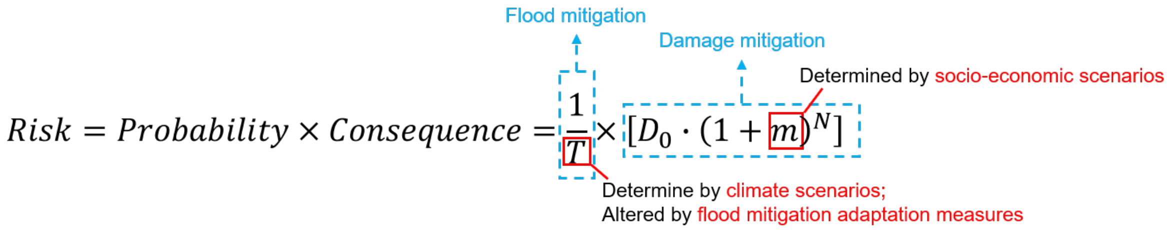


Figure 3.25: Factors determine the risk from two aspects: Probability and Consequence

Figure 3.25 above vividly shows the factors that determine the risk thus telling us from which aspects the risk can be reduced. On one hand, on the left-hand side of the multiplication sign, the probability of a hazardous event is mainly determined by the climate but can be altered by implementing flood mitigation adaptation measures, for example, improving the existing drainage system, building a water retention basin, *etc.* As such, the basic return period of the critical event T_0 is first changed to $f_c T_0$ by different climates and then is altered by the adaptation measures to $f_m f_c T_0$. Both $f_c T_0$ and f_m come from outcomes of the Urbanwb model. $f_c T_0$ is directly derived from modeling corresponding climate scenarios (see in Table 3.6), while f_m comes from the runoff frequency reduction factor of each adaptation measure after conversion to the entire area. The undertaken study mainly focuses on these flood mitigation measures that alter the probability of flooding.

On the other hand, on the right-hand side of the multiplication sign, the consequence of an extreme event is reflected by how much potential socio-economic damage is posed to the area of interest. The area with a higher concentration of population, infrastructure and economic functionalities has higher damage sensitivity to the same extreme event compared to areas with a lower concentration level. Therefore, growth in the economic value of the study area would lead to increasing potential consequence given no damage mitigation intervention is applied. That is how the three socio-economic scenarios developed in section 3.3 come into play. Hence, the increase in potential consequence is depicted by the specified annual growth rate of the socio-economic value of the area m (%). Therefore, if the initial potential damage is D_0 (€), then after N years, the potential damage becomes $D_0(1 + m)^N$ (€). Potential damage can be reduced by implementing damage mitigation strategies, ranging from structural measures such as flood barrier, raised levels, *etc.* to non-structural measures like an early warning system, insurance, *etc.* These measures do not influence the probability of flood but reduce the losses and damage. Both flood mitigation measures and damage mitigation measures are virtually quite significant to the flood risk management. However, the assessment model is only developed to incorporate structural adaptation measures that alter the probability of the flood. So the damage mitigation intervention is not within the research scope of the undertaken study. It is recommended in the future study to include the evaluation of damage mitigation measures if possible.

3.5.1.2 Adaptation tipping point — perspective-based socially acceptable risk

As calculated above, the initial risk faced by the study area is $R_0 = \frac{D_0}{T_0}$ (€/year) ($T_0 = 2$). We take R_0 as the baseline risk. Due to the economic growth and climate change, the risk is increasing over time, therefore, additional adaptation measures are necessary to enhance the system to reduce the risk and keep it within an acceptable range. Then here comes the question — How much risk is considered acceptable? People with different perspectives would have different judgment and answers to this question.

Attitudes towards the risks are determined by many dimensions, *e.g.* people, cultures, time, and experience (Dessai and van der Sluijs, 2007). Therefore, the acceptable risk in the undertaken study is a perspective-based adaptation tipping point (ATP). If the modeled risk exceeds the predefined acceptable threshold, the current adaptation strategies are considered no longer effective therefore switching to or combining with additional interventions becomes necessary. In the Waas case, the perspective method applied was based on the Cultural theory (Haasnoot et al., 2012). Cultural Theory is one of the most prominent risk perception theories, which elaborates people's attitude to risk and uncertainty in terms of their general worldview of the nature (Thompson et al., 1990).

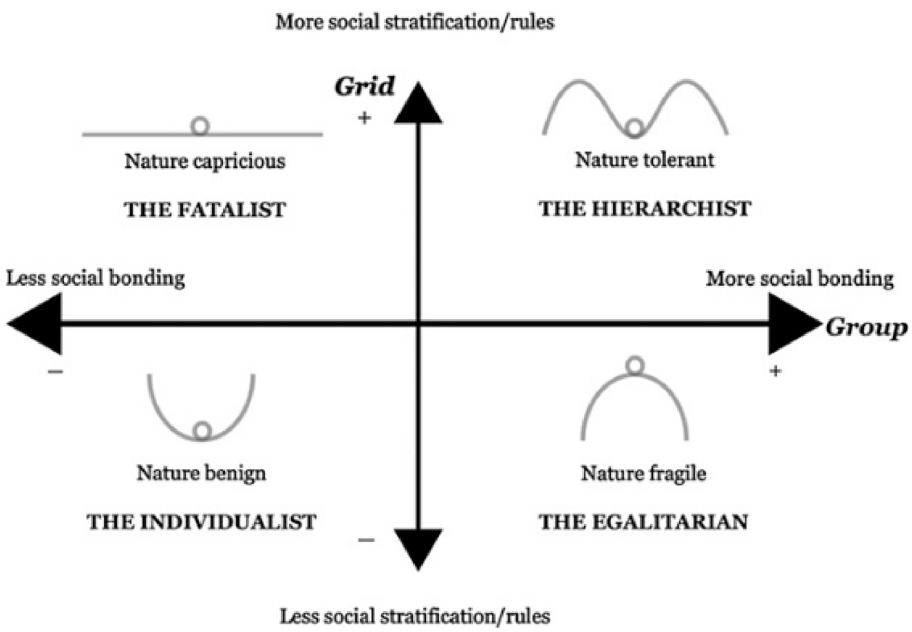


Figure 3.26: Four worldviews and myths of nature from the Cultural Theory, reprinted from McNeeley and Lazrus (2014)

As shown in Figure 3.26, peoples' views of nature are distinguished into four different types, namely *Fatalist*, *Hierarchist*, *Egalitarian*, and *Individualist*, with reference to two dimensions — social bonds (Group) and social rules (Grid). According to McNeeley and Lazrus (2014) and Dessai and van der Sluijs (2007): In an *Egalitarian*'s view, the nature is fragile and the climate system is in a delicate balance that is prone to collapse due to human interventions, therefore, the *Egalitarian* has a risk-averse attitude and prefers preventive management styles; An *Individualist* believes that the nature is benign and the climate system is robust that always find its equilibrium by auto-adjusting to human actions. So *Individualists* are characterized as self-seeking and risk-seeking and they tend to choose the adaptive management style for the short-term interests; From a *Hierarchist*'s perspective, the nature can tolerate some negative anthropogenic influences and is controllable up to a certain degree ("tipping point"). Therefore, the *Hierarchists*' attitude towards risk falls in between the *Egalitarian*'s and the *Individualist*'s and thus is risk-neutral. *Fatalist* is indifferent to risk since they view nature as completely capricious and unpredictable. Middelkoop et al. (2004) excluded the *Fatalist* perspective when applying the Cultural Theory to the field of water, therefore, three stereotypical perspectives were selected out *i.e. Hierarchist, Egalitarian*, and *Individualist*, each of which represents a different view about the risk and uncertainty thus implies different management strategy preference. No decision-maker can perfectly fit into each of the three perspectives, and the real-life perspective is always in the mixture of the three (Dessai and van der Sluijs, 2007). Middelkoop et al. (2004) thought that the Dutch water management style was more close to the *Hierarchist*. And Offermans (2010) argued that the dominant *Hierarchical* perspective had become more *Egalitarian* as the result of a series of disastrous events.

Therefore, in the undertaken research, we studied the differences in the perspectives by specifying different acceptable risks. The baseline risk R_0 is the acceptable threshold for the *Hierarchist*, while double this threshold ($2R_0$) and half of the baseline risk ($0.5R_0$) are the adaptation tipping points for the *Individualist* and the *Egalitarian* respectively. The threshold values are shown in Table 3.7 below. The proportions are based on the objective thresholds in the Waas case by Haasnoot et al. (2012), which were set as the cumulative damage of 1250M €, 2500M €, and 5000M € for three perspectives.

Table 3.7: Perspective-based acceptable risks as the adaptation tipping point (ATP)

Perspective	**Risk attitude**	**Acceptable risk**
Hierarchist	Risk-neutral	R_0
Egalitarian	Risk-averse	$0.5R_0$
Individualist	Risk-seeking	$2R_0$

3.5.2 Package of adaptation actions

Theoretically speaking, the portfolio of adaptive actions should be completely determined in the step "Define adaptation actions" in section 3.2. However, because some key concepts like effective depth and runoff frequency reduction factor are not introduced before section 3.4, and realistic measures that suit to the local context can only be roughly determined after performing preliminary trials, we put the final determination of the package of adaptive actions in this section.

Previously in section 3.2, we have selected 6 measures (*i.e.* rain barrel, extensive green roof, green roof with drainage delay, porous pavement, bioswale and water square) out from an array of 24 adaptation measures, three of which represent measures on private roofs and the other three of which are constructed in public space. Even though we have narrowed down the choice, there still needs additional simplifications on the configuration of these measures *e.g.* measure inflow area (*i.e.* runoff contributing area to the measure), design specifications of measures (*e.g.* structure, dimension, functionality), *etc.* Therefore, in this subsection, the package of adaptive options are finally determined with several logistic assumptions.

In a workshop-based transparent dialogue, an example of which is shown in Figure 3.27 below, urban planners, hydrology experts, and other relevant stakeholders can sit together to explore numerous possible strategies in an integrated and holistic manner by identifying what, how, and where these gray, blue, and green measures can be added to increase the system's resilience to flooding and droughts and meanwhile bring aesthetic value contributing to the quality of socio-economic life.

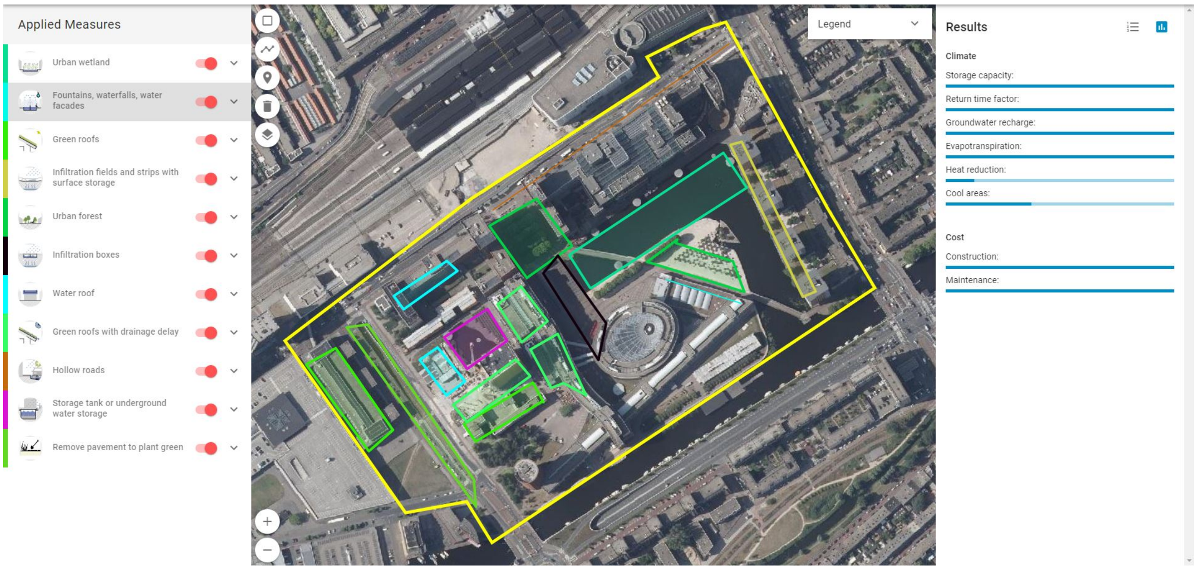


Figure 3.27: A workshop on Laakhaven-Oost based on the Adaptation Support Tool (AST), adapted from (Brolsma, 2018). The cost-benefit of a dozen of adaptation measures with varied specifications in isolation and combination to fit into the study area Laakhaven was discussed in the workshop to shed light on general directions at the preliminary urban planning stage.

3.5.2.1 Assumptions on runoff inflow area and combinations of measures

However, this undertaken study is not a workshop but a general research study on the future possible routes under adaptive planning. Unlike a workshop or a real design assignment where the spatial information and the hydrological connectivity are quite essential and indispensable in the analysis, a simplification is made here that the project area is a lumped and flat area with spatial configuration ignored. Therefore, the implementation of adaptation measures is only constrained by the available contributing area. For example, the actual routing routes of the runoff into the measure should be considered in the real design of a water square, however, in our hypothetical case study, we simply assume that the runoff from all paved land surface can flow into the water square by any means without a problem. As checked from Table 3.1, the project area is made up of 32.6% building, 11% closed paved, 41.60% open paved, 13.80% unpaved area and 1% surface water. Here, for simplicity, we assume no differentiation is made between the closed paved and the open paved, and therefore they compose 52.6% paved land surface of the entire study area. Undoubtedly, rain barrels, extensive green roofs, and green roofs with drainage delay function only for the building rooftops. However, theoretically speaking, many adaptation measures on the ground can collect the rainwater runoff not only from the roads but also from the rooftops. In some cases, a large detention basin can be designed to temporarily

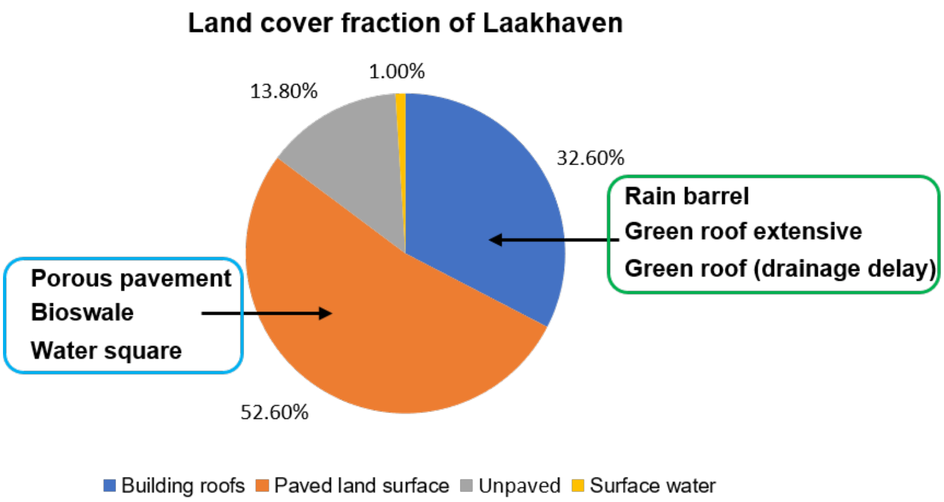


Figure 3.28: Land cover fractions of Laakhaven and measures applied on rooftops and land surface

store stormwater runoff from the entire catchment, and even from the outside area. For instance, the Water plaza Benthemplein in Rotterdam collects water from immediate surroundings within two shallow basins whenever it rains and can buffer extra runoff from the wider area in the deep basin (central sport court) under heavy rainfall events. To avoid unnecessary discussion, an assumption was made here that for the three adaptation measures on the paved land surface — porous pavement, bioswale, and water square, the runoff inflow area to these measures is limited to and equal to the total paved land surface of the entire study area (52.6%). In this way, we have determined that three measures deal with the paved area above the ground level *i.e.* building rooftops, and the other three measures exert their control on the paved area at the ground level *i.e.* paved land surface. The land cover fraction and related measures are shown in Figure 3.28 above.

Besides the issue of the contributing area to the measure, another assumption is made on the combinations of measures. In reality, a bunch of different measures are usually applied in together to contribute to the combined effect of flooding mitigation and bring other added-values. For instance, on the paved land surface, you can have at the same time the porous pavement for the parking lots, the ditches along the roads, the water square surrounded by buildings and these possibilities are endless. To avoid unnecessary discussions, another simplification is made here assuming that on the same land cover type (rooftops or paved land surface) only one measure type can be applied and runoff from 100% of the area where the measure is applied inflows to the measure. But measures on different land cover types can be applied at the same time, *i.e.*, measure on the private paved roofs can be combined with a measure on the public paved land surface as adaptation measures in combination. Actually, another concern why we made this assumption is due to the fact that we have not figured out the proper way to determine the combined effect of measures that are overlapped. For example, previously, we assume the overflow from the rain barrel as the uncontrolled runoff still flowing to the sewer system. However, in reality, the overflow from the rain barrel can be directed to another measure *e.g.* the infiltration trench where it recharges the groundwater. In this case, we have the overlapping of the runoff reduction effects of measures. For now, we have yet to know how to determine the combined effect of overlapping measures. Therefore, we have to assume that the measure applied has its independent runoff inflow area.

3.5.2.2 Assumptions on the specifications of measures

After specifying the runoff inflow area to the measures and defining the adaption actions in isolation and combination, the next important step is to determine the specifications of measures. As stated in section 3.4.3, the different specifications are described with varying levels of effective depth. This part is quite difficult and relatively subjective since there is basically no absolutely definitive answer to this question. Therefore, a series of reasonable assumptions have to be made.

In theory, people can build measures of whatever capacity they would like to have. There is usually a low limit for the specification of a measure due to the initial construction cost and the minimum protection requirement. But in terms of the optimal specification and the upper limit of specifications, it is a complicated question regarding the optimizations between costs and benefits under the budget constraint. In the Netherlands, since the consequence of the infrastructure failure is quite damaging, it is not uncommon to see very high flood protection standards of *e.g.* 1:10000 annual exceedance probability in comparison to the normative standards applied in other countries. People can make the measures to be extremely robust. For instance, in our study area, as shown in Figure D.11a, people can have a drainage delay green roof with the effective depth of $100mm$ given a large roof load bearing capacity. In this case, under the baseline climate, the outcomes of 30-year simulation show that all the rainfall falling on the roof does not run off, and is only temporarily detained in the drainage layer and gets drained at the delayed pace. Therefore, no point can be plotted in the semi-log scale graph of the return time and the runoff depth for the $100mm$ effective depth specification. As a simplified representation of the semi-log scale graph D.11a, Figure 3.29 below illustrates the relationship between the effective depth and the modeled runoff depth.

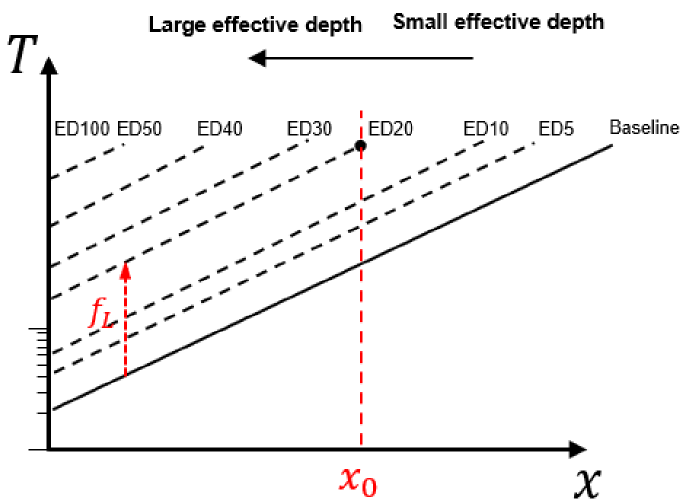


Figure 3.29: A simple illustration of the semi-log graph for the same type of measure with different specifications

This figure shows that with the increase in the specification, both the number and the magnitude of the modeled runoff events are reduced. And up to a certain specification, say around 100mm (ED100), there is no runoff generated throughout the simulation. Therefore, there is no point or curve for $ED100$ in the graph. Several points should be noted here regarding the $ED100$ specification: ***a.*** No runoff does not necessarily mean the drainage delay green roof with the effective depth of 100mm is a completely flood-proofing measure under the baseline climate scenario because the available time series is only 30-year and more extreme events could happen beyond the available time series of the baseline climate (*e.g.* 3000-year time series). Therefore, the effectiveness (*i.e.* runoff frequency reduction factor) of $ED100$ specification is definitely not infinite. So, we simply assume that it doubles the effectiveness of $ED50$ specification and is denoted with asterisk sign * in Table D.1. ***b.*** Apparently, the measure with even a higher specification (say 200mm effective depth) will also generate no runoff in the modeled results. Despite zero modeled runoff for both specifications, we cannot say $ED200$ is equivalent to $ED100$, because obviously, $ED200$ can cope with more extreme cases. However, the effectiveness of these large specifications cannot be clearly determined with certainty. ***c.*** If you carefully look at the many semi-log graphs for various measures in Appendix D, it is easy to find that the paralleling behaviors of curves are more obvious for small to medium specifications within lower to intermediate range of the runoff depth. Therefore, we are more confident about the performance indicators (*i.e.* runoff frequency reduction factor) for that range.

Besides the incomplete perception on the effectiveness of measures with the large specification, another problem on the measure configuration arises from the cost and benefits aspects of the measure. Cost of a measure is usually relatively easy to determine by considering the construction cost and the maintenance cost. However, the determination of the benefits of a (LID) measure is relatively complex since it is usually evaluated from an array of aspects. For instance, besides the main benefit in the stormwater management (*e.g.* runoff volume reduction, peak flow alteration, flood risk mitigation, water quality improvement, *etc.*), a (LID) measure also contributes to other environmental benefits (*e.g.* heat stress alleviation through evaporative cooling, drought relief through groundwater recharge, air quality improvement, *etc.*), economic benefits (*e.g.* municipal water demand reduction through rainwater recycling, energy consumption reduction) and social benefits (*e.g.* recreational spots, aesthetic values and livable environment, *etc.*) (SEMCOG, 2008). Therefore, the planning of LID measures is an iterative process of optimizing the cost and multi-dimensional benefits under the budget constraint in the local context, which involves the participation by stakeholders from various aspects.

Hence, to determine the appropriate specification range of the measure is itself an iteratively trial optimization process based on the local context of the study area (*e.g.* climate, current situation, *etc.*), the criteria-based trade-offs between the cost and benefits and expert judgment. It is a question that cannot be resolved within the undertaken study. Therefore, we propose a simple but straightforward assumption to decide the large specifications of measures. And that is the level of effective depth of a certain measure that results in the modeled maximum event-based runoff depth just below the critical runoff depth ($x_0 = 48mm$), as shown in Figure 3.29. This implies that, in the 30-year time span under the baseline climate scenario, previously there are approximate 15 events exceeding the considered magnitude, but after the implementation of the measure with the large specification, the return period of the critical event turns from $T = 2$year to $T \geq 30$year.

Based on the above assumptions, the range of specifications for six measures was determined, each of which has a small and large specification as its boundaries. Since the adaptation measures are usually modulated measures, we only use the upper and lower limits to represent the specification range expressed in the effective depth. The specifications are shown in Table 3.8 below. Note that, instead of using their AST IDs, the six measures namely rain barrel, green roof extensive, green roof with drainage delay, porous pavement, bioswale, and water square are abbreviated as RB, GRE, GRD, PP, BS, WS respectively in all the following sections. And RB1 means rain barrel with small specification and RB2 means rain barrel with large specification.

Table 3.8: The small and large specifications of 6 adaptation measures

Effective depth	**RB**	**GRE**	**GRD**	**PP**	**BS**	**WS**
Small specification	5mm	5mm	10mm	10mm	10mm	10mm
Large specification	30mm	30mm	30mm	40mm	40mm	40mm

Effectiveness of different measures with predefined specifications can thus be determined in terms of the runoff frequency reduction factor. Assumptions and simplifications made in this section in order to outline the appropriate measures' specifications are a major weak point of the undertaken research. This is because the iterative process of optimizing between costs and benefits is necessary to determine the design of the measure in a realistic manner. However, we reason that the measure specifications outlined above can be considered roughly right and used in the subsequent study given that this research only serves as the first-level assessment of the adaptive stormwater management planning. This preliminary investigation addresses the development roadmaps of adaptation measures from a macro level with the aim of exploring a broad range of possible strategies. As long as the general directions and some promising pathways have been outlined, the more in-depth assessment will have to be conducted in the practical design and implementation phase.

We can have measures on both private space and public space. Table 3.9 below shows the package of adaptation measures in isolation and in combination. As stated above, 1 and 2 indicate small and large specifications of the measure respectively. For instance, RB1PP2 means rain barrel with small specification applied on the paved roof in combination with porous pavement with large specification applied on the paved land surface. Notations starting with "S" indicate actions containing one single measure in isolation, whereas notations starting with "C" indicate actions comprised of two measures in combination.

Table 3.9: Package of adaptation actions

Notation	**Single measure**	**Notation**	**Combined measures**	**Notation**	**Combined measures**	**Notation**	**Combined measures**
S1	RB1	C1	RB1PP1	C13	GRE1PP1	C25	GRI1PP1
S2	RB2	C2	RB1PP2	C14	GRE1PP2	C26	GRI1PP2
S3	GRE1	C3	RB1BS1	C15	GRE1BS1	C27	GRI1BS1
S4	GRE2	C4	RB1BS2	C16	GRE1BS2	C28	GRI1BS2
S5	GRI1	C5	RB1WS1	C17	GRE1WS1	C29	GRI1WS1
S6	GRI2	C6	RB1WS2	C18	GRE1WS2	C30	GRI1WS2
S7	PP1	C7	RB2PP1	C19	GRE2PP1	C31	GRI2PP1
S8	PP2	C8	RB2PP2	C20	GRE2PP2	C32	GRI2PP2
S9	BS1	C9	RB2BS1	C21	GRE2BS1	C33	GRI2BS1
S10	BS2	C10	RB2BS2	C22	GRE2BS2	C34	GRI2BS2
S11	WS1	C11	RB2WS1	C23	GRE2WS1	C35	GRI2WS1
S12	WS2	C12	RB2WS2	C24	GRE2WS2	C36	GRI2WS2

With all the conditions developed above and the risk formula proposed in section 3.5, the sell-by dates (N) of all policy actions are computed for all the combinations of the climate scenarios, the socio-economic scenarios, and the societal risk perceptions.

3.6 Development of adaptation pathways

With the calculated sell-by dates of adaptation actions, we can assemble the adaptation pathways and later make them into a map, which is the so-called Adaptation Pathways map. An Adaptation Pathways map can be drawn based on the results of the assessment model or expert judgment. A well-crafted Adaptation Pathways map enables policymakers to identify opportunities, threats, timing and sequence of adaptation actions, no-regret actions, and future lock-ins (dead ends) in order to support developing adaptive water management roadmaps into the future in a changing environment characterized with uncertainties (Haasnoot et al., 2012).

As talked about in Appendix G, there are two kinds of adaptation pathways — time-based pathways and condition-based pathways, depending on how the Adaptation Pathway approach is implemented. Waas case by Haasnoot et al. (2012) was a top-down implementation, which took transient climate scenarios to drive the assessment model. Therefore, the resulting sell-by date was scenario-dependent and the final adaptation pathways (map) were time-based; In contrast, Kent Ridge Case by Manocha and Babovic (2017) was a typical bottom-up implementation, which extended the Adaptation Tipping Point approach (vulnerability assessment) with the Adaptation Pathway approach. The calculated adaptation tipping point (*i.e.* maximum annual rainfall the system can withstand) was not derived from climate scenarios but was only dependent on the system configuration. However, these tipping points could be positioned in the timeline assuming certain climate change scenario. Therefore, the resulting adaptation pathways (maps) were condition-based and could be easily updated with new information on climate change.

The undertaken study is closer to the top-down implementation since 5 transient climate scenarios are applied to the assessment model to determine the effectiveness of adaptation actions, although, taking different compounding growths of potential damage as transient socio-economic scenarios is a bit oversimplified. Anyway, with all these simplifications and assumptions made to the assessment model, the sell-by dates of adaptation actions are calculated. Adaptation pathways can then be generated by using these sell-by dates and under the assumption that, if an adaptive action fails to meet the objective (encounter the ATP — acceptable risk), it becomes necessary to level itself up (intensification), extend it with another action in combination, or abandon itself and shift to another action in sequence, in order to re-satisfy the pre-specified objectives.

The Adaptation Pathway map provides an overview of all optional pathways that lead the water management into the future, which is comparable to a metro map that presents multiple alternative routes to the final destination. In the undertaken study, a single storyline (adaptation pathway) is completed when the area has been managed under the acceptable risk for 100 years. Different adaptation pathways arise from different climate, social-economic, and societal perspective scenarios, representing the uncertainties in a changing environment. An Adaptation Pathways map presents not only the possible strategies to take, but also when an where they could fail. There have been various adaptation actions defined (12 "S" adaptive actions) in the study and a bulk of the calculated sell-by dates of these actions corresponding to different conditions. It is impossible to analyze all these possibilities within the current study in a trackable manner. Therefore, we craft (the maps of) adaptation pathways based on the median values of the calculated sell-by dates from a certain perspective.

In addition, an adaptation pathway should be assembled by possible actions in a logical manner. Some actions may be mutually exclusive from each other, some actions may improve the system only a little, some sequences of actions may be illogical, *etc.* All these irrelevant groups should be excluded from the pool of adaptation pathways. Besides, expert judgment is also involved in this process to evaluate the feasibility of the pathway from certain aspects, for example, the urgency of actions, the severity of consequence, the uncertainties involved. With predefined rules and expert judgment, a set of promising pathways can be selected and later made into an Adaptation Pathways map.

Using the knowledge from the two case studies (Haasnoot et al., 2012; Manocha and Babovic, 2017) as the reference, in the current study, adaptation pathways (maps) are assembled with the calculated sell-by date by following the rules shown below:

- Objectives should be met (*i.e.* risk below the acceptable threshold) over the entire 100-year planning time frame. Only the sequence of actions that meets the requirement until 2100 can be considered as a viable route — pathway.
- Excluding illogical sequences: ***a.*** Once built to the large specification, the specification of a certain adaptation measure itself cannot be lowered to its small specification. For example, if a rainwater harvesting device is leveled up from the small to the large specification, it is illogical to reverse it back to the small specification in the future actions.
- Excluding ineffective upgradation: ***a.*** After implementing additional interventions, whatever it is intensification, combination, or switching, a significant extension in the sell-by date of the strategy should be generated with at least 10 years increase.
- Excluding excessive capacity: If the strategy can be maintained with objectives met over 100 years with the lower configuration, there is no meaning employing the large specification.
- No major consequence: Adaptation measures on the ground or rooftops with large specifications (*e.g.* large rainwater harvesting, large porous pavement, large bioswale, large water square). Once they are built, it cannot be abandoned and replaced by other measures due to the high associated costs and high societal impacts (major consequence).

Chapter 4

Results and discussion

4.1 Effectiveness of measures

After analyzing the values of the runoff frequency reduction factors for various adaptation measures with different specifications in Table D.1, Table 4.1, and Figure 4.1, several discussions can be made as follows:

- In the context of Laakhaven, runoff reduction factors for measures with large effective depth are questionable. We have more confidence in the factors of measures with the effective depth ranging from 5mm to 40mm. This is because, if looking at the semi-log scale graphs where the factor is derived, the event with large depth can be coincidental — we don't know whether the largest event in the 30-year time series simulation is really a $T = 30 yr$ event. This empirical relationship of runoff frequency reduction is confirmed for various measures under various different climates using long-time series simulation. Therefore, it is a valuable indicator for the quick assessment of the effectiveness of measures.

- Given the same storage capacity, the measure's effectiveness is largely determined by the emptying (releasing) mechanisms. Rain barrels and water squares are effective because of the regulated emptying scheme. A normal extensive green roof is ineffective in the stormwater runoff buffering even with large effective depth (*i.e.* intensive green roof), since the emptying mechanism of a normal green roof is through evaporation only, therefore, the antecedent condition before another incoming storm allows only very limited buffering volume. The extensive green roof can thus be more effective to deal with regular small rainfall events rather than consecutive heavy rainfall events. Combine an extensive green roof with rainwater harvesting to make a green roof with drainage delay can largely increase its flood mitigation capacity.

- In general, for Laakhaven, measures for attenuation (*e.g.* water square, rain barrel) with a large regulated discharge are the most effective, measures for infiltration (*e.g.* bioswale, infiltration box) are the second effective, and measures for evapotranspiration only (*e.g.* extensive green roof, water roof) are the least effective. In other words, the measure effectiveness is essentially determined from two aspects — the static storage capacity depending on the design of the measure, and the active storage capacity depending on the antecedent conditions and the emptying mechanisms.

- As shown in Figure 4.1 and Table 4.1, the effectiveness of measures under the baseline climate scenario and 4 KNMI climate scenarios are roughly comparable to each other. However, other things being equal, based on the report by Zhang and Vergroesen (2018), given totally different climates in Japan (1350mm/year), Taoyuan (2000mm/year), and Galveston (1450mm/year), the resulting factors are quite different from the ones for Laakhaven. Rain barrel with 40mm effective depth is considered quite effective in Laakhaven, but in the other three climates, it can only improve the system a little. Galveston has almost the same amount of annual rainfall as Japan, but the efficacy of the rain barrel is only about half of the effectiveness of the same rain barrel if applied in Japan. Therefore, it can be imaged that climate variability plays an important role in the functioning of measures.

- Figure 4.1 also compares the emptying mechanism of a rain barrel. If the rain barrel is emptied twice as fast as the initial discharge rate, its efficiency is greatly increased. However, if it is drained at a slower pace, for example, people forget to use the stock in the barrel, the effectiveness is reduced quite a lot. This advocates the proper operation and maintenance of these detention measures.

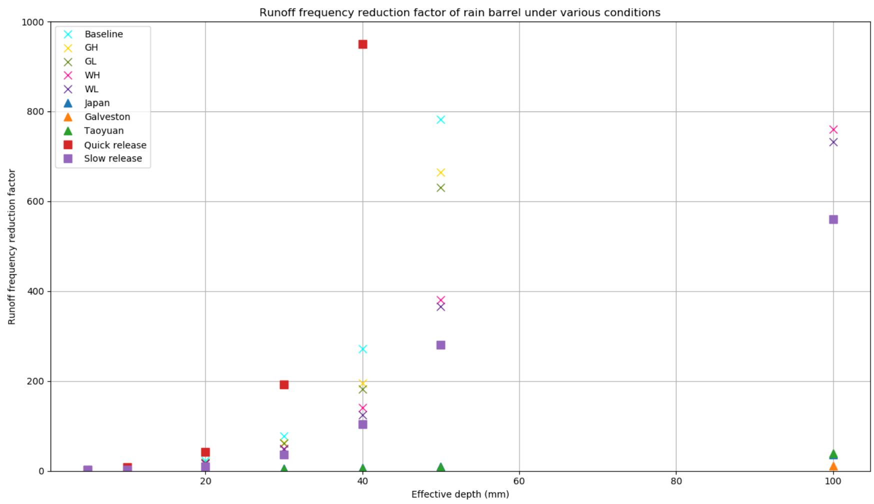


Figure 4.1: Runoff frequency reduction factor for rain barrels under different conditions

Table 4.1: Runoff frequency reduction factor for rain barrels with varied specifications under different cases

Effective depth	5mm	10mm	20mm	30mm	40mm	50mm	100mm
Baseline	2.01	4.33	22.61	77.93	271.75	781.68	1563.36*
GH	1.94	3.95	18.78	62.15	195.61	664.32	1328.64*
GL	1.98	3.99	18.79	61.5	182.03	629.97	1259.94*
WH	1.87	3.62	15.77	48.94	140.02	379.85	759.7*
WL	1.88	3.74	16.27	47.87	124.82	365.96	731.92*
Japan	1.36	1.8	2.99	4.66	7.14	9.55	35.61
Galveston	1.2	1.41	1.88	2.47	3.15	3.91	11.18
Taoyuan	1.26	1.57	2.4	3.46	5.09	7.81	39.33
Quick release	2.77	7.73	41.43	192.2	950.12	1900.24*	3800.48*
Slow release	1.57	2.63	8.88	35.6	103.17	279.65	559.3*

4.2 Sell-by dates

4.2.1 Sell-by dates in response to socio-economic uncertainties

The sell-by date of an action is the moment on the time frame, at which the adaptation tipping point (ATP) (*i.e.* the acceptable risk in the undertaken study) is reached, therefore, it asks for additional interventions afterward. Below Figure 4.2 shows an example of the computed sell-by dates of all the adaptive actions under the baseline climate scenarios at three socio-economic growth rate evaluated from a *Hierarchist* perspective.

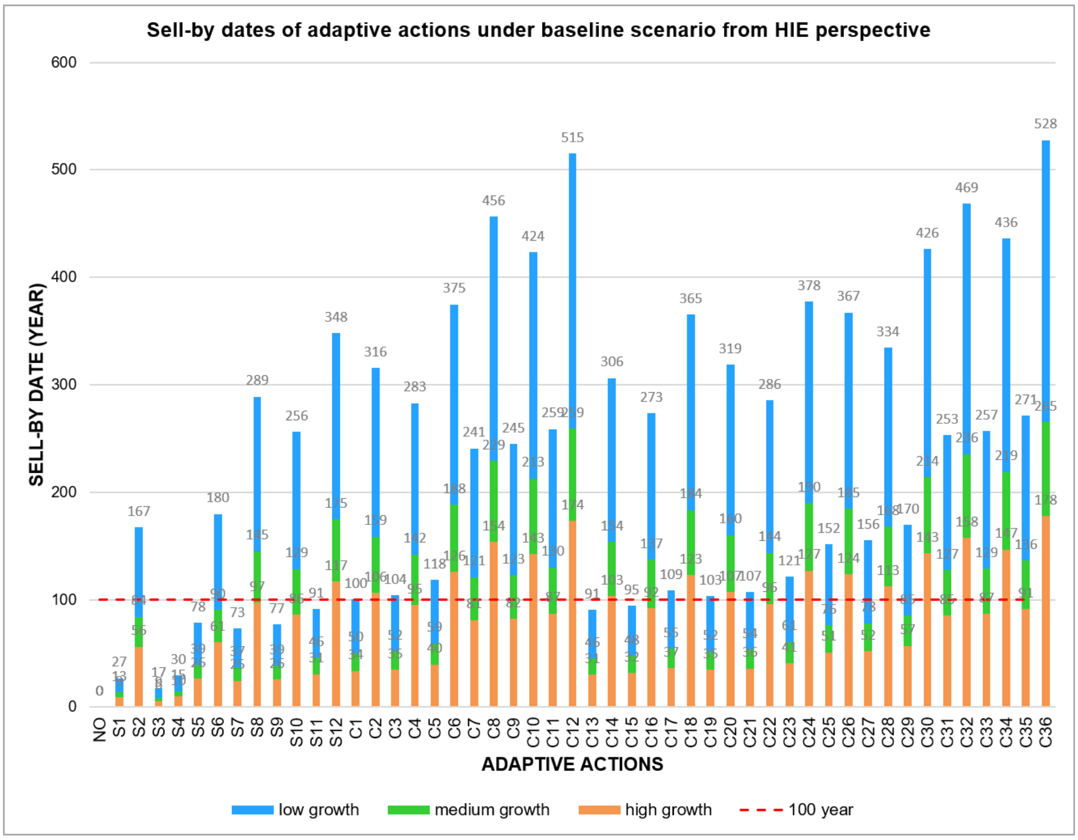


Figure 4.2: Sell-by dates of all adaptation actions under the baseline climate scenario in a *Hierarchist* future

Considering we have 5 climate scenarios, 3 socio-economic scenarios, and 3 perspective-based acceptable risks, then there are 3 × 3 × 5 = 45 combinations. We include three growth rates in one figure. Therefore, there are in total 15 figures of the calculated sell-by dates under 5 different climate scenarios evaluated from 3 perspectives, which can be found in Appendix E. We first describe what information we can learn from the figure above, and then we compare this figure with other figures configured with varied setup in Appendix E, to see the difference in the computed sell-by dates and study the factors contributing to the difference.

As shown in Figure 4.2, in the x-axis, besides "no action", there are 48 adaptation actions from Table 3.9, including 12 "S" actions, each of which is composed of an adaptation measure with small or large specification in isolation and 36 "C" actions, each of which consists of two adaptation measures with small or large specification (one on the roof, the other one on the ground) in combination. The y-axis represents the sell-by date in year.

The sell-by date of an adaptive action is the timing of the adaptation tipping point, *i.e.* the moment at which the adaptive action fails to meet the pre-specified target. In our case study, the sell-by date is the year in which a certain adaptation action reaches the predefined socially acceptable risk. The sell-by dates of these 48 adaptive actions are calculated with the formula below, which has been stated in section 3.5 previously:

$$N = \log_{1+m} a f_m f_c$$

, in which m denotes economic (potential damage) growth rate, a denotes people's perception on risk, f_m and f_c indicate how the runoff return time of the normative flood event is altered by the implementation of adaptation measures and the changed climate scenarios respectively.

Our goal is to make long-term adaptive stormwater management plans on adaptation measures and the word "long-term" here means 100-year planning time horizon. As can be seen from the figure above, the red dashed line indicate the time frame of our interest (100 years), which means we should not put the focus on the fraction of the bar exceeding this limit. However, we do not truncate the calculated results to 100 years in the figure in order to show the difference in the effectiveness between adaptation actions, and furthermore, in this way some over-safe adaptive actions can be identified and redefined. Identifying unreasonable actions after evaluation and discussion and later redefining a more appropriate one is an important feedback loop in developing adaptation pathways as shown in Figure 2.4. Though this loop is not performed in the undertaken study, we leave the possibilities and recommendations here for future studies.

Figure 4.2 above shows the case under the baseline climate scenario in a *Hierarchist* world, including three socio-economic scenarios (low growth, medium growth, and high growth). The endpoints of the blue, green, and orange bars represent the sell-by dates of a certain adaptation option at low, medium, and high growth rates respectively. If the bar ends before 100 years, it indicates that, under certain conditions, the acceptable risk (adaptation tipping point) is reached earlier than the future desired point (100 years) within the planning horizon. Consequently, it becomes necessary to switch to or extend with other more durable adaptive actions to extend the sell-by date. If the bar ends after 100 years, it means this policy option solely can manage the system within the entire planning time horizon. It is evident from Figure 4.2 that the sell-by date for a certain adaptation action depends largely on the socio-economic growth rate. Under the socio-economic scenario with low growth rate (blue bar), all "S" adaptive actions consisting of adaptation measure with large specification in isolation (*i.e.* S2, S6, S8, S10, S12 , except for S4 — large extensive green roof) are capable to manage the system up to 100 years, let alone "C" adaptive actions with appropriate specifications. However, given a medium economic growth rate (2% per year, green bar), two "S" adaptation actions (S2 — large rain barrel, and S6 — large green roof with drainage delay) are no longer the actions with 100-year durability, and they can only meet the requirement to keep the risk under the acceptable level up to 84 and 90 years respectively. Therefore, at that time, additional interventions are needed to extend the sell-by dates. For example, S2 (large rain barrel) can be combined with small porous pavement on the ground to make adaptive action C7, in which case, 84 years becomes 121 years (≥ 100year); S6 (large green roof with drainage delay) can be combined with small bioswale on ground to make adaptive action C33 to greatly extend the sell-by date. Or, we can choose in the beginning to apply adaptation measures on the public space (porous pavement, bioswale, water square) instead of installing measures on the private roofs. For instance, we can first take action S11 (small water square) to manage the system until 46 years and later level up the water square to the large specification *i.e.* adaptive action S12 to ensure the objective is met within the entire time horizon.

Most of the "S" adaptive actions with the large specification are successful within the entire time frame under the low and medium growth socio-economic scenarios. However, given a high annual growth rate in the potential damage (orange bar), the majority of all "S" adaptive actions becomes no longer capable of solely protecting the system for 100 years, except for the action S12 (large water square). Therefore, we can say that under the baseline scenario from a *Hierarchist* perspective, compared to other "S" actions, one solo large water square as an adaptation measure on the public space (S12) is a more static robust solution which can succeed under various socio-economic scenarios. People can also choose to have adaptation measures in both public space and private space at the same time to achieve their management requirement ("C" adaptive actions) based on their preferences, trades off between cost and benefits and resource availability.

After analyzing the example Figure 4.2, several conclusions can be drawn as follows. Since we study the problem with the risk-based approach, the potential damage measured in the growth rate of economic values is strongly influencing the calculated sell-by date, especially when we specify the consequence as a compounding function of the time. Therefore, despite the damage mitigation measures are not incorporated into the calculation formula, we can somehow feel their significance to mitigate the flood risk. It is recommended in future research to consider the efficacy of damage mitigation measures and further improve the damage function since the constant compounding of potential damage is a relatively weak assumption. Besides, in terms of actions to take, several lessons can be learned. Since adaptation measures on the public space are usually more centralized and built with larger capacity thus more effective than adaptation measures on the private roofs, they usually have longer durability period under various scenarios thus are considered more static robust. But adaptation measures on the private roofs, especially the measures with decent storage capacity and regular release mechanisms (*e.g.* rain barrel and green roof with drainage delay), are highly-recommended good options. This is because they efficiently contribute to the overall flood frequency reduction over the entire study area thus reduce the flood risk, and more importantly, they are decentralized modular devices which enable them to be easily leveled up and combined with other measures to suit new situations thus incorporating flexibility into the strategies. They can be adapted or changed without major consequences like high cost or high societal impacts. Besides, they can bring added-values like rainwater reuse, aesthetic values, *etc.* Even though due to the capacity limit of adaptation measures that function on the roof, they at times cannot get things done once for all and therefore require combinations with additional measures on the ground after decades of years, adaptation measures on private roofs can adequately meet the near-term objective. This feature of adaptation measures on private spaces is considered very valuable since small-step interventions allow flexibility in engineering and continuous adaptation to new circumstances with the latest information as the future unfolds. And well-designed pathways composed of these flexible actions are considered dynamic robust under various future scenarios.

4.2.2 Sell-by dates in response to climatic uncertainties

Above, we have mainly discussed the impact on the strategies' durability of anthropogenic factors — the compounding growth of potential damage due to different socio-economic development. Besides the socio-economic uncertainties, uncertainties in climate change should also be analyzed carefully.

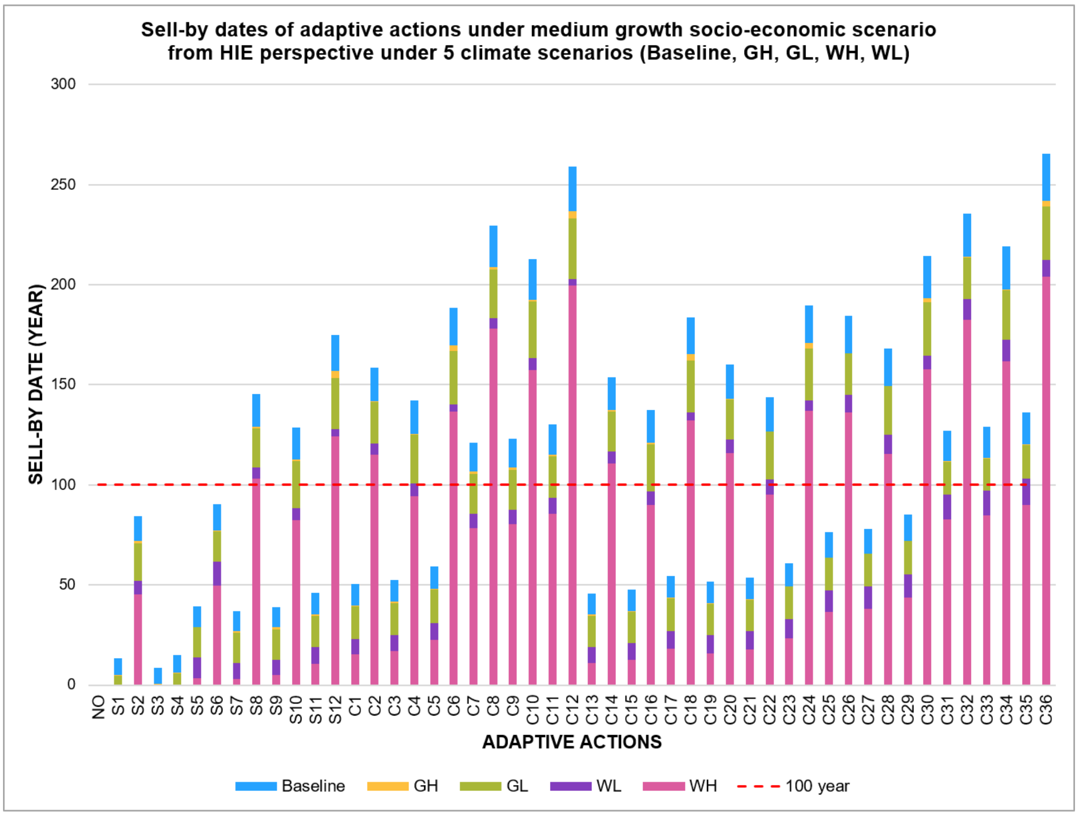


Figure 4.3: Sell-by dates of all adaptation actions under 5 different climate scenarios at the medium socio-economic growth rate in a *Hierarchist*'s future

Figure 4.3 above shows the sell-by dates of all policy actions under different climate scenarios at the medium socio-economic growth rate in a *Hierarchist* world. It extracts and summarizes the information from Figure 4.2 for the baseline climate scenario and the information from figures E.1b, E.1c, E.1d, and E.1e for the other four KNMI'14 climate scenarios namely G_H, G_L, W_H, and W_L scenarios. It is evident from Figure 4.3 that climate change also exerts considerable impacts on the durability of adaptive actions. For instance, looking at the "S" adaptive actions consisting of one adaptation measure in isolation, both G_H and G_L climate scenario will reduce the sell-by date of a certain action under the baseline climate by around ten to twenty years. However, the difference between the G_H and G_L scenarios is quite minor, only around one to three years. And as such, the yellow and green bars representing G_H and G_L scenarios in the figure are almost completely overlapped by each other. Meanwhile, two more extreme scenarios W_H and W_L (marked in pink and purple) would lead to a greater reduction in the durability period of adaptive actions. For "S" adaptive actions, the difference in the sell-by date for a certain action between the baseline climate and W_H scenario can range approximately from 10 to 50 years. The difference in results between W_H and W_L is also larger than the difference in results between G_H and G_L

scenarios.

Before further discussing the details, several concepts are recapped here and explained according to the local context. In the current study, the socially acceptable risk is the adaptation tipping point above which an action is considered no longer durable and additional interventions are necessary. The timing of this adaptation tipping point for a policy option is called the sell-by date, which depends on the climatic and socio-economic scenarios and the risk perceptions. Sell-by date is the N in the risk formula. In our case study, "S" adaptive action means the action containing one single adaptation measure in varied configuration either on the rooftop or on the ground. "C" adaptive action means the action consisting of two combined adaptation measures with small or large specifications (one on the private roof, one on the public ground) at the same time. Here presents a little bit more explanations on why we have "C" adaptive actions. For instance, we have defined three actions — S1 (RB1), S11 (WS1) and C5 (RB1WS1). Note that adaptation measures only alter the probability of flooding. Supposing under the same climate scenario, the same socio-economic scenario and the same risk perception, we can first take action S1, which will lead us to 13 years, and then combine it with action S11. Because we have just assumed the environment unfolds in an unchanged fashion, as such, extending S1 with S11 in year 13 as a sequence of actions should have the same sell-by date as C5 (59 year). Therefore, in this way, taking S1 first and then extending it with S11 in combination is no different from taking S1 first and then switching it to C5. Besides, the sell-by dates of these two sequences of actions are actually no different from the sell-by date of taking C5 in the very beginning, therefore, there is no meaning to take "C" adaptive actions in the beginning. Basically speaking, "C" adaptive actions should not be taken as optional choices, and they are actually used to roughly calculate the sell-by dates of the sequences of "S" adaptive actions. Hence, in the next section to develop adaptation pathways maps, only the "S" adaptive actions are plotted in the map while "C" adaptive actions are represented as the sequences of "S" adaptive actions in combination. Please note that the exact timing of an adaptation tipping point for a certain action is unimportant, but the range and the moment should be roughly right.

Pathway is a possible logical route into the desired point (100year) in the future. Pathways are assembled with these computed sell-by dates under certain rules stated in section 3.6. Lock-ins refer to situation where some future actions in a pathway can only be implemented against major consequences like high costs or high societal impacts. For instance, in some cases, large bioswale on the ground together with measures on roof can only meet the objective until 90 year, and the only way to address this problem is to abandon the bioswale and switch to a large water square, however it could bring massive decommissioning and retrofitting costs. Flexible actions are actions which can be adapted (*i.e.* be leveled up or intensified), abandoned (*i.e.* be decommissioned and switch to a different action) or extended (*i.e.* be combined with other actions) without causing major consequences (high cost or high societal impacts). Flexible actions do not lead to future lock-ins. And, potential future action should be less limited by the anterior flexible actions. No regret actions are actions that are robust or have additional benefits.

We first look into the "S" adaptive actions, each of which contains only one adaptation measure with small or large specification either on the roof or on the ground. As shown in Figure 4.3, only adaptive actions S8 (large porous pavement) and S12 (large water square) can succeed under all 5 climate scenarios. Therefore, if we choose to take action S10 (large bioswale) in the beginning with the intention to solve the problem once for all as a static robust option, we are taking the risk that the target will not be achieved under the W_H and W_L climate scenario, where it can only meet the objective up to 82 and 88 year respectively. Therefore, from that point on, large bioswale needs to be combined with measures on the roof to extend the sell-by date to 100 years. For instance, it can be combined with green roof with drainage delay with small specification to make S10 switched to C28 action (*i.e.* extend S10 with S5) thus leading to the full 100-year management.

Then we look into the "C" adaptive actions. As stated above, "C" adaptive actions are mainly used as proxies for calculating the sell-by dates of the sequences of "S" adaptive actions. However, it is theoretically possible to take "C" action in the beginning if people want. As can be seen from Figure 4.3, many of them with enough capacity have the resulted sell-by dates greater than 100 years for all climate scenarios. Therefore, if you implement these effective "C" adaptive actions (for instance C28 — large bioswale + small green roof with drainage delay) in year 1, it means you do not have to do anything else within 100 years, provided that the corresponding socio-economic scenario is at the medium growth rate and people have a *Hierarchist* risk perception. However, there are several major drawbacks with these static robust "C" strategies. First, this strategy (take action C28 in the beginning) involves considerably huge up-front investment, which may not be economically beneficial given the time value of money. Besides, its efficacy in flood risk reduction is no different from implementing S5 first and then extending it with S10. Second, because the bioswale with large specification involves a lot of public space and is relatively difficult to retrofit, it can later be an unexpected hindrance especially to urban development and spatial adaptation. Third, if the climatic, socio-economic scenario, and socially acceptable risk occur differently from what are initially assumed, it could leads to two undesirable aspects — ***a.*** the strategy fails to survive under some severe scenarios. For instance, under the high growth scenario in a *Egalitarian* world, extending C28 to C34 still does not meet the objective and the only way to meet the requirement is to switch large bioswale to large water square which can bring major consequences. Therefore, it is a potential future lock-in; ***b.*** this strategy can be deemed as over-safe thus bringing unnecessary costs. Besides, making things pretty robust and fixed in the beginning brings the opportunity cost people have to take. As such, it makes it difficult for them to benefit from other possible actions and to seize advantages of adaptation opportunities. Hence, in the next section to make adaptation pathways map, only "S" adaptive actions are explicitly plotted, while "C" actions are represented in a different way as the sequence of actions in combinations.

The impacts of different climate scenarios on the sell-by date are exerted from two aspects: ***a.*** changing the probability of hazardous events (see in Table 3.6, f_c in the formula); and ***b.*** reducing the effectiveness of adaptation measures (see in Table D.2 to D.6, changing f_m in the formula). Within the 100-year planning time frame, the impacts of climate scenarios on the policy durability reduction is comparable to the impacts of socio-economic scenarios. If looking beyond the 100-year time-line, it seems that the socio-economic scenarios have larger influences than climate scenarios. Anyway, the differences in the sell-by dates due to either changing climate scenarios or changing social-economic scenarios are largely resulted from the model applied, the formula used, the assumptions and simplifications made, *etc.* Therefore, the study of the sell-by dates and adaptation pathways should be more qualitative rather than quantitative. As long as the sell-by dates of possible policy options are roughly right, the subsequent study can be performed to provide some first-level insights on the general directions of the long-term adaptive planning.

4.2.3 Sell-by dates in response to uncertainties in risk perception

As we have discussed above the sell-by dates in response to the climatic and socio-economic uncertainties, in this section, the impact of the perspective-based socially acceptable risk is studied. Supposing a condition under the baseline climate scenario and under the medium growth socio-economic scenario, the information is extracted from Figure 4.2, E.2a, and E.3a, and it is then summarized into Figure 4.4 below.

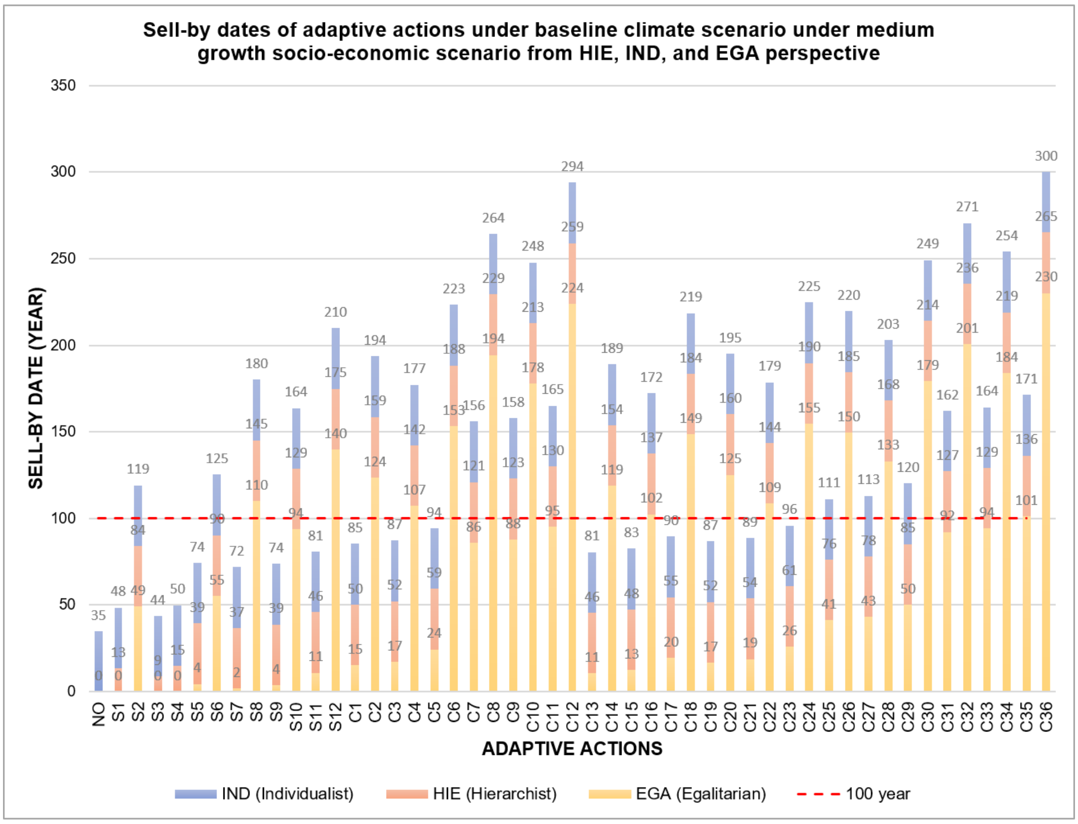


Figure 4.4: Sell-by dates of all adaptation actions evaluated from 3 different perspectives under baseline climate scenario at the medium socio-economic growth rate

As shown in the figure, under the assumptions made by the undertaken study, the difference in the calculated sell-by dates due to people's different risk perception is quite large, even larger than the difference in sell-by dates due to climate change and the socio-economic change. Actions considered acceptable over the planning time frame by an *Individualist* may be rejected some time before 100 years by people holding a *Hierarchist* world view, for example, the action S2 (large rain barrel) and S6 (large green roof with drainage delay). A *Hierarchist* may consider action S10 (large bioswale) as a static robust action that meets the objective over 100 years, but in an *Egalitarian* future this action may need additional inventions. Adaptation to climate change is essentially adapting to the adverse impacts induced by climate change, mainly focusing on reducing the risks faced by individuals and societies. However, the way in which people perceive the nature and climate change is subjective and is dependent on their beliefs and worldviews. Therefore, people holding various perspectives may have different preferences for risks and levels of risk tolerance. How much risk is socially acceptable? This is an important question to answer in regards to policymaking. Besides, the perspectives do change with the continuous development of economics and technology, and unanticipated extreme events can also give triggers to the shifting in the perspectives. Hence, the aspect of the societal environment is also filled with uncertainties. This advocates the significance of incorporating not only the changing physical and socio-economic conditions but also the changing societal conditions in the decision-making and strategy-planning.

Risk perception is a in the formula, and a is 1, 0.5, and 2 respectively for *Hierarchist*, *Egalitarian*, and *Individualist* (see in Table 3.7). The value for a is not directly indicated in any literature, but as stated in section 3.5 we borrow the setup from Haasnoot et al. (2012) where the cumulative damage (ATP) for *Hierarchist*, *Egalitarian*, and *Individualist* are 2500M€, 1250M€, and 5000M€ respectively. The dominant perspective in the Netherlands can be deemed as *Hierarchist*, which has a risk-neutral perception. Therefore, the subsequent section 4.3 mainly evaluates the adaptation pathways from a *Hierarchist* point of view. Another reason for this is that we would like to avoid the discussions on why a is 0.5 or 2.0. Please keep in mind that this implementation of adaptation pathway approach is not a detailed analysis or a realistic design project, but a quick and simple assessment in order to identify general directions and potential options. A more detailed assessment needs to be conveyed in a real design case.

4.2.4 Box-whisker plots of sell-by dates

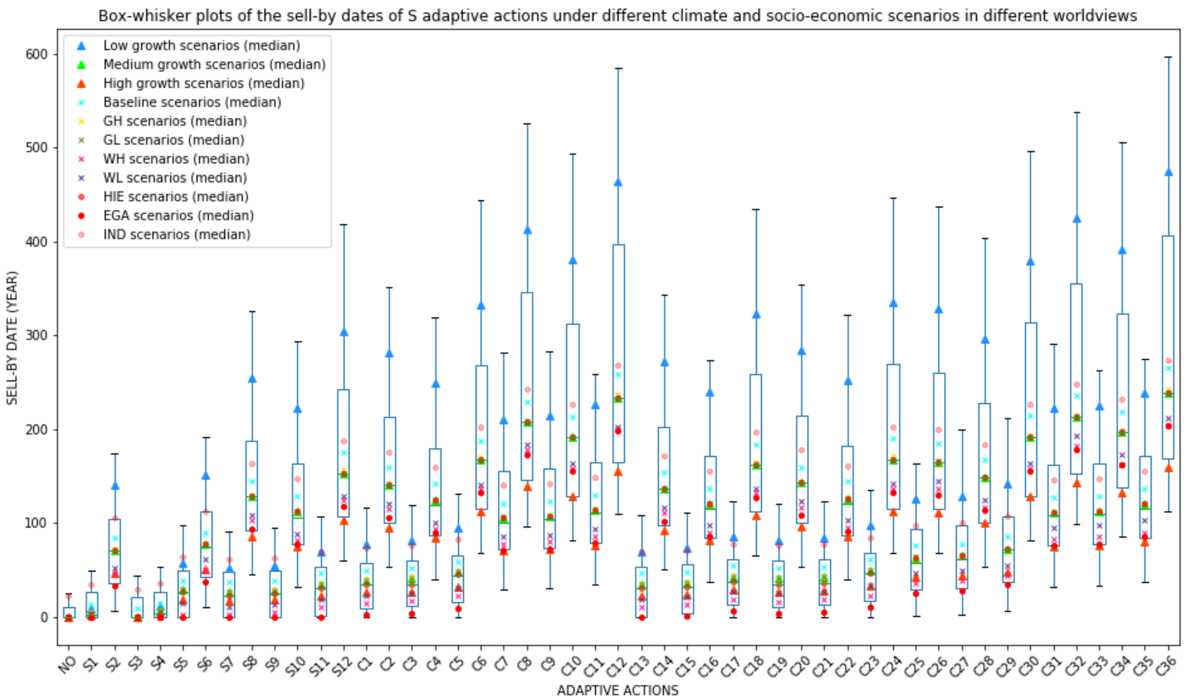


Figure 4.5: Box-whisker plots of sell-by date of all adaptive actions based on the results for all climate scenarios, socio-economic scenarios and people's perspectives. The median values for each climate scenario, each socio-economic scenario, and each perspective-based acceptable risk with its corresponding all realizations are presented in the figure. For adaptive action abbreviations see table 3.9.

Figure 4.5 above is the box-whisker plot of the sell-by dates for 45 combinations of climate, socio-economic, and perspective conditions. In the figure, three triangles colored in blue, green, and red denote the median values of all realizations under low, medium, and high growth socio-economic scenarios respectively. Three red points in varying levels of transparency indicate the median values of all realizations under three perspective-based acceptable risks. Low, medium, and high transparency indicate *Egalitarian*, *Hierarchist* and *Individualist* perspective one by one. Five cross marks in cyan, yellow, green, pink, and purple indicate the median values of all realizations corresponding to five climate scenarios namely baseline, G_H, G_L, W_H, and W_L. The calculated sell-by dates are not truncated to 100 years in order to illustrate the differences in the effectiveness of actions. Several pieces of information can be read from this figure. The actions that are more effective in altering flooding probability (having large f_m) are obviously more durable. Looking at the "S" adaptive actions, especially "S" actions with small specification (S1, S3, S4, S5, S7, S9, and S11), the difference in the sell-by date caused by different perspectives seems larger than the difference caused by different climate and socio-economic scenarios. But, if looking at "S" actions with large specification and "C" actions, it can be roughly read from the figure that, the difference in the sell-by dates due to the difference in socio-economic scenarios is larger than the difference caused by various risk perceptions, and the later is larger than the difference in the sell-by date due to different climate scenarios.

Figure 4.6 below shows the box plots for "S" actions only, in which Figure 4.6b presents the results that have been truncated to the 100 years. It is evident from these two figures that the different socio-economic scenarios (growth rate of the potential damage) and different socially acceptable risks lead to a larger difference in the calculated sell-by dates of the same adaptation actions compared to the different climate scenarios. Besides, it is obvious that the adaptation measure with greater efficacy (larger runoff frequency reduction factor) is more durable (have a longer sell-by date), which implies that this empirical factor itself can be used as a good performance indicator and it does not necessarily have to be combined with other approaches to be useful.

Below are the formulas derived for the analytic sensitivity analysis of the parameters a, f, and m on the computed sell-by dates:

$$\because aR_0 = \frac{1}{f_m f_c T_0} \cdot D_0 (1+m)^N, R_0 = \frac{D_0}{T_0}$$

$$\therefore N = \log_{1+m} a f_m f_c = \log_{1+m} af$$

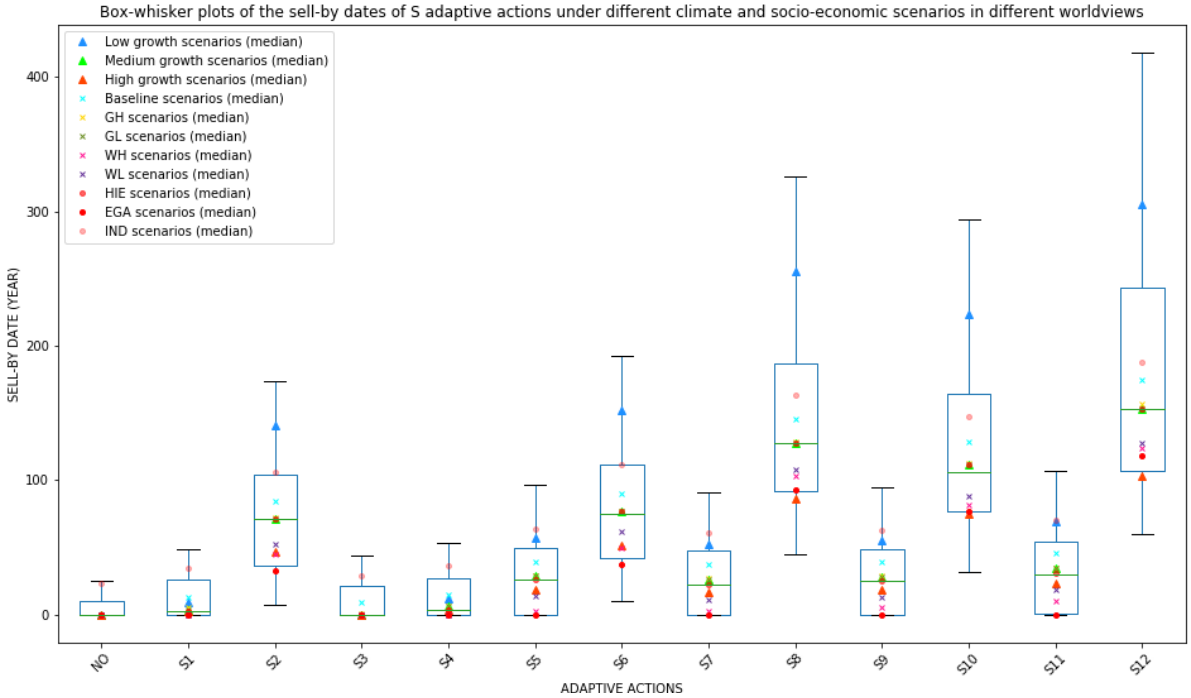
$$\therefore N(a+\Delta a, f+\Delta f, m+\Delta m) \cong N(a,f,m) + \frac{\partial N}{\partial a}\Delta a + \frac{\partial N}{\partial f}\Delta f + \frac{\partial N}{\partial m}\Delta m$$

$$\therefore \Delta N = \frac{1}{\ln(1+m)}\frac{\Delta a}{a} + \frac{1}{\ln(1+m)}\frac{\Delta f}{f} - \frac{\ln(af)}{(m+1)(\ln(1+m))^2}\Delta m$$

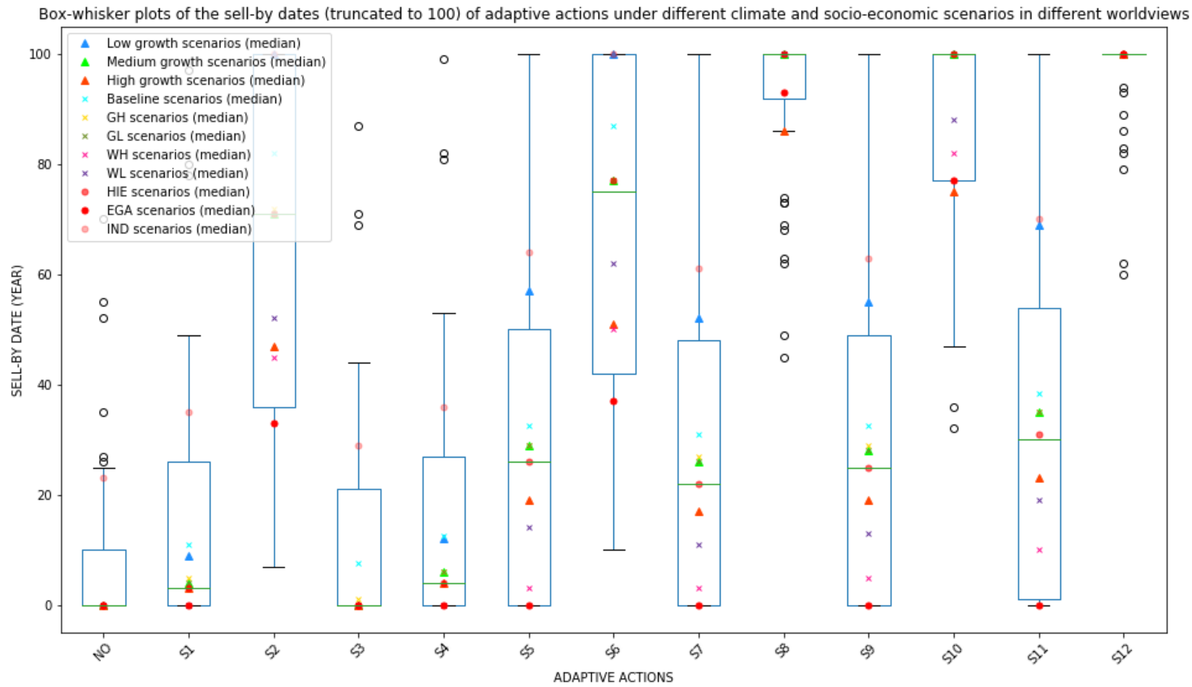
$$\therefore \frac{\Delta N}{N} = \frac{1}{\ln(af)} \cdot \frac{\Delta a}{a} + \frac{1}{\ln(af)} \cdot \frac{\Delta f}{f} - \frac{m}{(1+m)\ln(1+m)} \cdot \frac{\Delta m}{m}$$

in which roughly $0.5 \le a \le 2$, $1\% \le m \le 3\%$, $f = f_m f_c$, $1 < f < 200$. The varying degree of sensitivity for a certain parameter can be verified with the above formula.

Please note that the results are highly determined by the formula and the model applied. It is strongly recommended in future research studies to come up with a better function to represent the potential damage rather than the compounding over time with a constant growth rate. A possible solution is to use the Monte Carlo Simulation to model the dynamic potential damage growth to represent transient socio-economic scenarios.



(a) Box-whisker plots of the sell-by dates of "S" adaptive actions



(b) Box-whisker plots of the sell-by dates of "S" adaptive actions (data truncated to 100 years)

Figure 4.6: Box-whisker plots of the sell-by dates of "S" adaptive actions based on the results for all climate scenarios, socio-economic scenarios, and perspectives.

4.3 Adaptation pathways map

4.3.1 Adaptation Pathways map for the baseline case

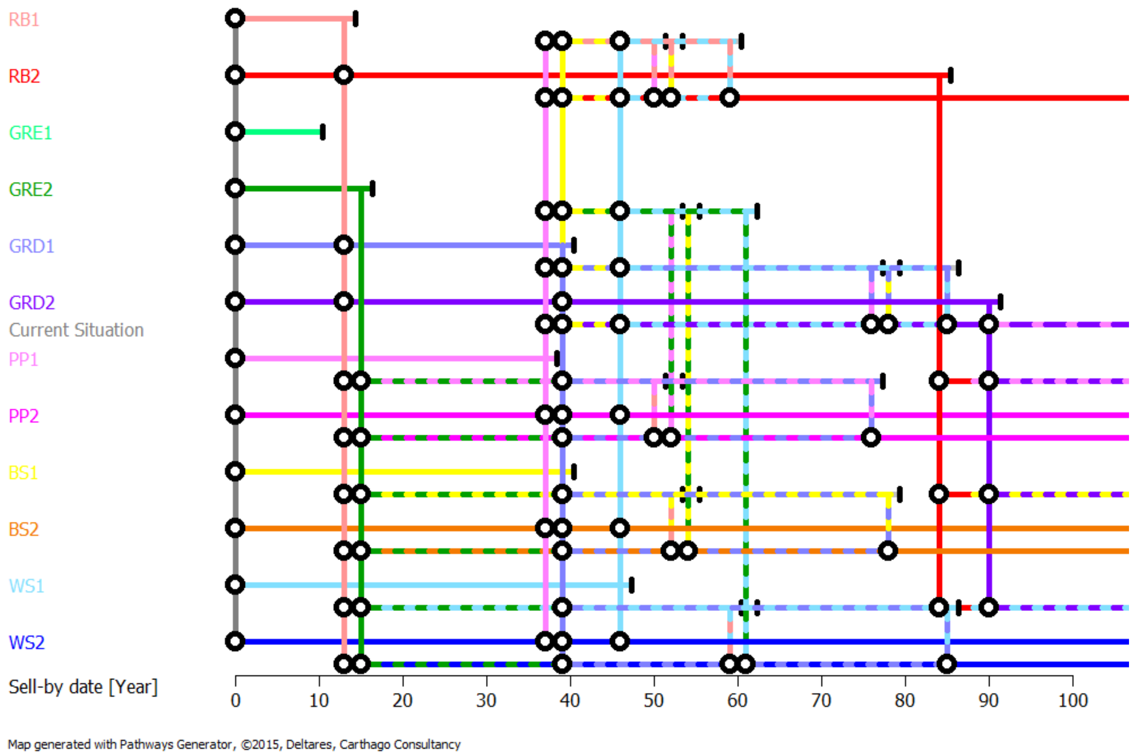


Figure 4.7: Adaptation Pathway map under the baseline climate scenario, under the medium growth socio-economic scenario, from a *Hierarchist* perspective

The Adaptation Pathways map in Figure 4.7 above is based on the sell-by dates for the baseline climate scenario and the medium growth socio-economic scenario from a *Hierarchist* perspective. We take this as an exemplary baseline case with the basic setup to develop a range of possible adaptation pathways. The adaptation pathways (maps) are generated with the Pathways Generator developed by Deltares, which enables exploring potential pathways under various scenarios and supports figure printing. As you can see from the figure above, the map is quite intricate due to so many possible routes into the desired point in the future. Under the rules proposed in section 3.6, all the available pathway options are identified and outlined under this basic case. As can be found in Figure F.3, there are 104 sequences of actions, only 69 of which are pathways under the basic case. Besides, this figure also provides the descriptions of action elements in the sequences of actions and the corresponding sell-by dates in the context of the column.

When developing adaptation pathways with Pathway Generator, numerous actions, sequences of actions, and pathways are all typed in the "Action or Pathway" panel in the software, that is the reason why we not only have the pathways but also a large number of sequences of actions in Figure F.3. Pathways are sequences of actions that are able to meet the objectives over the entire planning time frame, while sequences of actions may not be pathways since they can be incomplete and only half-way from the desired destination. However, given different scenarios and changing conditions, it is possible to have some incomplete sequences of actions become adaptation pathways, or vise versa.

In addition to the baseline case shown in Figure 4.7 above as an example, we have also developed the Adaptation Pathways maps based on the median values of the sell-by dates of adaptation actions for all realizations in terms of one particular dimension, including *Hierarchist*, *Egalitarian*, *Individualist*, low socio-economic growth, medium socio-economic growth, high socio-economic growth, baseline climate scenario, G_H scenario, G_L scenario, W_H scenario, and W_L scenario. The figures of these adaptation pathways maps are provided in Figure F.1 in Appendix F. Comparing these resulting pathways maps, it is evident that different scenarios and changing conditions will influence the timing of when a strategy no longer meets the objectives, *i.e.* adaptation tipping points. Therefore, sets of different adaptation pathways arise from different climate, socio-economic and societal perspective scenarios, which are assembled into different Adaptation Pathways maps, implying the uncertainties for water management into the future. And a well-made Adaptation Pathways map presents not only the feasible strategy options to take, but also when and where the adaptation tipping points are reached and further interventions become necessary. It is not possible for the undertaken study to analyze all the crafted maps one by one. But it is necessary to find the commonalities in the pathways under all conditions. Finding the commonality asks for identifying the pathways that can succeed under all the conditions.

4.3.2 Identification of robust pathways

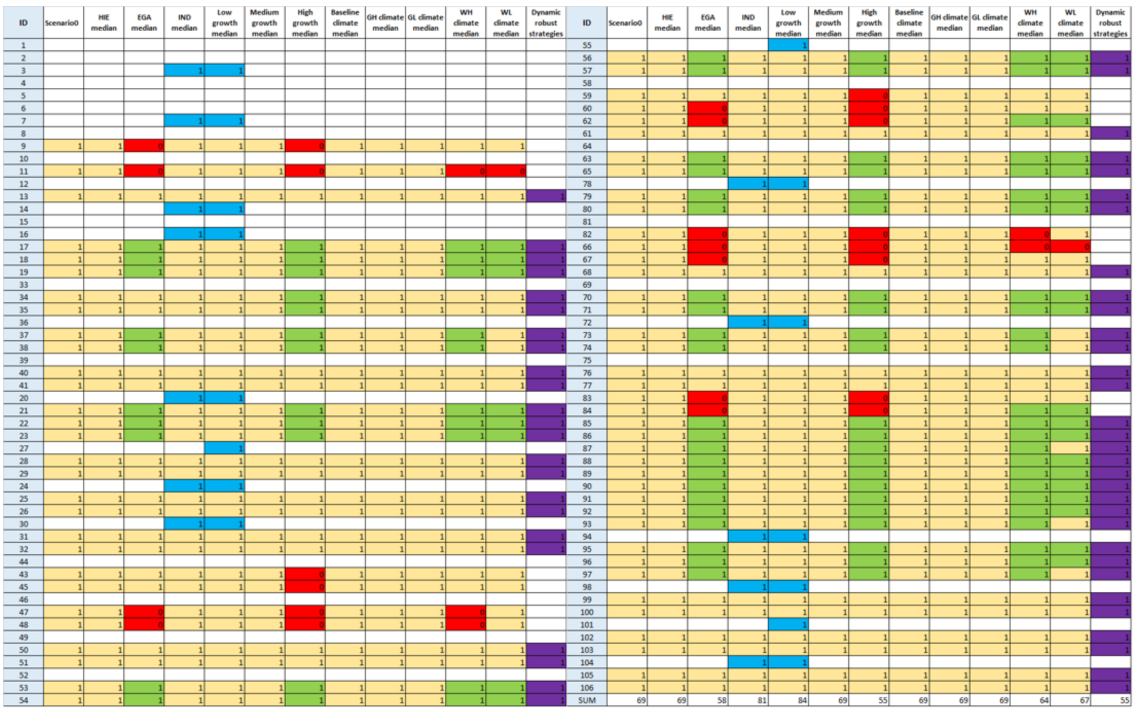


Figure 4.8: Identification of robust pathways under all conditions by comparing the applicability of pathways under different conditions, see figure F.2 for a detailed overview.

Figure 4.8 above shows the applicabilities of pathways derived from the baseline case (denoted as "Scenario0" in the figure) under other different dimensions. For a clearer view of the figure, please refer to Figure F.2 in Appendix F. As previously discussed, under the basic case, we have 104 sequences of actions, in which 69 are possible pathways. These 69 options are colored in yellow in the first column "Scenario0" in the figure. Besides the baseline case, we also develop Adaptation Pathways maps based on the median values of the sell-by dates for all realizations specific to other dimensions. We indicate the applicabilities of the initial 69 pathways under these different conditions as different columns in the above figure. Cell in yellow means the pathway is still viable under the current condition; Cell in red indicates the pathway is no longer feasible and reaches a dead-end which cannot be extended; Cell in green presents the pathways that can be improved with possible further inventions in order to meet the objective until 100 years; Cell in blue means the sequences of actions, which previously are incomplete, now become pathways under the current condition; Cells in purple outline the pathways that can succeed under all these conditions, therefore, are considered as (dynamic) robust pathways. If the color of the cell changes from yellow to green or even to red, it indicates it becomes harder (or even impossible) for the strategy to be feasible given the certain context. If the cell color turns from yellow to blue, it means the sequence of actions previously unable to achieve the goals now becomes a possible pathway.

As can be easily seen from this figure, the number of available pathway options is the smallest for the "High Growth — median" column (55) and for the "Egalitarian — median" column (58), and is the largest for the "Low Growth — median" column (84) and for the "Individualist — median" column (81). The difference in the numbers of possible pathways for the five climate scenarios is small, in which the W_H climate scenario has the greatest influences among them. This finding once again confirmed the conclusion drawn from the sensitivity analysis discussion in section 4.2, that, the socio-economic growth scenario and the societal perspective condition have greater influences on the timing of the adaptation tipping point (sell-by date) for an adaptation action then climate scenarios.

Figure 4.9 below shows the outlined robust pathways that can succeed under many possible futures. These robust pathways are not only resilient to the uncertain physical conditions due to climate change, but also to the uncertain societal conditions such as socio-economic growth and people's perspective. We plot the results in a fashion similar to the baseline case for the illustration purpose, but the timing of the adaptation tipping points of the actions should be subject to the corresponding conditions. Therefore, the figure is similar to the example figure 4.7, but it excludes the irrelevant and unrobust strategies. Despite the refinement on the pool of pathways, the map is still a little bit unreadable because of various sequences of actions. It is not possible to describe every storyline due to the limited pages. Hence, the pathways are discussed in a generalized manner here without diving into the details. Below are what we can learn from this map of adaptation pathways:

- Building a large water square in the beginning is a static robust strategy that can succeed over many futures and requires no other inventions. So if people want to solve the problem once for all and there is no budget or spatial planning constraints, they can take this action.

- First installing rain barrels on the private roofs, of which the capacity can be easily increased due to the modular structure, can manage the system under control up to decades of years. After that, adaptation measures with appropriate specifications,

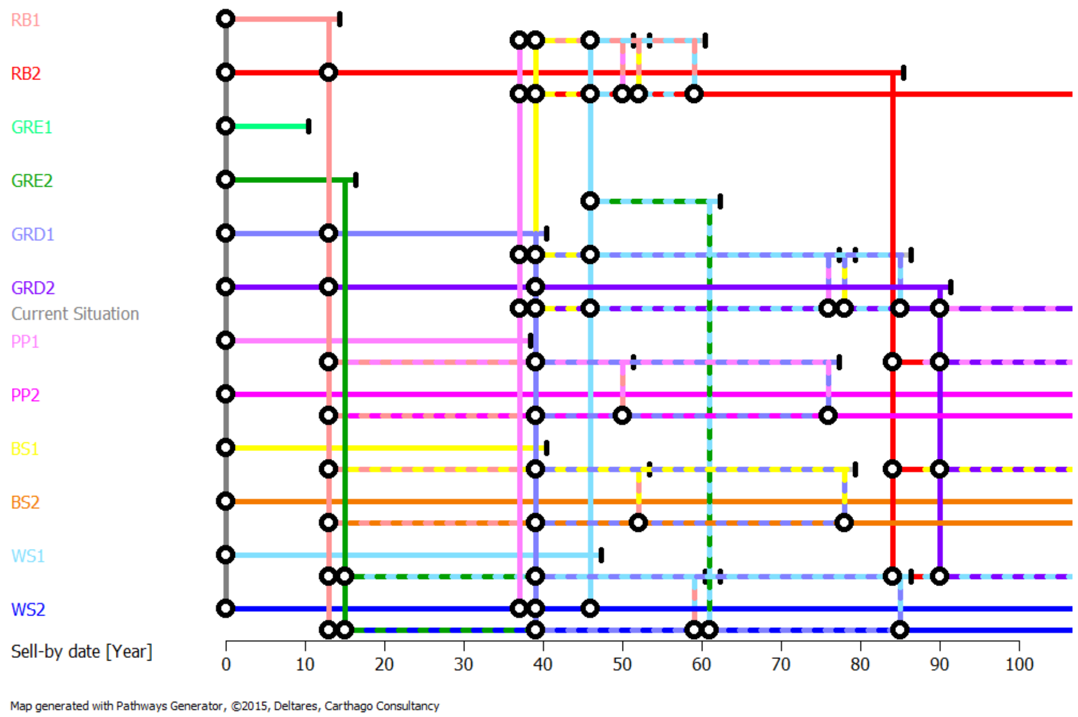


Figure 4.9: A map of 55 dynamic robust pathways outlined after the analysis, presented in the fashion similar to the basic case

such as porous pavement, bioswale, or water square can be constructed on the public places to extend the durability of the management strategy to 100 years. Besides, given mild conditions (*e.g. Individualist* perspective, low socio-economic growth, *etc.*), there is no further need for these measures on public spaces. This is a potential opportunity that we may benefit from uncertainties.

- A green roof with drainage delay can be deemed as a normal green roof plus a rainwater harvesting device. So actually, its efficacy is quite similar to a rain barrel. Therefore, the above conclusion also holds true to a green roof with drainage delay. Compared to a normal rainwater harvesting device, a green roof with drainage delay may be more expensive, less flexible and has additional requirements such as roof loads limits. Anyway, the cost-benefit is not the concern of the undertaken study. Implementing green roofs with drainage delay and later combining it with public measures when necessary is also a feasible strategy.

- A normal (extensive) green roof is not an efficient action to take, even it is an intensive green roof. Besides, it may arise the threats of future lock-ins. This is because an extensive green roof with large specification can only be combined with a large public water square in order to solve the problem for 100 years over many future scenarios. However, it is not always possible to have enough public space for a large water square. Therefore, building a large extensive green roof may lead to potential dead-ends in the future. The decommissioning of large extensive green roof for switching to a more effective measure can only be made against major consequences and therefore is considered as a lock-in situation.

- It is also possible to start from building measures on public places. If you build porous pavement or bioswale first, given the moderate to severe conditions, after certain decades of years, it has to be combined with rainwater harvesting on private rooftops in order to meet the objective over the entire planning time frame. But under mild conditions, a large porous pavement or bioswale can solely solve the problem, therefore, taking this action may seize some opportunities coming with adaptation. Besides, porous pavement has a similar effect as bioswale. However, if you opt to build a small water square first, later you can either combine it with rainwater harvesting on private roofs, or simply level up the water square to the large specification.

As the recap to the rules of developing pathways in section 3.6, it has been stated that a measure with the large specification cannot be lowered back to the small specification of itself, or be abandoned and removed due to the high associated costs and high societal impacts. It is to be questioned whether the adaptation measures on the public ground such as bioswale, porous pavements, and water squares can be easily intensified or not. But it seems logical that, the decentralized rainwater harvesting devices on privates places, especially the rain barrels (tanks, cisterns, *etc.*), are much more easily adaptable because they are modulated measures that allow conveniently increasing the adaptive capacity in a cascade manner. Therefore, installing rain barrels is a very flexible adaptation action that allows continuous adaption with only minor consequences without resulting in potential future lock-ins. It is also a no-regret action that is dynamic robust under various future conditions and has additional benefits. Compared to the rain barrel, green roof with drainage delay is also a possible action, but it is less flexible and is often only implemented with new building retrofitting plans. In terms of measures on public places, starting from building a small bioswale, porous pavement or water square which allows further extension is also a possible option, but it requires more discussions among all stakeholders and more detailed designs. Besides, the routing of the runoff to these less decentralized measures can also bring hidden problems. Therefore, we can draw the conclusion that it is recommended to make investments on the rainwater harvesting devices on private spaces in order to incorporate the efficiency and flexibility into the long-term adaptive stormwater management planning to mitigate the pluvial flooding.

Chapter 5

Conclusions and recommendations

5.1 Conclusions

The major goal of this master thesis is to realize a viable implementation of the adaptation pathway approach to develop robust adaptation pathways in order to support the first-level adaptive planning on urban pluvial flooding mitigation measures. This approach is illustrated based on a case study of Laakhaven, The Hague. The main research objective is divided into a few subquestions introduced in Chapter 1. Therefore, the conclusions of the undertaken study are summarized in the form of answers to the outlined research questions.

- In response to the research objective (iii):

  Q: Given the numerous types of urban adaptation measures, how to categorize and conceptualize these structural adaptation measures and later formulate them into the dynamic urban water balance model?

  A: Adaptation measures can be classified in the dimension of Storage-Discharge relationship, SuDS component representation, emptying mechanisms, installation location, *etc.*, which is talked in detail in section 3.2. Descriptions and conceptualizations of these measures are presented in Appendix A. Their setups in the Urbanwb model is recorded in the tables from A.2 to A.5.

  Q: With the massive simulation runs of various measures using long-term time series, can we confirm the validity of the empirical performance indicator (*i.e.* runoff frequency reduction factor) and the validity of this hydrological model?

  A: Almost all the results from the urban water balance model computed under different climates for various adaption measures seem to confirm this empirical relation of the *runoff frequency reduction factor*. The water balance is strictly closed for this model in all simulations. Therefore, this innovative performance indicator for the effectiveness of measures and the dynamic urban water balance model itself are valuable tools for the quick assessment of the adaptation measures when used appropriately.

  Q: What are the distinctions in the effectiveness of different adaptation measures, what factors potentially influence their efficacy, and what lessons can we learn from it regarding the operations and maintenance of adaptation measures?

A: The measures are differentiated based on the hydrological mechanisms, *e.g.* evaporation, infiltration, fast pumping, and drainage delay. The design storage capacity of the measure is important to its efficacy in stormwater runoff buffering, and the emptying mechanism of the measure is quite significant as well — how much room is available for the upcoming rainfall runoff as the antecedent condition. As such, the normal extensive green roof is not effective in stormwater runoff buffering since the stock is emptied through evapotranspiration only. Measure with decent storage and regulated discharge is usually more effective and preferred. For measures of this kind, more focus should be put on the humans' control routine on the measure (operation and management). Climate change will also influence the measure's effectiveness. The same measure can perform quite differently due to different climate variability.

- In response to the research objectives (i) and (ii):

Q: How to formulate the urban pluvial flooding problem and implement the Adaptation Pathway approach to develop adaptation pathways for the long-term adaptive planning of stormwater management measures for urbanized areas?

A: We implement the adaptation pathway approach with the risk-based way of thinking and the performance indicator called the *runoff frequency reduction factor* for the effectiveness of measures obtained with the urban water balance modeling as the critical part of the assessment model. In this way, we can determine the durability of numerous adaptation actions in consideration of the climatic, the socio-economic and the societal perspective uncertainties. The sell-by dates of these policy options are later used to assemble reasonable adaptation pathways maps under certain rules.

Q: Based on the resulting adaptation pathways generated with this first-level assessment, what lessons can we learn regarding the general directions in which the adaptation development should be focused.

A: Climate scenarios, socio-economic scenarios, and societal perspectives like people's risk perceptions are quite significant in determining the timing of adaptation tipping point for certain policy action, the latter two of which can sometimes have greater influences. In terms of the general directions of the urban pluvial flooding adaptation development, it is recommended to make investments on rainwater harvesting devices on private spaces. This is because rainwater harvesting is not only a flexible action that allows easy adaptation and avoids future lock-ins but also no-regret action that brings additional benefits and prevents some dormant problems of centralized measures. It can incorporate both the effectiveness and the flexibility into the management strategy to make it more dynamic robust thus successful over various future scenarios.

Q: Is this methodology theoretically sound? What are the advantages and limitations of the proposed methodology? Which parts are recommended to be improved for future studies?

A: The entire implementation methodology is theoretically viable, from the underlying thinking to the final results and conclusions. The advantage of the method is that it takes the risk-based way of thinking and deals with flood probability and potential damage separately. Compared to other case studies, the methodology is rather innovative, and we have shown the potential of this methodology to make a more complete and comprehensive study. The limitations of the method are mostly due to the simplifications and assumptions made. It is highly recommended in the future studies to improve especially the socio-economic scenario part of the simulation, where the potential damage is expressed as the compounding function of time, and to make more appropriate selections of measures, setup of measures, and other parameters and assumptions involved. Besides, the undertaken study does not give the ultimate answer but only a range of possible options. Therefore, the sub-selection of the preferred pathways can be a quite interesting separate topic.

5.2 Recommendations

The entire implementation example shown in this thesis is valid in terms of the requirements of the first-level assessment. The limitations are due to all the assumptions and simplifications made. But we are confident that the general directions on the conclusions are roughly right. In light of the limitations of the undertaken study, several recommendations are made for future researches:

- It is recommended to incorporate more transient climate scenarios generated with the Weather Generator in the assessment model in order to study the impacts of the climate variability.
- All the combinations of the climatic and socio-economic scenarios are not equally likely to happen. So the probability distribution of these scenarios can be studied.
- It is recommended to rethink about the package of measures to model and their corresponding setups including *e.g.* specifications.
- It is recommended to include the damage mitigation measures into the risk formula since they are an indispensable part of flood risk management.
- It is recommended to come up with better representation for the socio-economic uncertainties, for example, using Monte Carlo Simulation to model the damage growth rather that the specified constant growth rate.
- It is recommended to do more research on the people's risk perception for example through surveys to better represent their risk attitudes quantitatively.
- It is recommended to consider the implementation time (*e.g.* construction, decommission time) of measures in developing adaptation pathways using, for example, Exploratory Modeling and Analysis.
- After making a nice adaptation pathways map, the economic evaluation and sub-selection of pathways can be conducted through traditional NPV method and advanced real option analysis method that can calculate the benefits due to the engineering flexibility. Multi-criteria analysis on the selection of measures can also be

conducted. It is highly recommended to conduct an individual study on this to find the final answer.

Appendix A

Setup of Measures

Before implementing various measures in the Urbanwb model, descriptions and conceptualizations of these measures should be performed carefully. Theoretically, there can be endless design possibilities of urban adaptation measures for pluvial flooding mitigation purpose, since the structure, dimensioning and specifications of these measures can be arbitrarily chosen. Under a more realistic condition, urban adaptation measures shall be designed specially to suit the local context, of which the collaborative planning process involves the participation of various stakeholders from multiple disciplines like engineering and ecology, spatial planning and urban design, and policy and management (Voskamp and Van de Ven, 2015). Even in the practical case, usually a bunch of options can be available.

One important functionality of Measure module and basic Urbanwb model is to enable tuning the setup of measures, however, the undertaken study is not a practical urban design project, but a hypothetic study case that attempts to incorporate selections of urban adaptation policies with adaptive planning under uncertainties. Therefore, urban adaptation measures in question of the undertaken study are set up in a generalized manner and parameterized with some standardized settings. Consequently, similar results are expected for measures behaves similarly. Descriptions of measures reference some points from two books (Huber et al., 2010; Pötz et al., 2012) and two website — (Urban Green-Blue Grids) [1] and (ClimateAPP) [2]. For readability, in-table citations are omitted.

Runoff inflow area to a measure is the connected area to the measure. Runoff from connected paved area is first drained to a measure instead of directly flows to the sewer system. According to functionalities of a measure, water temporarily detained in the measure can evaporate, transpire, infiltrate, or be drained at a delayed or accelerated pace. Water under the normal control routine of the measure is called controlled runoff. Water exceeding the control capacity of the measure is called uncontrolled off, which is usually drained to the sewer system/surface water again. Effectiveness of a measure is evaluated based on the runoff reduction, i.e. how much controlled runoff is realized by this measure.

The model does not make a distinct differentiation between above-ground and underground measures, meaning that underground measures which require virtually no space at ground levels still need to be specify a relatively small surface area. If set up properly, it will not be a hindrance.

[1] https://nl.urbangreenbluegrids.com/
[2] http://climateapp.org/

AST ID	Measure	Model adjustment	Measure description and conceptualization
3	Adding trees to streetscape	**Location:** Open paved **Interception capacity:** 1.6 to 5 mm **Infiltration capacity:** 10.9 to 26.5 mm/d **Module:** Basic model	Adding green to streetscape is to incorporate green treens into the streetscape in the form of tree-lined lanes. It creates shade and enables evapotranspiration therefore has a cooling effect which helps alleviate heat island effect. The type of tree to be chosen should suit the local moisture system. Adding trees to streetscape is implemented with basic model. It is assumed that trees are planted every 30 meters along the sidewalk on open paved area. A tree block is deemed as an unpaved block, hence a new infiltration capacity for open paved area is recalculated as: $\frac{1}{30} \times 480 + \frac{29}{30} \times 10.9 = 26.5mm/d$.
4	Urban wetland	**Location:** Closed paved **Inflow area:** $10 \times A_{measure}$ **Storage capacity:** $H_{max} = 50 - 1000mm$ **Drainage resistance:** $2d, drain. = \frac{H_{act}}{2} mm/d$ **Module:** Measure	Urban wetland is a rainwater retention basin which has similar mechanisms as a wet pond's (ID 71). It can serve as both a runoff buffering system and a water purification system. It also brings added value like enhancing biodiversity and creating recreational area. Design and dimensioning of an urban wetland depend on the buffering capacity and the contamination level. Usually 10-15% of the connected area is a suitable area of a wetland to ensure sufficient storage capacity to cope with heavy precipitation events. Compared to natural wetlands, flow regime in urban wetlands is more artificially controlled to sustain less dynamism. Urban wetland is implemented as a 2-layer structure with Measure module. Interception layer is a pseudo layer. In the bottom layer, a controlled runoff is defined to represent the drainage at a delayed pace. Recharge to groundwater is constrained since urban wetland is usually applied at areas where groundwater table is relatively high or where there is a low-permeability strata limiting the interactions between aquifer and wetland, otherwise urban wetland is under the pressure of depletion.
6	Bioswale (with drainage)	**Location:** Closed paved **Inflow area:** $10 \times A_{measure}$ **Storage capacity:** $H_{max} = 50 - 1000mm$ **Percolation resistance:** $2d, prec. = \frac{H_{act}}{2} mm/d$ **Module:** Measure	A bioswale (Wadi) is a vegetated ditch on a porous bottom. It is an infiltration installation. Runoff from roofs and roads is directed to the bioswale via above-ground gutters or ditches instead of entering the sewer system. Bioswale contains two layers — top layer is enhanced soil aggregate with vegetation and bottom layer is a gravel base packed in clogging-proof geotextile with a perforated overflow underdrain connected to the sewer system. An overflow gate linked to the drainpipe is placed on the surface to incorporate larger storm events. If the drain and overflow both fill up, bioswale is then turned into an above-ground conveyance system directly connected to the surface water, and this is designed to occur only once every 25 years. Evapotranspiration is encouraged in the soil layer, and roots can suck up water from gravel base for more evaporation. Bioswale systems are suitable for areas with porous soil type and relatively low groundwater table to ensure sufficient room for infiltration. It is implemented as a 3-layer structure with Measure module. Bioswale is an excellent instrument that not only buffers runoff and increases infiltration but also enhances biodiversity.

10	Deep groundwater infiltration	**Location:** Entire area **Equivalent to:** Increasing pump capacity **Module:** Basic model, SDF-curve	Deep groundwater aquifers are used in many areas as a source of water. Recharging deep groundwater reservoir to avoid depletion is necessary for sustainable use. Rain water is harvested and infiltrated through deep wells to recharge the aquifer. Since deep groundwater is an external exchange of the model, this measure can be considered equivalent to increasing pump capacity to outside. Hence, deep groundwater infiltration is implemented with basic model and SDF-curve module.
11	Ditches	**Location:** Closed paved **Inflow factor:** $10 \times A_{measure}$ **Storage capacity:** $H_{max} = 50 - 1000 mm$ **Drainage resistance:** $2d, drain. = \frac{H_{act}}{2} mm/d$ **Module:** Measure	A ditch is a small to moderate depression built to channel water for above-ground drainage to surface water alongside roadways or for crops irrigation around farms. In that case, constructing a ditch can be considered equivalent to "creating extra open water" (ID 19). However a ditch in the urban context is usually defined as an infiltration installation. During rainfall events, runoff from connected area is drained through gutters into a ditch, temporarily detained and slowly infiltrates there. Water exceeding storage capacity of a ditch overflows to the surface water. Thus a ditch is implemented as a 2-layer structure with Measure module. Interception layer is a pseudo layer whereas bottom layer allows limited percolation which is modeled as the controlled runoff to groundwater. Overflow from the bottom storage layer is led to the surface water. Please note that even though a preset percolation to groundwater can be defined relevant in the Measure module, which by assumption is determined by the saturated permeability of the soil and available room for percolation plus dynamic groundwater level if defined relevant, percolation is usually conceptualized by the modeler as a controlled runoff driven by drainage level and resistance. This is due to two reasons — the emptying routine of a drainage delay or an infiltration installation is usually defined at the design, construction and operation stage, in a manner that the system capacity is emptied within a certain time range and stock drains more quickly under higher head difference; water jamming in the soil surroundings near the measure bottom decelerates the rate of percolation. Drainage resistance equal to 2d is just a standardized setting. Setup of measures for a more practical and ad hoc use requires specific information and expert judgment. This point is not elaborated repeatedly for the rest of relevant measures.
14	Green facade	**Location:** Paved roof **Interception capacity:** 1.6 to 5 mm **Module:** Basic model	A green facade is created to adorn building facade with climbing plants. Three types of plants are discerned: self-climbing plants rooted in soil beds at the structure base, climbing plants grew in elevated planters at intermediate levels, or hanging plants grew from pots on rooftops. It is assumed that a green facade simply slightly increases interception storage on the roof thus is implemented with basic model by varying predefined interception storage capacity on paved roof.

16	Green roof (extensive)	**Location:** Paved roof **Inflow area:** $1 \times A_{measure}$ **Growing medium storage capacity:** 5-100 mm **Module:** Measure	A green roof (extensive) is a building roof covered with plants, consisting of a vegetation layer, a thin substrate layer and a small drainage layer placed over a waterproofing membrane. It is an evapotranspiration installation atop buildings. Moss/sedum plants are suitable vegetation since they are resistant to prolonged dry spells due to their water-storing capacity. Herbs and grasses can be supplementary. Compared to an intensive green roof, an extensive green roof has a lighter and less diverse vegetation layer thus has lower demands for roof loads and regular maintenance. The porosity of the growing medium in the substrate layer is around 0.3, so it creates storage to accommodate stormwater and reduce runoff during rainfall events. Water exceeding the storage capacity is instantaneously drained through the drainage layer into the sewer system regardless of capacity to avoid plants suffocation during submergence. The stock in the soil layer is only emptied by gradual evapotranspiration from the root zone. Hence the rainwater runoff attenuation effect of an extensive green roof largely dependents on the antecedent conditions. A green roof can be more efficient when adapting to regular flash storms other than continuous storms and extreme events. A green roof (extensive) is therefore implemented as a 3-layer structure with Measure module. Calculation formulas are tailored for measures akin to green roofs to ensure no surface submergence. Evapotranspiration happens in the top layer. When potential evapotranspiration rate exceeds transpiration from the top layer, roots will suck up water from bottom drainage layer for further transpiration. Contrary to a green roof (with drainage delay) (ID 42), an extensive green roof has very limited storage in the discharge layer and drains excessive water that has not been absorbed by the substrate layer instantaneously to sewer system. As such, it is less effective in rainwater buffering than an intensive green roof. A green roof (extensive) also helps to cool the air, enhance biodiversity and increase livability.
19	Create extra surface water	**Location:** Closed paved part becomes open water **Surface water percentage:** 1% to 5% **Module:** Basic model	Wetter winters and drier summers are expected in the future according to KNMI'14 projections. Therefore seasonal storage becomes a practical solution to compensate for possible water shortages in the summer with storage of water surpluses in the winter. Additional storage volume in surface water can be realized by two means — creating more space for open water or allowing greater fluctuations in water levels. The latter option puts higher requirements on the embankments and is hostile to flora along the banks. Having more surface water serves to create extra storage volume in the meanwhile water level fluctuation limit remains unchanged. Creating extra surface water is implemented with basic model by converting part of closed paved area to surface water.

20	DIT drain	**Location:** Closed paved **Inflow factor:** $500 \times A_{measure}$ **Storage capacity:** $H_{max} = 1000mm$ **Percolation capacity:** $2d, perc. = \frac{H_{max}}{2} mm/d$ **Module:** Measure	A DIT (Drainage-Infiltration-Transport) drain is an underground perforated horizontal pipe drainage system. It is an underground infiltration installation. A DIT drain is usually applied at places where there is inadequate above-ground space for above-ground infiltration measures such as bioswale, since it requires virtually no space at ground level. A DIT drain can also be employed at areas where the ground cover has an insufficient permeability factor. It facilitates water infiltration into the surrounding soil while transporting the flow, thus reduces stormwater load on the sewer system. During heavy storm events, after surrounding soil gets completely saturated and infiltration stops, the DIT drain works as an emergency overflow system that diverts the water to surface water or to rainwater sewage system. The storage of a DIT drain is 2 mm averaged over the connected area (considered as combined sewer system). Urbanwb model does not make allowance for a distinct differentiation between above-ground measures and underground ones. Therefore, since a DIT drain occupies very limited space at ground level, it is modeled as a structure of 1000 mm design depth with inflow factor equal to 500. A DIT drain is implemented as a 2-layer structure with Measure module. Infiltration to surrounding soil is modeled as a drainage delay controlled runoff and overflow from the bottom layer enters the sewer system.
22	Infiltration fields	**Location:** Closed paved **Inflow area:** $5 \times A_{measure}$ **Storage capacity:** $H_{max} = 25-500mm$ **Percolation resistance:** $2d, prec. = \frac{H_{act}}{2} mm/d$ **Module:** Measure	Infiltration field is an infiltration strip with above ground storage. It is similar to a ditch that combines water detention and infiltration. These infiltration measures with above-ground storage basically have the same mechanisms. The difference lies in the dimensioning, which depends on the local context and the design standard like buffering capacity. Infiltration field is usually constructed next to paved surfaces to buffer rainwater runoff through infiltration. Roots and creature activities in the subsurface ensure that the infiltration capacity of the ground is retained. An infiltration field is implemented as a 2-layer structure with Measure module. A relatively large interception capacity is defined in the interception layer to represent its above-ground storage. Infiltration is modeled as a drainage delay controlled runoff to groundwater. Uncontrolled overflow is led to the sewer system or to the surface water. Infiltration fields can be incorporated in public green space to enhance biodiversity and livability.
25	Urban forest	**Location:** Open paved **Module:** Basic model	An urban forest is a collection of woody plants growing around human settlements in a city neighborhood. Besides stormwater buffering with its natural drainage system, it has multiple functionalities like heat stress alleviation, air purification, recreational space, biodiversity enhancement and etc. Urban forest is implemented with basic model by specifying total surface area as unpaved area.

26	Permeable pavement system (infiltration)	**Location:** Open paved: **Interception capacity:** 1.6 to 100 mm **Infiltration capacity:** 10.9 to 2400 mm/d **Module:** Basic model	Permeable pavements contain porous material through which water can pass (*e.g.* pervious concrete, porous asphalt) or spaced nonporous material that allows water infiltrating between the cracks (*e.g.* paving stones, open cell concrete blocks, grass concrete pavers). These paving materials have several favorable aspects: infiltrating rainwater into the ground, recharging the groundwater and relieving the sewer system. It is usually applied at places like footpaths, playgrounds and forest service roads. Normally, permeable pavement is seldom used for intensively-used roads or car parks because of unbearable large loads and potential risk of pollution unless special materials is available. Permeable pavement is implemented with basic model by specifying the interception capacity and infiltration capacity of open paved area with large values.
29	Rain barrel	**Location:** Paved roof **Inflow area:** $20 \times A_{measure}$ **Storage capacity:** $H_{max} = 100 - 2000 mm$ **Discharge capacity:** $Q_{const.} = \frac{H_{max}}{2} mm/d$ **Module:** Measure	A rain barrel (rainwater tank) is a household rainwater harvesting device. It is a decentralized water detention installation. It collects and stores rainwater runoff from rooftops via gutters during a rainfall event for reuse purposes, *e.g.* watering gardens, washing cars, flushing toilets and etc. Normally, rain barrels installed for households are not overly large, thus an overflow system is needed. During rainfall events, a rain barrel is filled up to its storage limit, then the excessive water overflows to the sewer system. The stock in the barrel is released through taps between rainfall events to serve for different purposes of use, to maximize storage capacity for incoming events and to avoid problems like bad odor and mosquito caused by water stagnancy. A rain barrel can be completely emptied quickly through taps or even pumps. Since people's control routine of a rain barrel is difficult to model, we assume that full water stock is released within 2 day at a constant discharge rate. A rain barrel is implemented as a 2-layer structure with Measure module. Interception layer is a pseudo layer. Bottom layer has a constant controlled runoff that empties the system capacity within 48 hours. This controlled runoff is directed to the surface water therefore reducing the pressure on the sewer system. Uncontrolled overflow flows to sewer system.
32	Storage by creating extra freeboard	**Location:** Open water **Target water level:** 1.03 to 1.53 m-SL **Module:** Basic model, SDF-curve	Creating extra freeboard is an alternative to creating more open water space for the purpose of realizing additional storage volume (ID 19). It handles greater fluctuations in water levels to allow more storage capacity with virtually no extra needs for additional surface area. However this measure will place greater demands on the banks and is inapplicable in case of a high groundwater level. Adding freeboard is implemented with basic model by lowing the target water level from 1.03 m-SL to 1.53 m-SL. Since it is a measure aiming at increasing overall system storage capacity, the results of SDF-curve can also be useful.

33	Infiltration boxes	**Location:** Closed paved **Inflow area:** $10 \times A_{measure}$ **Storage capacity:** $H_{max} = 50 - 1000mm$ **Percolation resistance:** $2d, perc. = \frac{H_{act}}{2} mm/d$ **Module:** Measure	An infiltration box (infiltration crate) is an underground infiltration installation that buffers stormwater and allows it to gradually infiltrate into the soil. Compared to above-ground infiltration installation like bioswale and ditches, infiltration boxes require virtually no above-ground space and offer more storage volume. Infiltration boxes are usually installed at places where the groundwater level is relatively low and soil is sufficiently permeable. They can be used under roads, sports court and parking garages for urbanized areas of small to moderate scope. Infiltration boxes are usually comprised of light synthetic boxes with a high void ratio thus have a large storage capacity. The rainwater runoff is directed into the infiltration box through a pipe collector and temporarily stores there where the water is released into the groundwater gradually. An infiltration box is implemented as a 2-layer structure with Measure module. Since, it is beneath ground surface, interception layer is a pseudo layer. Bottom layer has infiltration to groundwater modeled as a drainage delay controlled runoff. Overflow is led to the sewer system. Apart from buffering stormwater, extra infiltration into groundwater is beneficial to drought damage reduction, land subsidence alleviation and etc.
40	Water roof	**Location:** Paved roof **Inflow area:** $1 \times A_{measure}$ **Storage capacity:** 5-100 mm **Module:** Measure	A water roof (blue roof) temporarily stores rainwater on the roof. Depending on the purposes, water roofs can be categorized into two types — water roofs for rainwater detention and water roofs for evaporative cooling. A rainwater detention roof is designed to buffer a fraction of rainwater by slightly elevating the overflow level. The stock is drained off at a delayed pace within a short period of time after the rainfall to maximize storage capacity for incoming storm events. Hence a rainwater detention blue roof behaves similarly to an intensive green roof. A water roof for evaporative cooling is different from a detention roof in that it retains the water on rooftop for gradual evaporation only. Since evaporation absorbs latent heat of vaporization, it cools the surrounding environment. A water roof for evaporative cooling is comparable to an extensive green roof. By the way, a new water roof which is embedded with an electronic real-time-control system would make it possible to achieve both functions. Unlike a water pond, water roofs only need to store precipitation falling on the roofs. Besides, the roof weight limit must be taken into account to ensure safety. As such, the storage depth needs not be so large as that in water ponds. Water exceeding the storage capacity overflows to the sewer system. Here, a water roof is narrowly defined as an evaporative cooling roof. It is implemented as a 1-layer structure with Measure module. Storage in the interception layer is only emptied through evaporation thus it can be foreseen that it is less efficient in terms of stormwater buffering than a detention roof.

41	Water square	**Location:** Closed paved **Inflow area:** $20 \times A_{measure}$ **Storage capacity:** $H_{max} = 100 - 2000mm$ **Discharge capacity:** $Q_{const.} = \frac{Hmax}{2} mm/d$	A water square is a rainwater detention infrastructure which at the same time incorporates multiple urban functions such as entertainment areas, green areas, aesthetic landscape and etc. It has been most often used in densely built-up inner-city areas where the groundwater level is too hight to allow sufficient infiltration and where there is little room available for single-functional buffering facilities. In case of heavy rainfall, runoff from surrounding area is led to the square via the sewer system or open drains, and then the square is submerged from its lowest point up to being completely filled. The great buffering height allows substantial fluctuations in water levels thus offering a considerably large storage capacity. The careful, functional and aesthetic design of water squares draws a great deal of attention. However, great storage height, low bottom level and high groundwater table indicate the square's lower part is usually below phreatic table. Hence, to prevent groundwater seepage, a water square is designed to be waterproof. Consequently, apart from large loads to the ground under the condition of saturation, the upward forces should also be given serious consideration, which may add considerable construction costs. Besides design and construction, maintenance and management are important as well. Because the pollutants such as mud, litter, leaves and branches brought by the rainwater have to be cleaned away immediately after the square is drained off to make sure that the square becomes attractive and usable again. A water square is implemented as a 2-layer structure with Measure module. Interception layer is a pseudo layer. Bottom layer represents the main body of a water square. Since the bottom is sealed, direct percolation to groundwater is not possible. Regular water release from the water square through pumping is a controlled runoff. The controlled runoff is modeled as a constant discharge that empties the system capacity within 48 hours and flows to open water. Uncontrolled overflow is drained to the sewer system. A water square, as an innovative multi-functional rainwater detention installation, efficiently buffers stormwater and meanwhile improves the quality of urban public space. A successful design of a water squares stems from an intensive participation process involving various stakeholders. Follow-up maintenance and management is crucial to ensure the functionality and attractiveness of a water square.

42	Green roof (with drainage delay)	**Location:** Paved roof **Growing medium storage capacity**: 30 mm **Drainage layer storage capacity:** $H_{max} = 5 - 100mm$ **Drainage resistance:** $2d, drain. = \frac{H_{act}}{2} mm/d$ **Module:** Measure	A green roof with drainage delay is a green roof that has relatively decent storage capacity in the drainage layer for irrigation purpose. It can refer to intensive green roofs, garden roofs and etc. Compared to an extensive green roof, a green roof with drainage delay usually has a thicker substrate layer which depends on the desired vegetation types. Heavier substrate layer and larger storage in drainage layer indicate more loads on the building. Regular irrigation is required to maintain the vegetation, making it necessary to harvest rainwater which is not absorbed by substrate layer inside the drainage layer for reuse. A green roof with drainage delay is implemented as a 3-layer structure with Measure module. Vegetated surface provides certain interception capacity in the interception layer. Top layer represents the growing medium layer where the water stock is emptied by evapotranspiration. Water surplus in the top layer percolates downward to the bottom drainage layer where the water is modeled to be drained at a delayed pace. Uncontrolled overflow in the bottom layer flows to the sewer system.
46	Underground storage tank	**Location:** Closed paved **Inflow area:** $20 \times A_{measure}$ **Storage capacity:** $H_{max} = 100 - 2000mm$ **Discharge capacity:** $Q_{const.} = \frac{Hmax}{2} mm/d$ **Module:** Measure	An underground storage tank is a storage installation. It can be deemed as an underground rain barrel. Underground storage tanks are designed to store excess runoff in urban drainage systems during wet periods. It can have massive forms depending on the local context. It can be a large concrete off-line vault underneath a parking garage. Or it can be underground crates beneath a sport field. The basic ideas behind these many possibilities of underground storage tanks are the same — to create additional underground storage volume for rainwater buffering during wet periods without taking much space at surface level. These underground storage installation requires virtually no surface area at ground level. An underground storage tank is implemented as a 2-layer structure with Measure module. Interception layer is a pseudo layer. Bottom layer represents the main body of a storage tank where controlled runoff empties the system at a constant discharge rate. It is assumed that the full stock shall be emptied within 48 hours. Uncontrolled overflow in the bottom storage layer is drained to the sewer system.

71	Wet pond	**Location:** Closed paved **Inflow area:** $10 \times A_{measure}$ **Storage capacity:** $H_{max} = 50 - 1000mm$ **Percolation capacity:** $2d, perc. = \frac{H_{act}}{2} mm/d$ **Module:** Measure	A wet pond remains a permanent pool of water with minor function of water pre-purification. It is a water retention installation that buffers rainwater runoff and allows it to drain off gradually. Urban wet ponds are often combined with underground storage installations for extra water supplements during long dry spells. An artificial wet pond can be designed to have an almost natural appearance thus brings a good deal of ecological and aesthetic value. Because a wet pond is often used to capture a large amount of stormwater runoff including the first flash from intensively-used roads and car parks, the water is moderately or sometimes extremely polluted thus needs pre-purification. So the bottom of a wet pond is sealed by means of a film in order to prevent direct infiltration of polluted water. Wet ponds remove pollutants through biological uptake processes and sedimentation. When there is no surface water in vicinity as recipient and local infiltration is impossible, the overflow will then be connected to the sewer system. A wet pond is modeled as a 2-layer structure with Measure module. Interception layer is a pseudo layer. In the bottom layer, there is a reference water level functioning as the drainage level above which the excessive water will be drained to surface water or percolate to groundwater. Hence the controlled runoff is determined by head difference and drainage resistance. When there is massive inflow to the wet pond as a result of extreme storm events, water exceeding the storage capacity overflows to the sewer system.
82	Gravel layers	**Location:** Closed paved **Inflow area:** $10 \times A_{measure}$ **Storage capacity:** $H_{max} = 50 - 1000mm$ **Drainage resistance:** $2d, drain. = \frac{H_{act}}{2} mm/d$ **Module:** Measure	A gravel layer is an underground layer or shaft packed with gravel. It is an infiltration installation. Runoff is led into this layer where it infiltrates to groundwater. Gravel layer can be applied at places where there is insufficient room for above-ground infiltration installations and where the ground has an insufficient permeability factor. Relatively large porosity of gravel layer creates additional underground storage to temporarily capture the rainwater runoff and allow it slowly infiltrates. A gravel layer is implemented as a 2-layer structure with Measure module. Interception layer has a great infiltration capacity. Infiltration to groundwater is modeled as a controlled runoff in the bottom layer, which is dependent on drainage level and drainage resistance.

90	Porous pavement	**Location:** Closed paved **Inflow area:** $1 \times A_{measure}$ **Storage capacity:** $H_{max} = 5 - 100mm$ **Percolation resistance:** 2d, $perc. = \frac{H_{act}}{2} mm/d$ **Module:** Measure	Porous pavements is made up of porous material through which water can pass. It is similar to permeable pavement system (infiltration) (ID 19), but puts an accent on the available storage capacity. Porous pavement makes sure that the rainwater being absorbed into the ground, saturated zone being replenished with extra infiltration and stress put on the sewer system being relieved. Porous pavements has a permeable surface layer through which water quickly infiltrates into the ground. Beneath the surface paver, an underground storage layer consisting of coarse aggregate like sand and gravel creates considerable storage volume and encourages gradual infiltration of water stock. Porous pavement is implemented as a 2-layer structure with Measure module. Interception layer is modeled in a manner that all water infiltrates into the bottom layer with no difficulty. In the bottom layer, percolation to groundwater is relevant and is modeled as a controlled runoff to groundwater. When the storage layer is fully filled, excessive water overflows to the sewer system.
91	Remove pavement to plant green	**Location:** Open paved **Module:** Basic model	Remove pavement to plant green meaning replacing hard surface that is unnecessarily paved with vegetated surface. Hard paving surfaces dry out quickly and have no cooling capacity. Vegetated ground improves surface infiltration capacity. Taller plants with strong roots make the ground more porous thus increases ground's absorption capacity. Consequently, less paving surface and more unpaved vegetated surface bring a few benefits like increasing infiltration, recharging groundwater, evaporative cooling, enhancing biodiversity and etc. Remove pavement to plant green is implemented with basic model by converting total open paved area to unpaved area.
45	Hollow road	**Location:** Closed paved **Inflow area:** $1 \times A_{measure}$ **Storage capacity:** $H_{max} = 5 - 100mm$ **Drainage resistance:** 2d, $drain. = \frac{H_{act}}{2} mm/d$ **Module:** Measure	A hollow road is a road of a hollow shape or a flat road with raised curbs, the idea of which is to temporarily detain water directly on the road instead of only in gutters. Therefore, it has a larger storage and discharge capacity than normal gutters. However, splashing water can be a nuisance to bikes and cars running on these sunken channels when it rains. That is the reason why a hollow road is not applicable in all situations and is especially suitable only in sub roads. A hollow road is implemented as a 2-layer structure with Measure module. Interception layer is a pseudo layer. Bottom layer has a controlled runoff to the sewer system dependent on drainage level and resistance, which drains at a delayed pace.

Table A.1: Descriptions, conceptualization and model adjustments of 26 measures in AST

Table A.2: Setup of measures (AST ID 4, 6, 11, 16)

Measure AST ID	4	6	11	16
Measure name	Urban wetland	Bioswale (with drainage)	Ditches	Green roof (extensive)
Location	CP	CP	CP	PR
Inflow factor	10	10	10	1
Measure area [m^2]	1595	1595	1595	47270
Measure inflow area [m^2]	15950	15950	15950	47270
Number of layers (1,2 or 3)	2	3	2	3
EV (evaporation)	0	1	0	1
ET (evapotranspiration)	1	1	1	1
IN (infiltration)	0	1	1	0
DD (delayed drainage)	1	1	1	0
FP (fast pumping)	0	0	0	0
Surface overflow to	SWDS	SWDS	OW	SWDS
Bottom controlled runoff to	OW	GW	GW	SWDS
Bottom overflow to	SWDS	SWDS	OW	SWDS
Interception capacity [mm]	0	20	0	5
Infiltration capacity [mm/d]	1000000	4800	1000000	5760
Top layer area [m^2]	1595	1595	1595	47270
Top layer storage capacity [mm]	0	100	0	[5,10,20,30,40,50,100]
Top layer infiltration capacity [mm/d]	0	480(0)	0	5760
Bottom layer area [m^2]	1595	1595	1595	47270
Bottom storage range (min,dflt,max)	(100,300,750)	(100,200,500)	(500,750,1000)	5
Array of values to run in Urbanwb [mm]	[50,100,200,300,400,500,1000]	[50,100,200,300,400,500,1000]	[50,100,200,300,400,500,1000]	5
Percolation to GW	No	No	No	No
Evapotranspiration from bottom layer	Yes	Yes	Yes	Yes
Controlled runoff type (0-flux, 1-level)	1	1	1	0
Flux [mm/d]	0	0	0	5760
Drainage level [mm]	0	0	0	0
Drainage resistance [d]	2	2	2	0
Initial bottom layer storage [mm]	0	0	0	0
Measure evaporation factor [-]	1	0.9	1	0.9
Void ratio [-]	1	0.3	1	0.3
Effective depth [mm]	[5,10,20,30,40,50,100]	[5,10,20,30,40,50,100]	[5,10,20,30,40,50,100]	[5,10,20,30,40,50,100]

Table A.3: Setup of measures (AST ID 20, 22, 29, 33)

Measure AST ID	20	22	29	33
Measure name	Drainage-Infiltration-Transport (DIT) drain	Infiltration fields	Rain barrel	Infiltration box
Location	CP	CP	PR	CP
Inflow factor	500	5	20	10
Measure area [m^2]	31.9	3190	2363.5	1595
Measure inflow area [m^2]	15950	15950	47270	15950
Number of layers (1,2 or 3)	2	2	2	2
EV (evaporation)	0	1	0	1
ET (evapotranspiration)	0	1	0	0
IN (infiltration)	1	1	0	1
DD (delayed drainage)	1	1	0	0
FP (fast pumping)	0	0	1	0
Surface overflow to	SWDS	SWDS	SWDS	SWDS
Bottom controlled runoff to	GW	GW	OW	GW
Bottom overflow to	SWDS	SWDS	SWDS	SWDS
Interception capacity [mm]	0	20	0	0
Infiltration capacity [mm/d]	1000000	4800	1000000	1000000
Top layer area [m^2]	31.9	3190	2363.5	1595
Top layer storage capacity [mm]	0	0	0	0
Top layer infiltration capacity [mm/d]	0	0	0	0
Bottom layer area [m^2]	31.9	3190	2363.5	1595
Bottom storage range (min,dflt,max)	(1000)	(50,150,500)	(100,1000,1500)	(200,400,1200)
Array of values to run in Urbanwb [mm]	[1000]	[25,50,100,150,200,250,500]	[100,200,400,600,800,1000,2000]	[50,100,200,300,400,500,1000]
Percolation to GW	No	No	No	No
Evapotranspiration from bottom layer	No	Yes	No	No
Controlled runoff type (0-flux, 1-level)	0	1	0	1
Flux [mm/d]	[500]	0	[50,100,200,300,400,500,1000]	0
Drainage level [mm]	0	0	0	0
Drainage resistance [d]	0	2	0	2
Initial bottom layer storage [mm]	0	0	0	0
Measure evaporation factor [-]	1	0.9	1	1
Void ratio [-]	1	1	1	1
Effective depth [mm]	[2]	[5,10,20,30,40,50,100]	[5,10,20,30,40,50,100]	[5,10,20,30,40,50,100]

Table A.4: Setup of measures (AST ID 40, 41, 42, 46)

Measure AST ID	40	41	42	46
Measure name	Water roof	Water square	Green roof (with drainage delay)	Underground storage tank
Location	PR	CP	PR	CP
Inflow factor	1	20	1	20
Measure area [m^2]	47270	797.5	47270	797.5
Measure inflow area [m^2]	47270	15950	47270	15950
Number of layers (1,2 or 3)	1	2	3	2
EV (evaporation)	1	0	1	0
ET (evapotranspiration)	0	1	1	0
IN (infiltration)	0	0	0	0
DD (delayed drainage)	0	0	1	0
FP (fast pumping)	0	1	0	1
Surface overflow to	SWDS	SWDS	SWDS	SWDS
Bottom controlled runoff to	SWDS	OW	OW	OW
Bottom overflow to	SWDS	SWDS	SWDS	SWDS
Interception capacity [mm]	[5,10,20,30,40,50,100]	0	5	0
Infiltration capacity [mm/d]	0	1000000	5760	1000000
Top layer area [m^2]	47270	797.5	47270	797.5
Top layer storage capacity [mm]	0	0	30	0
Top layer infiltration capacity [mm/d]	0	0	5760	0
Bottom layer area [m^2]	47270	797.5	47270	797.5
Bottom storage range (min,dflt,max)	0	(100,750,1200)	(5,30,100)	(500,1500,5000)
Array of values to run in Urbanwb [mm]	0	[100,200,400,600,800,1000,2000]	[5,10,20,30,40,50,100]	[100,200,400,600,800,1000,2000]
Percolation to GW	No	No	No	No
Evapotranspiration from bottom layer	No	Yes	Yes	No
Controlled runoff type (0-flux, 1-level)	0	0	1	0
Flux [mm/d]	0	[50,100,200,300,400,500,1000]	0	[50,100,200,300,400,500,1000]
Drainage level [mm]	0	0	0	0
Drainage resistance [d]	0	0	2	0
Initial bottom layer storage [mm]	0	0	0	0
Measure evaporation factor [-]	1	1	0.9	1
Void ratio [-]	1	1	0.3	1
Effective depth [mm]	[5,10,20,30,40,50,100]	[5,10,20,30,40,50,100]	[5,10,20,30,40,50,100]	[5,10,20,30,40,50,100]

Table A.5: Setup of measures (AST ID 71, 82, 90, 45)

Measure AST ID	71	82	90	45
Measure name	Wet pond	Gravel layer	Porous pavement	Hollow road
Location	CP	CP	CP	CP
Inflow factor	10	10	1	1
Measure area [m^2]	1595	1595	15950	15950
Measure inflow area [m^2]	15950	15950	15950	15950
Number of layers (1,2 or 3)	2	2	2	2
EV (evaporation)	0	1	1	0
ET (evapotranspiration)	1	1	0	1
IN (infiltration)	0	1	1	0
DD (delayed drainage)	1	1	1	1
FP (fast pumping)	0	0	0	0
Surface overflow to	SWDS	SWDS	SWDS	SWDS
Bottom controlled runoff to	GW	GW	GW	OW
Bottom overflow to	SWDS	SWDS	SWDS	SWDS
Interception capacity [mm]	0	0	1.6	0
Infiltration capacity [mm/d]	1000000	1000000	1000000	1000000
Top layer area [m^2]	1595	1595	15950	15950
Top layer storage capacity [mm]	0	0	0	0
Top layer infiltration capacity [mm/d]	0	0	0	0
Bottom layer area [m^2]	1595	1595	15950	15950
Bottom storage range (min,dflt,max)	(1100,1300,2000)	(100,300,500)	(5,30,100)	(5,30,100)
Array of values to run in Urbanwb [mm]	[1050,1100,1200,1300,1400,1500,2000]	[50,100,200,300,400,500,1000]	[5,10,20,30,40,50,100]	[5,10,20,30,40,50,100]
Percolation to GW	No	No	No	No
Evapotranspiration from bottom layer	Yes	Yes	No	Yes
Controlled runoff type (0-flux, 1-level)	1	1	1	1
Flux [mm/d]	0	0	0	0
Drainage level [mm]	1000	0	0	0
Drainage resistance [d]	2	2	2	2
Initial bottom layer storage [mm]	1000	0	0	0
Measure evaporation factor [-]	1	1	1	1
Void ratio [-]	1	0.75	0.3	1
Effective depth [mm]	[5,10,20,30,40,50,100]	[5,10,20,30,40,50,100]	[5,10,20,30,40,50,100]	[5,10,20,30,40,50,100]

Appendix B

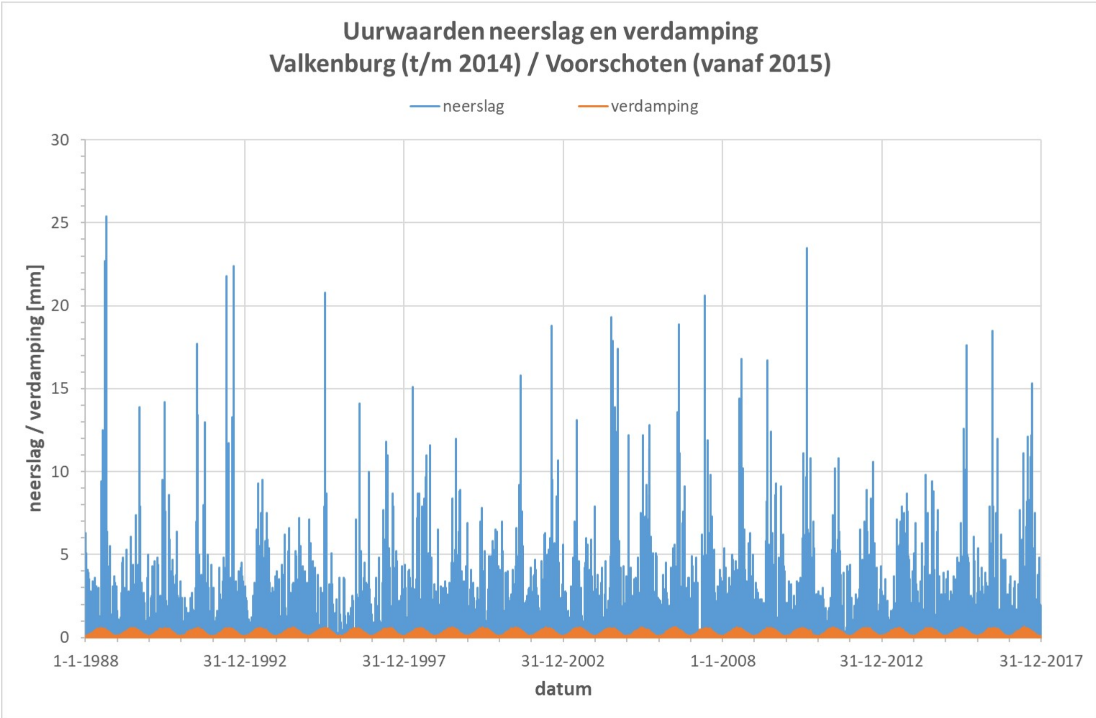
Synthetic time series

For the baseline climate scenario, a 30-year hourly time series of precipitation and evaporation was made from available KNMI meteorological data.
Information on the meteorological data for baseline climate scenario is listed as follows:

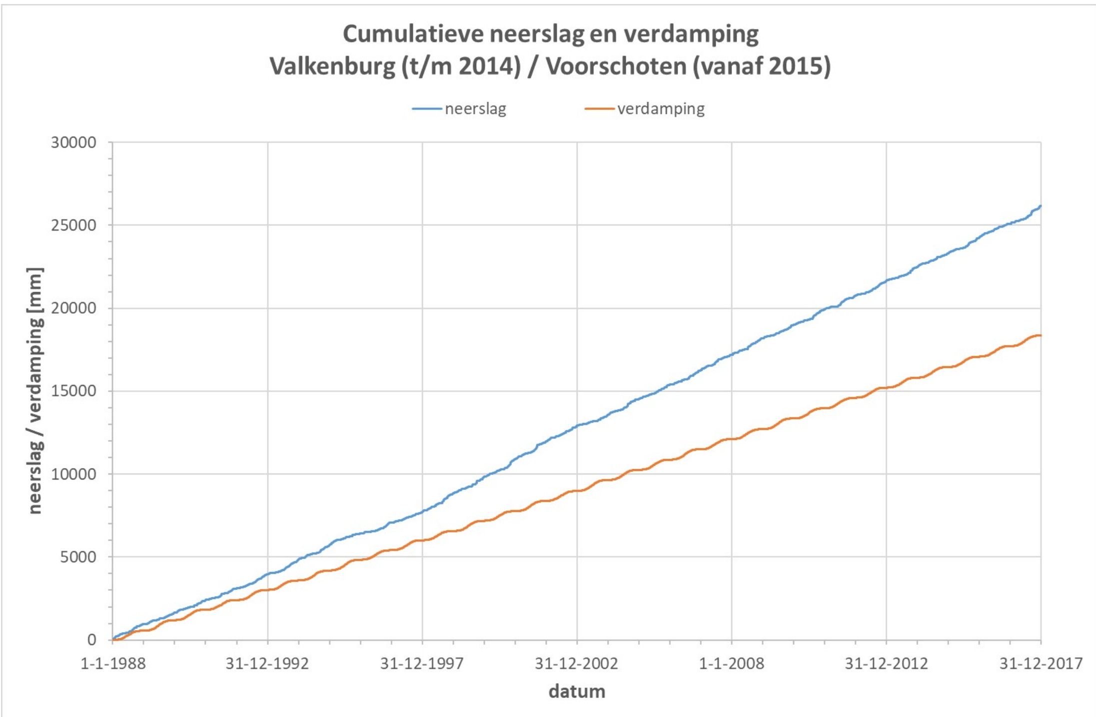
- KNMI weather station Valkenburg (available until May 2, 2016)
- KNIM weather station Voorschoten (available from Jul 16, 2014)
- Hourly precipitation (minimum scale division 0.1mm) and global radiation data (J/cm^2)
- Daily reference crop evapotranspiration (Makkink) (minimum scale division 0.1mm)
- Period: From 1-1-1988 00:00 to 31-12-2017 23:00 (30-year hourly time series)
- Precipitation value -1 meaning smaller that 0.05mm, thus is replaced with 0.025mm
- Precipitation events are separated by at least 6 hours without rainfall
- Hourly evapotranspiration is derived by interpolation using daily Makkink evaporation data and hourly radiation data.

Results of preliminary analysis on the baseline time series of precipitation and evaporation are shown below:

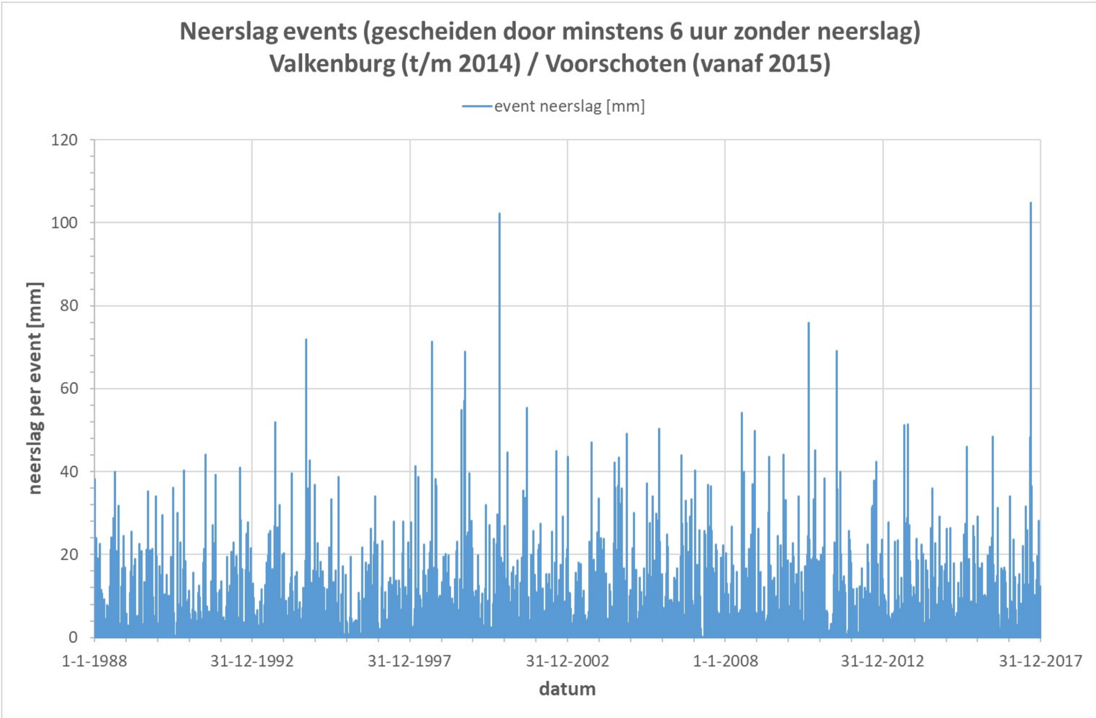
- Cumulative precipitation and evaporation over 30 years are 26187.83mm and 18356.60mm respectively (figure B.1a and B.1b)
- Maximum measured hourly precipitation is 25.4mm (figure B.1e)
- Number of events in 30 years is 5986 (200 events per year in average)
- Maximum event precipitation is 104.93 mm (figure B.1c and B.1f)
- Maximum length of precipitation event is 121 hours (figure B.1d)
- Maximum rainfall in a 24-hour period is 77.65mm
- Maximum daily rainfall is 77.65mm (Sep 8, 2017)



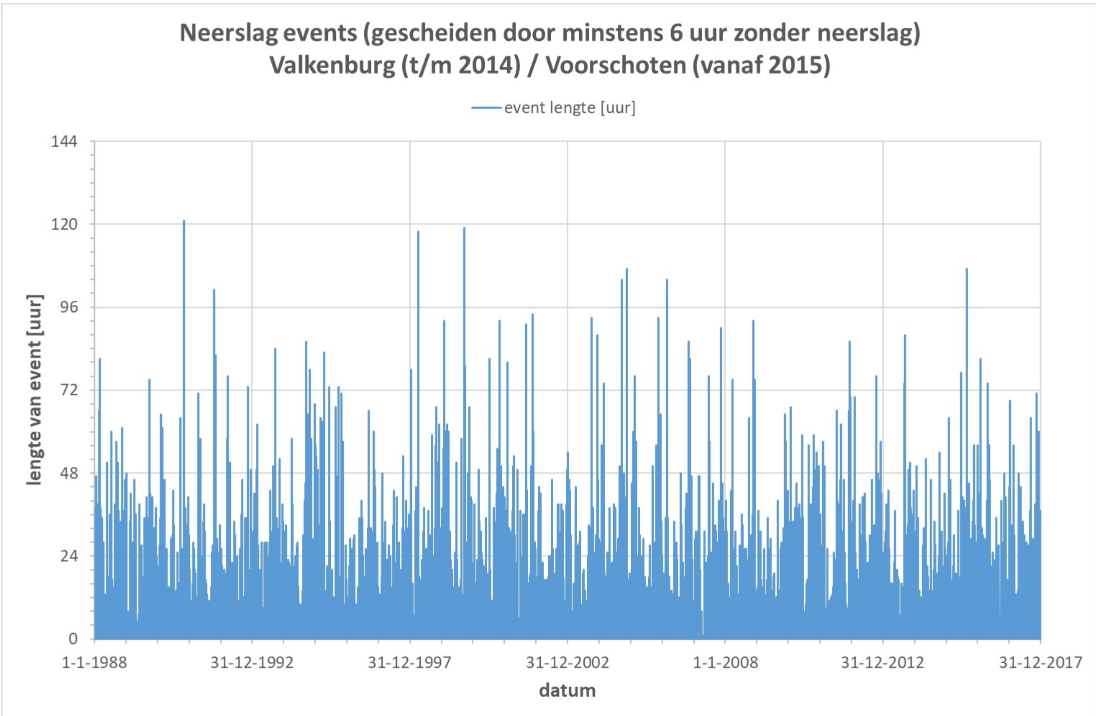
(a) 30-year hourly time series of precipitation and evaporation of Den Haag



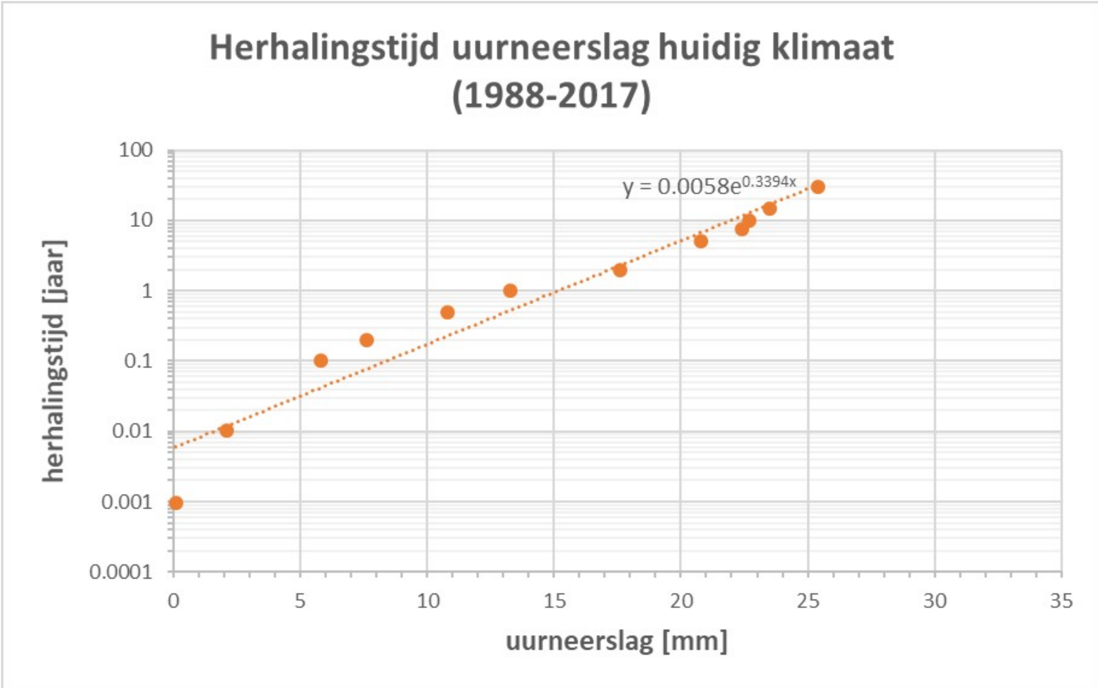
(b) Cumulative precipitation and evaporation of Den Haag over 30 years



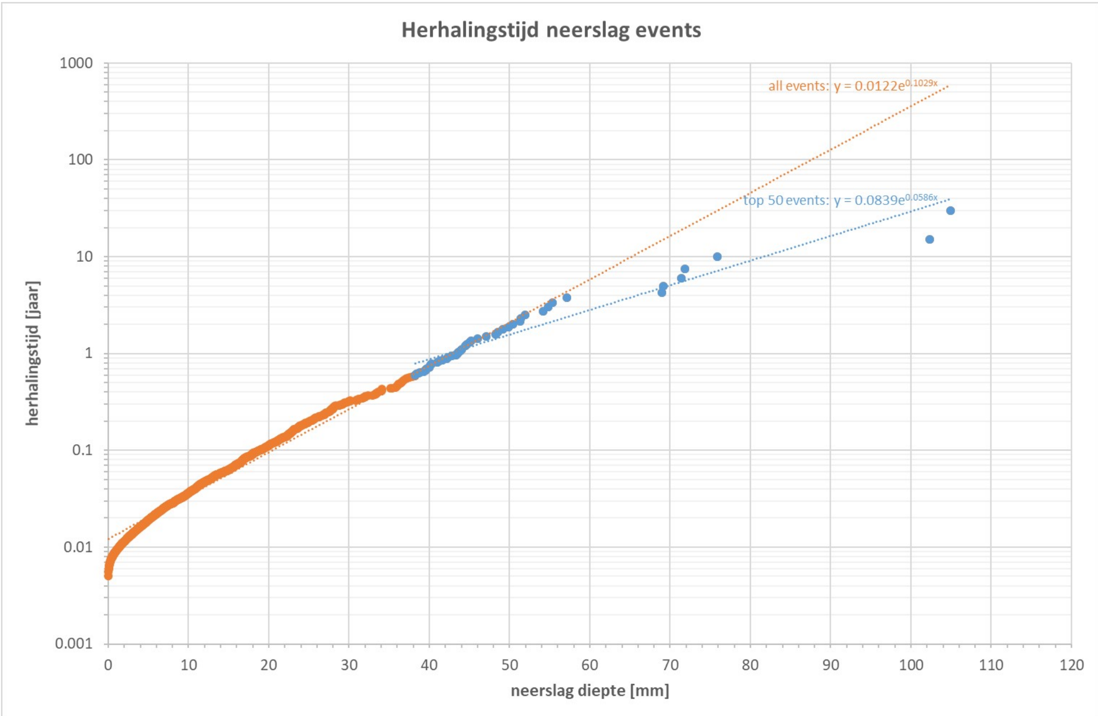
(c) Depth of precipitation events over 30 years of baseline scenario for Den Haag



(d) Length of precipitation events over 30 years of baseline scenario for Den Haag



(e) Return period of hourly precipitation intensity of baseline climate scenario for Den Haag



(f) Return period of event-based precipitation depth of baseline climate scenario for Den Haag

Figure B.1: Analysis of meteorological data of baseline climate scenario

KNMI'14 climate scenario report integrated the evidence from IPCC report (IPCC, 2014) with the local context specific to the Netherlands to provide future climate projections around 2050 and 2085 (Klein Tank et al., 2014). According to the report, future trends likely to happen are higher temperatures, wetter winters, more intense downpours and increased chances on drier summers, however, four scenarios differ from each other by the degree of global temperature rising and possible change of air circulation as shown in figure B.2.

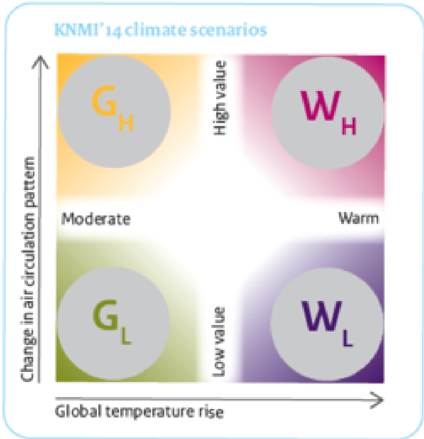


Figure B.2: KNMI'14 climate scenarios, copied from Klein Tank et al. (2014)

As reported by Klein Tank et al. (2014), precipitation in general will increase, moreover, intensity of extreme showers in summer and extreme precipitation in winter will increase, thus thunderstorms and hail will become more severe. In spite of more intense summer rain downpours, more dry summers are predicted in G_H and W_H scenarios (Klein Tank et al., 2014). The report says in terms of precipitation, scenarios are less different from each other due to relatively large natural variations in precipitation.

Synthetic meteorological time series of four climate scenarios based on KNMI'14 (2085) were made by changing the baseline records according to the change values in table 3.3. The change in maximum hourly precipitation intensity per year in summer was also taken into account to represent more intense showers. We put a predefined increase for precipitation which is more intense than 5 mm/hour so the decrease in the rest is so great that the total summer rainfall decreases. 5 mm/hr was chosen as the threshold as it is approximately top 1% hourly rainfall intensity. The change values are summarized in the table B.1. Instead of using stochastic weather generators to produce ensembles of meteorological records, direct modifications on original data were applied for the sake of simplicity.

Table B.1: Scenario change value applied to generate synthetic meteorological time series for four KNMI climate scenarios (2085)

Scenario	**Precipitataion**					**Evaporation**	
	Winter	**Spring**	**Summer**		**Autumn**	**Summer**	**Others**
			Peak (> 5mm/hr)	**Rest**			
G_L	+4.5%	+8.0%	+13.0%	−3.8%	+7.5%	+3.5%	+1.6%
G_H	+12.0%	+7.5%	+15.0%	−17.3%	+9.0%	+8.5%	+2.8%
W_L	+13.0%	+15.0%	+35.0%	−21.2%	+6.5%	+9.0%	+3.3%
W_H	+30.0%	+12.0%	+35.0%	−46.4%	+12.0%	+15.0%	+5.5%

Appendix C

Model structure

C.1 Schematic overview of Urbanwb model

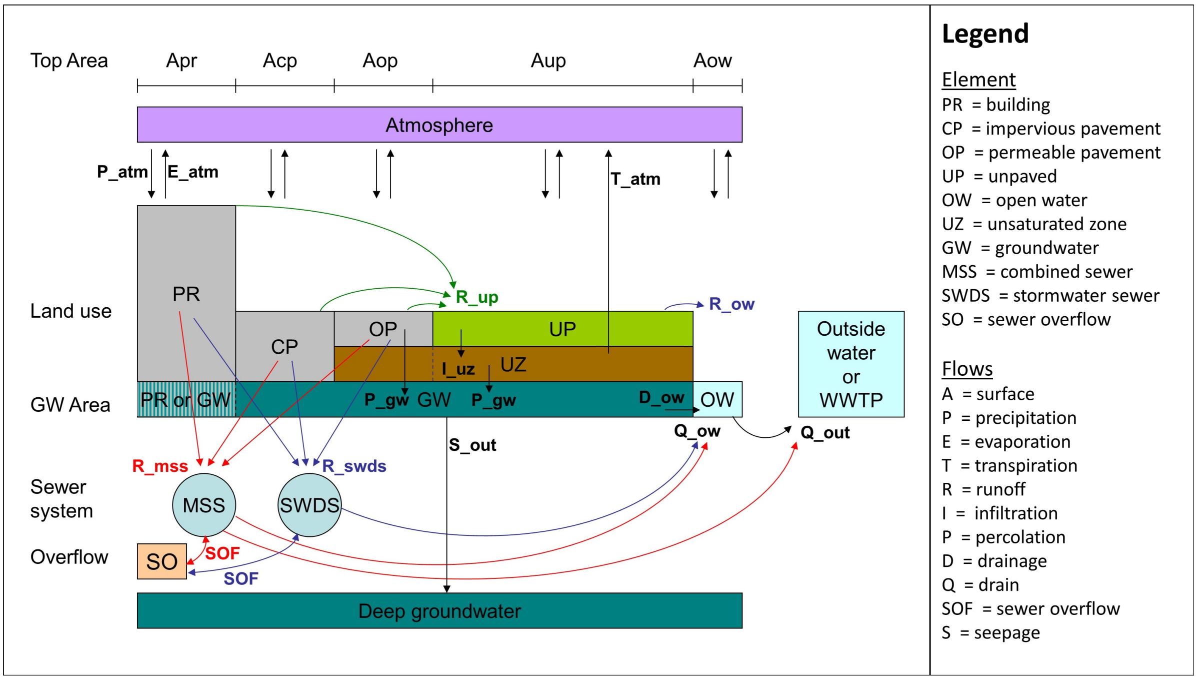


Figure C.1: Schematic overview of Urbanwb model, modified from Excel-based model by Toine Vergroesen

As depicted in Figure 3.7, an urban water system is partitioned into "Watersystem" and "Waterchain". Urbanwb model is a lumped conceptual water balance model, which enables dynamical modeling of dominant hydrological processes in a neighborhood-scale "Watersystem" using long time-series forcing. Thus the water supply chain — "Waterchain" is irrelevant with the Urbanwb model. As shown in Figure C.1 above, rainfall-runoff processes, subsurface (saturated and unsaturated zone), urban surface water and sewer systems (combined and separate sewer system) formulate the basic structure of the Urbanwb model. For detailed information about this model please refer to Deltares[1].

[1] https://publicwiki.deltares.nl/display/AST/

Different land covers of an urban area have different hydrological regimes. Four types of land cover are differentiated in the Urbanwb model as follows:

- **Paved area above ground level:** Paved building roofs (paved roof, *abbr.* **PR**)
- **Paved area at ground level:** Paved land surface (closed paved and open paved, *abbr.* **CP** and **OP**)
- **Unpaved area at ground level:** Unpaved land surface (Unpaved, *abbr.* **UP**)
- **Surface water below ground level:** Urban surface water (Open water, *abbr.* **OP**)

Below the ground level, three components of subsurface are distinguished:

- **Unsaturated zone** (*abbr.* **UZ**)
- **Shallow groundwater** (*abbr.* **GW**)
- **Sewer system** (*abbr.* **SWDS** and **MSS**)

Three external water exchanges comprise the boundary conditions of the model:

- **Atmosphere** (Atm)

  Rainfall, potential open water evaporation and potential reference crop evaportranspiration are the only forcing to the Urbanwb model. Potential open water evaporation is computed with Penman equation (Penman, 1948). Although from 1990 the Food and Agriculture Organization (*abbr.* FAO) has recommended Penman-Monteith method (Monteith, 1965) as the sole standard method to compute reference crop evapotranspiration (Allen et al., 1998), since 1987 Makkink method has been adopted by KNMI in the Netherlands as an alternative because it achieves similar efficiency with less detailed meteorological data (De Bruin, 1987). According to the STOWA report (Droogers, 2009), Makkink evaporation is approximately 0.8982 times Penman-Monteith evaporation. They both can be taken as the forcing of reference crop evapotranspiration to the Urbanwb model and the difference in outcomes is acceptable. Urbanwb model is capable of running decades-long hourly or daily time-series (one hundred years or even more, only constrained by the PC memory) within minutes.

- **Deep groundwater** (Deep GW):

  Seepage from shallow groundwater to deep groundwater can be defined relevant in the Urbanwb model, either as a constant flux or a dynamically-computed flux which depends on the head difference and vertical flow resistance.

- **Outside water and waste water treatment plant** (Outside and WWTP):

  There are two outflows from model internal to this external exchange: ***a.*** Combined sewer system (MSS) discharges water at limited pumping rate to the waste water treatment plant (WWTP) which is located outside the study area; ***b.*** excess water on the urban surface water is pumped through pumping stations to outside watercourses. Both outflows are limited by predefined discharge rate — the maximum discharge capacity of combined sewer system (MSS) to waste water treatment plant (WWTP) and the maximum discharge capacity of open water (OW) to outside water.

Several general assumptions are made in the Urbanwb model as following:

- Only rainfall is considered as precipitation. Rainfall falls instantaneously at the beginning of current time step.
- After rainfall is completed, interception evaporation starts, which is limited by the potential open water evaporation during current time step.
- Runoff from paved areas connected with drainage systems enters the storm sewer and combined sewer at predefined propositions regardless of their capacities, and the exceedance of sewer system capacities is dealt with separately as sewer overflow on the street. Runoff from paved areas disconnected to sewers flows to unpaved area by assumption.
- Routing between model internal interconnected reservoirs is irrelevant. Hydrological process in an urban water system is relatively fast. For instance, rainfall falling on the roof runs off, enters the storm sewer where it outflows to the surface water and this process is completed within hourly time step. Therefore, the Urbanwb model is applicable at neighborhood scale, but use at large spatial scale is questionable.
- Computed fluxes and states are expressed in depth (mm) averaged over the individual component. Fluxes between components are converted with the area ratio of donor component over recipient component. Flux from A to B is constrained by three aspects: ***a.*** available water in A as outflow ***b.*** available space in B to accommodate inflow ***c.*** limitation of transport capacity between A and B. In this manner, water quantity is ensured strictly conserved both for individual reservoirs and the entire model at every time step throughout the entire simulation.
- Parameters to initialize the model are predefined by users in accordance with the local context of the study area, based on literatures, empirical evidence and expert judgment. "Garbage in, garbage out" should be avoided by cautious parameterization.

C.2 Model components

Nine basic internal components are explained in brevity in this section. Simple descriptions together with schematic diagrams of components are provided. Detailed information like calculation formulas will be available in the documentation of the Urbanwb package.

C.2.1 Paved roof

Paved roof (PR) refers to all kinds of buildings in an urban area ranging from low-rise buildings (*e.g.* single dwelling, apartment complex) to high-rise buildings (*e.g.* skyscraper). On rooftops, a roof drainage system collects rainwater through gutters and drains it into the sewer system through a downspout pipe. A small amount of rainwater intercepted on the roof is defined as interception storage, which is emptied only through evaporation. Water exceeding the interception storage capacity becomes runoff from the paved roof. Part of the roof may be disconnected from the sewer system, therefore runoff from the disconnected part flows to unpaved area (*e.g.* private gardens) by assumption. Runoff from roofs connected with sewer systems flows to storm water drainage system (SWDS) and combined sewer system (MSS) at predefined ratios. In the case a measure connected to the roofs is applied, runoff flowing to the measure is subtracted from the runoff entering sewer systems. If interception storage of the paved roof bucket is not depleted at current time step, it remains for the next time step where the above process repeats itself. Figure C.2 below shows the schematic sketch of paved roof component.

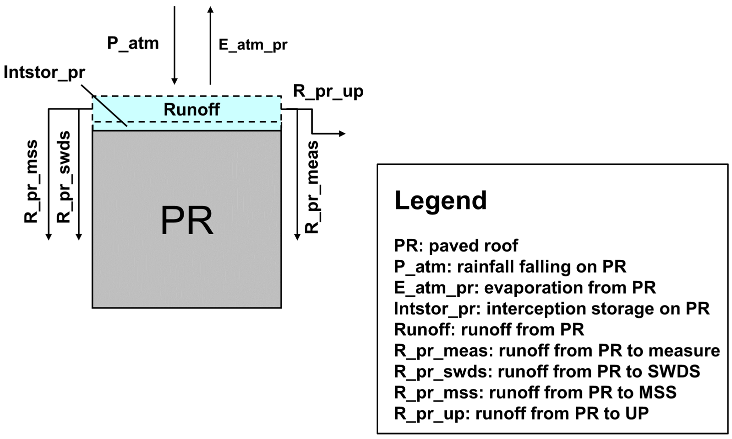


Figure C.2: Schematic representation of paved roof component structure

C.2.2 Closed paved

Closed paved (CP) mainly refers to impervious land surface *e.g.* roads, parking lots, asphalt street and *etc.* This land cover type is made of impermeable materials like cement concrete and bituminous concrete. Closed paved is modeled with the same bucket structure as the Paved roof. Water exceeding the interception threshold runs off to the sewer system. Runoff from disconnected closed paved area is assumed to flow to unpaved area. In the case runoff from part of closed paved area inflows to the measure, that amount of runoff is deducted from the runoff entering the sewer systems. Figure C.3 below shows the schematic representation of closed paved. As can been seen from it, the structure is no different from that of paved roof component.

C.2.3 Open paved

Open paved (OP) refer to partially permeable paved land surface *e.g.* paths, sidewalks, parking area and other less impervious land cover with relatively limited infiltration capacity. This land cover type uses porous material that allows water flowing through it (*e.g.* pervious concrete, porous asphalt) or spaced nonporous material (*e.g.* paving stones, permeable interlocking concrete pavement) that allows water to infiltrate between the cracks.

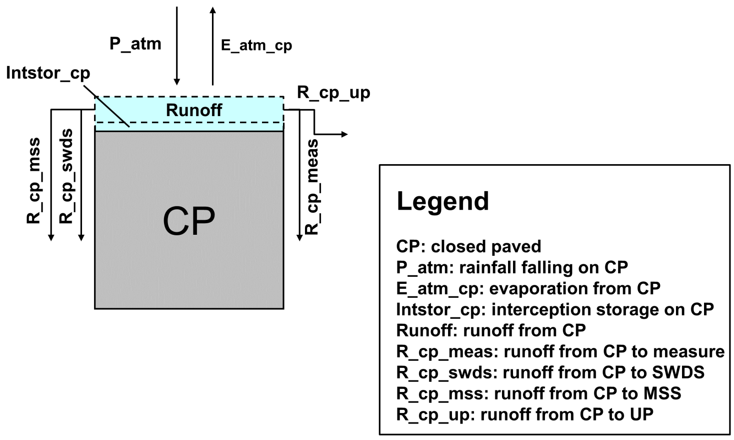


Figure C.3: Schematic representation of closed paved component structure

Therefore, compared to paved roof and closed paved component, open paved component allows infiltration. Infiltration starts after interception storage is filled and it is limited by predefined infiltration capacity. Interception storage can only be emptied through evaporation. Since root zone is irrelevant beneath open paved surface, the infiltration is assumed to skip the unsaturated zone and directly recharge the groundwater. Runoff from the open paved enters the measure and sewer systems according to predefinition. Figure C.4 shows the schematic diagram of open paved component.

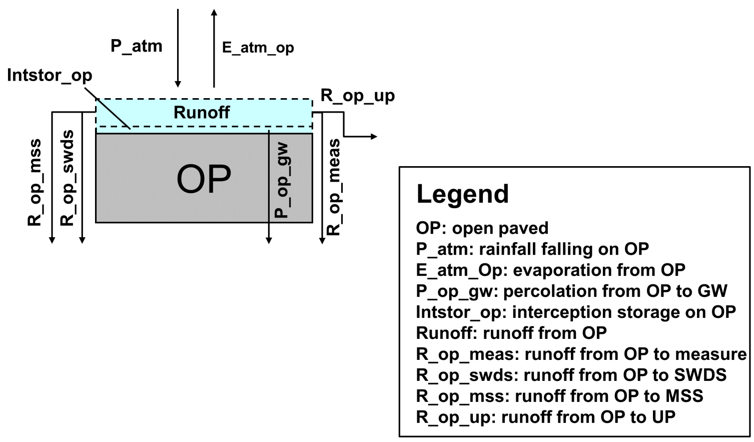


Figure C.4: Schematic representation of open paved component structure

C.2.4 Unpaved

Unpaved (UP) refers to permeable unpaved land surface *e.g.* private gardens and public green space. Rainfall falling on unpaved land surface and runoff from paved areas that are disconnected from sewer system are two source of incoming water to the unpaved area. Water on unpaved land surface can infiltrate much more easily than on paved land surface. Contrary to paved areas where the most of the water drains through sewer systems, runoff from unpaved area takes natural drainage pathway — it infiltrates into the unsaturated zone and from there further percolate to the groundwater reservoir. Crop type and soil type on unpaved area determine the interception capacity and infiltration capacity. Intercepted water on unpaved land surface is assumed to simultaneously evaporate to the atmosphere and infiltrate to the unsaturated zone. Water exceeding the interception threshold becomes overland flow to surface water. Below figure C.5 is the schematic representation of unpaved component.

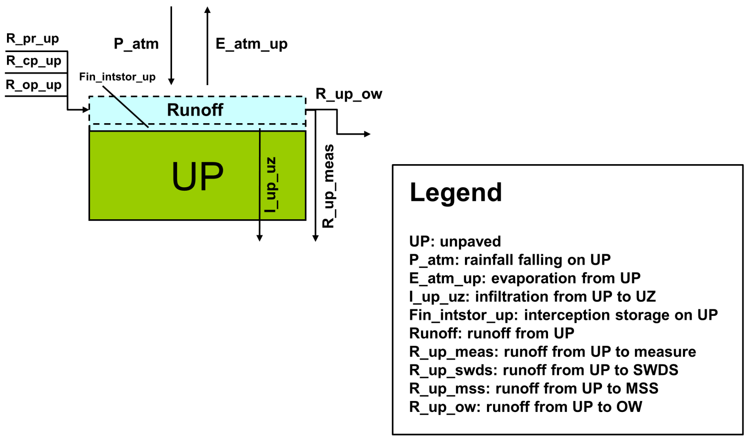


Figure C.5: Schematic representation of unpaved component structure

C.2.5 Unsaturated zone

The unsaturated zone (UZ), often called the vadose zone, is the portion of the subsurface above the phreatic table. Since water is assumed to flow mainly vertically in the unsaturated zone, unsaturated zone is irrelevant below paved roof and closed paved land surface where runoff mainly enters sewer systems. It is neither relevant below the open paved land surface where the limited infiltration is assumed to percolate directly into the groundwater reservoir. Unsaturated zone is taken into account only when evapotranspiration from the root zone is possible. As such, unsaturated zone is only relevant below the unpaved land surface, and therefore unsaturated zone only spans the area of unpaved component by assumption. Incoming infiltration from unpaved surface and capillary rise from groundwater are two inflows to the unsaturated zone, whereas evapotranspiration and percolation to groundwater are outflows that depletes the water content. These fluxes are dynamically computed per time step according to the moisture content budget and the equilibrium moisture content of the root zone during the same time step. Detailed explanations are provided below. In the unsaturated zone, we put our focus on the root zone part. The root zone can be represented as a container in which the water content may fluctuate — Rainfall infiltration and capillary rise of groundwater towards root zone recharge water content of the root zone and decrease depletion, while soil evaporation, crop transpiration and percolation losses remove water from the root zone and increase depletion. Figure C.6 below gives a schematic representation of the unsaturated zone component of Urbanwb model. Evapotranspiration from the root zone is modeled as the product of reference crop evapo-

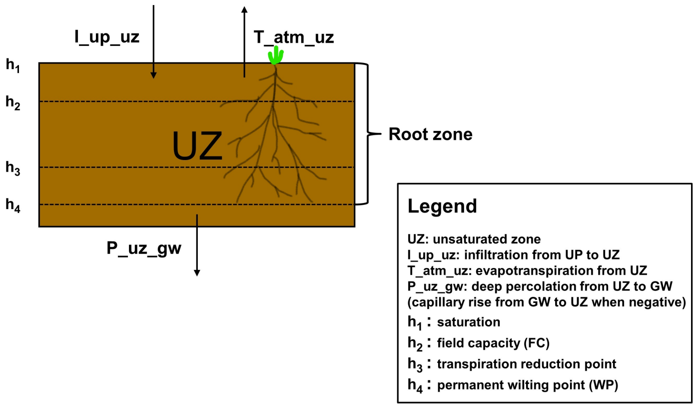


Figure C.6: Structure of Unsaturated zone component in Urbanwb model

transpiration (Makkink evaporation) and transpiration reduction coefficient. Transpiration reduction coefficient comes from the concept of water stress factor of Feddes's root water uptake model (Feddes, 1982). Figure C.7 shows the relationship between transpiration reduction factor α_{rw} and soil water pressure head (*i.e.* root zone moisture potential) h. h is relative moisture content of the root zone and calculated as

$$h = \frac{\text{moisture content}}{\text{moisture content at equilibrium}}$$

As shown in the figure C.7, under conditions wetter than h_1 (anaerobic point), the root water uptake is zero. Under conditions drier than h_4 (permanent wilting point[2]), the root water uptake is also zero. In the range between h_3 (transpiration reduction point) and h_2 (field capacity[3]), the root water uptake is optimal, indicating the transpiration reduction factor (*i.e.* plant water stress factor) $\alpha_{rw} = 1$. When $h_4 < h < h_3$ or $h_2 < h < h_1$, there

[2]In the absence of water supply, the water content in the root zone decreases as result of water uptake by the crop. As water uptake progresses, the remaining water is held to the soil particles with greater force, lowering its potential energy and making it more difficult for the plant to extract it. Eventually, a point is reached where the crop can no longer extract the remaining water. Therefore, the water uptake becomes zero when wilting point is reached. Wilting point is the water content at which plants will permanently wilt.
[3]Field capacity is the amount of water that a well-drained soil should hold against gravitational forces.

is drought stress for water uptake by roots and the decrease in the factor α_{rw} is assumed linear.

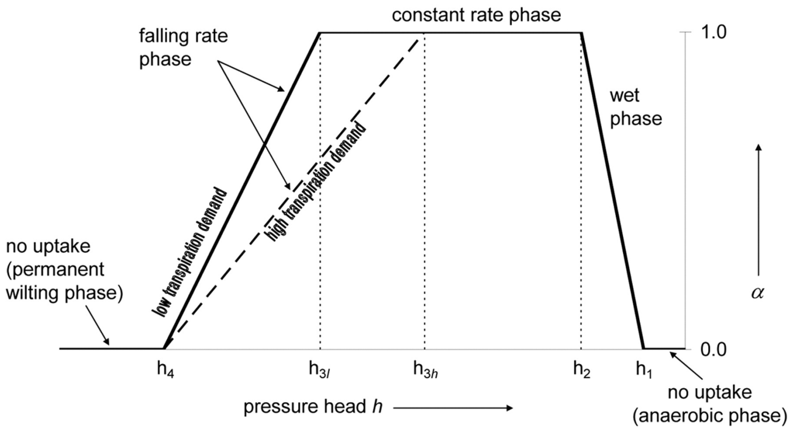


Figure C.7: Transpiration reduction coefficient in Urbanwb model (*i.e.* plant water stress factor) in relation to root zone water potential, reprinted from De Jong van Lier et al. (2008)

C.2.6 Groundwater

In the Urbanwb Model, underneath the Unsaturated Zone is the saturated zone, *i.e.* the Groundwater reservoir (GW). The Groundwater reservoir is modeled as an unconfined aquifer which consists of a pervious layer underlain by a (semi-)impervious layer, below which lies the deep groundwater, one of the boundary components that exchanges water with the Urbanwb model. Percolation from Unsaturated zone (UZ) and Open paved (OP) recharges the groundwater, while downward seepage to deep groundwater and drainage to Open water (OW) deplete the Groundwater reservoir. The inflow (percolation from unsaturated zone) and outflow (seepage and drainage) are driven by the head difference, so the value of these fluxes can both be positive or negative. Figure C.8 shows the schematic overview of the groundwater reservoir. The area of the groundwater reservoir is calculated as the area of the total model minus the area of open water fraction that is not above the groundwater level and minus the area of Paved Roof fraction of which the basement is below groundwater. The maximum capillary rise and the storage coefficient for the current time step are determined by interpolation based on the groundwater level at the end of the previous time step.

The formula of groundwater level during current time step h(t) and its derivation are shown in below Figure C.9. In this figure, P is percolation (assumed to be constant during a time step), q_s is downward seepage to deep groundwater, q_d is drainage to open Water. All these water flows can get positive as well as negative values, negative meaning flow in the other direction. In Urbanwb all relevant levels are relative to the surface level, where the unit (m-SL) means meter below surface level. Groundwater level is dynamically calculated with the following formula:

$$h(t) = \frac{H \cdot w + PP \cdot c + P \cdot c \cdot w}{w + c} + \left(h_0 - \frac{H \cdot w + PP \cdot c + P \cdot c \cdot w}{w + c}\right) \cdot e^{-t \cdot \frac{w+c}{\mu \cdot w \cdot c}}$$

Several assumptions are made here: The infiltration water from open paved flows directly to the groundwater (percolation), thus skipping the unsaturated zone. Drainage and seepage are calculated based on the groundwater level at the end of previous time step. Drainage and seepage are reduced due to the changing groundwater level caused by the fluxes. It means that larger the head difference between shallow groundwater and deep groundwater (or open water) is, larger the driving force is, and thus larger the water flow is. With water exchanging, the head differences get smaller, so the flux get smaller.

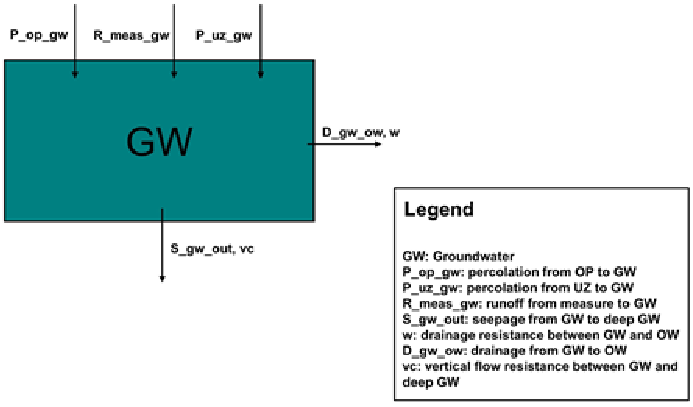


Figure C.8: Structure of Groundwater component in Urbanwb model

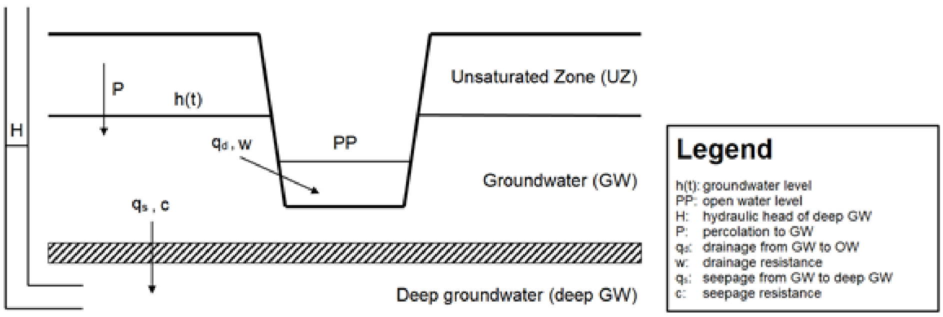


Figure C.9: Groundwater level h(t) calculation

C.2.7 Sewer system

The sewer system in Urbanwb model is the combination of a Storm Water Drainage System (SWDS) and a Combined or Mixed Sewer System (MSS). In urban areas both systems can be applied in practice. Hence, the proportion and system capacity of sewers systems should be predefined by the user to according to the local situation.

C.3 Parameters estimation

The parameters for the study area Laakhaven are estimated based on available information and expert judgment, the results of which are summarized in Table C.1 below.

Table C.1: Static input parameters for the Laakhaven neighborhood

Total area	145000 m2		Soil type	9 - Podzol	
Land use	Paved roofs	32.6%	Crop type	1 - grass	
	part above GW	0%	Groundwater	drainage resistance w	50 d
	part disconnected	0%		initial GWL	1.03 m-SL
	Closed paved	11.0%		deep GW seepage type	flux
	part disconnected	0%		deep GW seepage flux	0.25mm/d
	Open paved	41.6%	Target owl	1.03 m-SL	
	part disconnected	0%	Interception storage capacity	Paved roof	1.6 mm
	Unpaved	13.8%		Closed paved	1.6 mm
	Open water	1.0%		Open paved	1.6 mm
	part above GW	0%		Unpaved	20 mm
Sewer system	seperate sewer	100%		SWDS storage	2 mm
	combined sewer	0%	Infiltration capacity	Open paved	10.9 mm/d
	discharge capacity	16.8 mm/hr		Unpaved	480 mm/d

Below is an example of parameters estimated with available information. Figure C.10 below shows the sewer systems according to the current Dutch design standards. The storage of a combined sewer system averaged over the entire contributing area is 9mm, in which 7mm is in pipes and manholes, and 2 mm is in additional storage installations in the sewer system *e.g.* collection pits, off-line tanks. The improved separate sewer system has 4mm storage. A normal separate sewer system usually has zero storage. Therefore, we define 2mm and 9mm as the storage capacities for storm water drainage system (SWDS) and combined sewer system respectively.

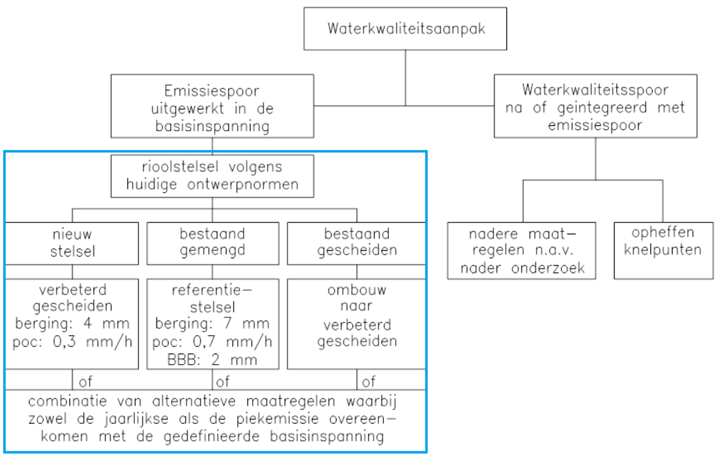


Figure C.10: Current design standards of sewer systems in terms of storage volume

Appendix D

Runoff frequency reduction factor

Table D.1: Runoff frequency reduction factor for measures with different effective depth specifications

ID	Measure	eff.depth	Event-based runoff depth (mm)															Avg.
			1	2	3	4	5	6	7	8	9	10	15	20	30	40	50	
3	Add trees in streetscape	all	2.28	2.47	2.61	2.88	3.08	3.20	3.49	3.69	3.97	4.18	5.01	4.57	5.41	6.89	5.10	3.92
4	Urban wetland	$5mm$	1.89	1.83	1.77	1.78	1.77	1.75	1.73	1.71	1.75	1.74	1.81	1.91	1.84	2.45	1.28	1.80
	Urban wetland	$10mm$	3.59	3.42	3.36	3.30	3.24	3.13	3.10	3.20	3.15	3.24	3.66	3.49	3.90	3.50	1.85	3.28
	Urban wetland	$20mm$	13.58	13.17	12.87	12.72	13.02	12.22	11.47	12.46	12.12	11.90	13.17	12.45	9.74	6.88	3.84	11.44
	Urban wetland	$30mm$	60.75	55.62	49.36	50.79	56.56	51.77	47.40	45.34	43.61	43.22	37.21	31.91	16.24	17.28	8.34	41.03
	Urban wetland	$40mm$	181.92	175.19	154.65	144.11	137.04	127.34	115.90	107.53	98.52	88.68	68.16	43.06	55.75	30.70	inf	109.18
	Urban wetland	$50mm$	341.75	312.12	282.17	254.89	226.74	201.43	180.64	165.27	149.99	133.98	230.79	161.62	inf	inf	inf	220.12
	Urban wetland	$100mm$	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	440.24*
6	Bioswale (with drainage)	$5mm$	1.91	1.86	1.81	1.84	1.83	1.81	1.77	1.78	1.83	1.81	1.96	1.99	1.96	2.63	1.32	1.87
	Bioswale (with drainage)	$10mm$	3.69	3.53	3.51	3.40	3.29	3.26	3.29	3.33	3.32	3.53	3.85	3.85	4.62	3.58	1.98	3.47
	Bioswale (with drainage)	$20mm$	14.07	14.37	13.40	13.59	13.47	12.36	12.15	13.04	13.13	13.49	15.58	14.01	10.14	7.13	4.08	12.27
	Bioswale (with drainage)	$30mm$	44.53	43.07	39.70	40.17	41.43	41.88	39.84	40.15	43.06	45.54	37.57	33.31	17.20	19.13	8.94	35.7
	Bioswale (with drainage)	$40mm$	67.13	66.60	62.82	58.24	60.89	63.39	59.37	65.21	78.02	77.85	68.08	48.17	59.74	32.41	inf	61.99
	Bioswale (with drainage)	$50mm$	75.27	73.71	73.15	65.95	70.91	76.41	71.75	76.73	136.85	181.43	216.31	161.39	inf	inf	inf	106.66
	Bioswale (with drainage)	$100mm$	85.67	89.67	88.12	80.09	90.86	105.23	101.73	118.73	200.40	251.10	inf	inf	inf	inf	inf	121.16
11	Ditches	$5mm$	1.89	1.83	1.77	1.78	1.77	1.75	1.73	1.71	1.75	1.74	1.81	1.91	1.84	2.45	1.28	1.80
	Ditches	$10mm$	3.59	3.42	3.36	3.30	3.24	3.13	3.10	3.20	3.15	3.24	3.66	3.49	3.90	3.50	1.85	3.28
	Ditches	$20mm$	13.58	13.17	12.87	12.72	13.02	12.22	11.47	12.46	12.12	11.90	13.17	12.45	9.74	6.88	3.84	11.44
	Ditches	$30mm$	60.75	55.62	49.36	50.79	56.56	51.77	47.40	45.34	43.61	43.22	37.21	31.91	16.24	17.28	8.34	41.03
	Ditches	$40mm$	181.92	175.19	154.65	144.11	137.04	127.34	115.90	107.53	98.52	88.68	68.16	43.06	55.75	30.70	inf	109.18
	Ditches	$50mm$	341.75	312.12	282.17	254.89	226.74	201.43	180.64	165.27	149.99	133.98	230.79	161.62	inf	inf	inf	220.12
	Ditches	$100mm$	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	440.24*
14	Green facades	all	1.22	1.21	1.19	1.18	1.19	1.17	1.15	1.17	1.15	1.13	1.13	1.17	1.11	1.23	1.01	1.16
16	Green roof (extensive)	$5mm$	1.74	1.71	1.64	1.63	1.60	1.54	1.55	1.57	1.54	1.54	1.58	1.49	1.57	1.61	1.17	1.57
	Green roof (extensive)	$10mm$	1.97	1.94	1.84	1.83	1.81	1.75	1.76	1.78	1.75	1.75	1.72	1.72	1.77	1.79	1.17	1.76
	Green roof (extensive)	$20mm$	2.28	2.24	2.11	2.10	2.05	2.00	2.02	2.03	2.01	2.01	2.03	2.00	2.09	1.79	1.17	1.99
	Green roof (extensive)	$30mm$	2.45	2.42	2.28	2.28	2.23	2.18	2.21	2.23	2.20	2.20	2.19	2.22	2.26	1.89	1.32	2.17
	Green roof (extensive)	$40mm$	2.59	2.55	2.41	2.40	2.35	2.30	2.36	2.38	2.32	2.34	2.34	2.36	2.32	2.13	1.79	2.33
	Green roof (extensive)	$50mm$	2.67	2.66	2.51	2.51	2.47	2.43	2.49	2.52	2.46	2.45	2.45	2.47	2.46	2.46	1.79	2.45
	Green roof (extensive)	$100mm$	3.11	3.12	2.95	2.97	2.94	2.87	2.99	3.06	3.03	3.06	3.14	3.43	3.74	4.49	4.22	3.27
20	D.I.T. drain	$2mm$	1.38	1.34	1.31	1.32	1.30	1.30	1.30	1.30	1.30	1.27	1.33	1.35	1.27	1.41	1.20	1.31
22	Infiltration fields	$5mm$	2.75	2.68	2.50	2.52	2.48	2.45	2.38	2.35	2.41	2.32	2.53	2.34	2.51	3.32	1.31	2.46
	Infiltration fields	$10mm$	5.53	5.27	4.95	4.98	4.80	4.75	4.76	4.93	5.16	5.05	4.88	5.26	6.91	3.59	2.13	4.86
	Infiltration fields	$20mm$	24.00	21.80	19.53	19.79	19.58	19.66	21.53	23.04	21.56	19.53	20.01	20.82	11.40	7.60	4.47	18.29
	Infiltration fields	$30mm$	106.29	98.37	84.20	75.38	73.85	72.13	75.58	74.03	68.51	62.07	47.35	36.47	27.75	21.42	9.60	62.20
	Infiltration fields	$40mm$	275.59	239.34	206.65	185.93	166.13	148.15	133.34	122.42	119.80	113.46	74.20	114.99	65.02	inf	inf	151.16
	Infiltration fields	$50mm$	427.56	368.54	316.12	282.69	251.70	263.47	418.76	449.64	419.32	384.14	277.04	187.78	inf	inf	inf	337.23
	Infiltration fields	$100mm$	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	674.46*
29	Rain barrel	$5mm$	2.13	2.10	2.03	2.02	2.02	1.97	1.91	1.90	1.96	1.93	2.07	2.12	1.95	2.69	1.30	2.01
	Rain barrel	$10mm$	4.97	4.79	4.50	4.40	4.28	4.36	4.31	4.41	4.52	4.51	4.54	4.36	5.22	3.58	2.19	4.33
	Rain barrel	$20mm$	31.38	30.77	28.23	27.98	26.39	23.66	25.71	24.47	23.04	21.69	22.05	23.70	13.12	11.57	5.37	22.61
	Rain barrel	$30mm$	125.50	109.62	103.70	93.14	92.98	89.22	89.27	85.32	81.97	87.64	75.65	49.93	49.62	25.49	9.85	77.93
	Rain barrel	$40mm$	464.65	428.09	370.62	334.30	300.06	268.82	242.99	235.47	226.33	212.91	225.29	150.09	73.07	inf	inf	271.75

Table D.1 continued from previous page

ID	Measure	eff.depth	Event-based runoff depth (mm)															Avg.
			1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**15**	**20**	**30**	**40**	**50**	
	Rain barrel	50mm	1305.56	1143.80	995.99	903.18	814.67	733.18	665.52	615.86	564.91	509.71	346.12	inf	inf	inf	inf	781.68
	Rain barrel	100mm	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	1563.36*
33	Infiltration boxes	5mm	1.85	1.78	1.72	1.75	1.74	1.71	1.70	1.68	1.71	1.72	1.78	1.87	1.81	2.44	1.28	1.77
	Infiltration boxes	10mm	3.51	3.37	3.26	3.26	3.16	3.08	3.05	3.09	3.08	3.16	3.61	3.33	3.87	3.48	1.82	3.21
	Infiltration boxes	20mm	13.41	12.83	12.73	12.23	12.70	11.98	11.33	11.74	11.79	11.52	12.67	12.14	9.65	6.86	3.78	11.16
	Infiltration boxes	30mm	56.15	54.52	49.12	50.25	49.77	51.67	46.91	44.15	43.19	42.24	36.97	31.77	16.20	17.22	8.27	39.89
	Infiltration boxes	40mm	174.39	164.50	149.03	141.41	132.87	124.73	114.32	106.74	98.12	88.34	68.00	42.91	55.49	30.47	inf	106.52
	Infiltration boxes	50mm	339.58	307.40	275.02	252.07	224.63	199.89	179.54	164.52	149.52	133.74	226.30	159.33	inf	inf	inf	217.63
	Infiltration boxes	100mm	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	435.26*
40	Water roof	5mm	1.22	1.21	1.19	1.18	1.19	1.17	1.15	1.17	1.15	1.13	1.13	1.17	1.11	1.22	1.01	1.16
	Water roof	10mm	1.39	1.38	1.35	1.34	1.34	1.32	1.29	1.31	1.29	1.27	1.25	1.27	1.34	1.32	1.01	1.30
	Water roof	20mm	1.57	1.56	1.54	1.51	1.52	1.50	1.49	1.50	1.48	1.45	1.40	1.48	1.47	1.44	1.11	1.47
	Water roof	30mm	1.69	1.67	1.65	1.62	1.62	1.60	1.59	1.61	1.58	1.56	1.56	1.56	1.52	1.66	1.11	1.57
	Water roof	40mm	1.76	1.76	1.73	1.69	1.69	1.67	1.65	1.67	1.64	1.63	1.65	1.70	1.75	1.66	1.25	1.66
	Water roof	50mm	1.82	1.82	1.79	1.76	1.75	1.73	1.72	1.75	1.73	1.72	1.72	1.79	1.78	1.75	1.25	1.72
	Water roof	100mm	2.07	2.09	2.08	2.05	2.03	1.99	2.00	2.04	2.01	2.03	2.06	2.13	2.05	2.08	2.66	2.09
41	Water square	5mm	2.15	2.13	2.05	2.04	2.04	1.99	1.93	1.91	1.98	1.94	2.07	2.13	1.98	2.70	1.31	2.02
	Water square	10mm	4.99	4.82	4.51	4.44	4.29	4.39	4.33	4.49	4.55	4.56	4.62	4.43	5.23	3.58	2.20	4.36
	Water square	20mm	31.40	31.42	28.71	28.14	26.44	23.77	25.72	24.48	23.05	21.99	22.06	23.72	13.14	11.60	5.38	22.74
	Water square	30mm	125.52	110.07	103.70	93.14	93.17	89.53	89.29	85.33	82.02	87.84	76.48	49.99	49.65	25.51	9.85	78.07
	Water square	40mm	466.79	428.47	371.13	334.92	300.74	269.54	243.73	236.92	227.28	213.45	225.40	150.16	73.11	inf	inf	272.43
	Water square	50mm	1305.66	1143.96	996.19	903.41	814.92	733.43	665.78	616.12	565.17	509.97	346.34	inf	inf	inf	inf	781.91
	Water square	100mm	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	1563.82*
42	Green roof (with drain delay)	5mm	4.35	4.25	4.00	4.13	4.10	3.97	3.83	3.81	3.90	4.02	4.48	5.09	4.70	3.97	2.30	4.06
	Green roof (with drain delay)	10mm	7.85	7.71	7.50	7.35	7.49	7.50	7.65	7.74	8.81	8.87	9.97	8.11	9.06	5.64	3.85	7.67
	Green roof (with drain delay)	20mm	40.15	35.72	37.08	38.56	33.93	33.40	33.88	36.39	33.41	32.99	32.45	28.51	22.43	12.45	5.11	30.43
	Green roof (with drain delay)	30mm	159.56	152.15	136.86	136.79	130.58	116.62	105.10	96.61	91.14	84.78	94.62	61.60	30.42	inf	inf	107.45
	Green roof (with drain delay)	40mm	424.43	422.21	387.88	368.50	330.21	292.61	261.77	238.95	216.39	192.89	124.39	100.05	inf	inf	inf	280.02
	Green roof (with drain delay)	50mm	654.30	574.44	501.17	455.26	411.30	370.70	396.00	424.55	455.19	468.37	inf	inf	inf	inf	inf]	471.13
	Green roof (with drain delay)	100mm	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	942.26*
46	Storage tank	5mm	2.13	2.10	2.03	2.02	2.02	1.97	1.91	1.90	1.96	1.93	2.07	2.12	1.95	2.69	1.30	2.01
	Storage tank	10mm	4.97	4.79	4.50	4.40	4.28	4.36	4.31	4.41	4.52	4.51	4.54	4.36	5.22	3.58	2.19	4.33
	Storage tank	20mm	31.38	30.77	28.23	27.98	26.39	23.66	25.71	24.47	23.04	21.69	22.05	23.70	13.12	11.57	5.37	22.61
	Storage tank	30mm	125.50	109.62	103.70	93.14	92.98	89.22	89.27	85.32	81.97	87.64	75.65	49.93	49.62	25.49	9.85	77.93
	Storage tank	40mm	464.65	428.09	370.62	334.30	300.06	268.82	242.99	235.47	226.33	212.91	225.29	150.09	73.07	inf	inf	271.75
	Storage tank	50mm	1305.56	1143.80	995.99	903.18	814.67	733.18	665.52	615.86	564.91	509.71	346.12	inf	inf	inf	inf	781.68
	Storage tank	100mm	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	1563.36*
71	wet pond	5mm	1.96	1.91	1.84	1.86	1.85	1.81	1.79	1.79	1.84	1.83	1.89	1.93	1.93	2.45	1.28	1.86
	wet pond	10mm	3.72	3.54	3.52	3.46	3.38	3.29	3.26	3.31	3.25	3.33	3.79	3.64	4.08	3.50	1.85	3.39
	wet pond	20mm	14.21	13.85	12.96	12.94	13.41	12.59	11.86	12.64	12.53	12.77	15.15	12.45	9.74	6.95	3.84	11.86
	wet pond	30mm	64.64	57.76	50.82	52.61	57.25	51.77	47.40	45.35	45.47	43.30	37.27	31.91	16.24	17.28	8.34	41.83
	wet pond	40mm	184.27	175.60	156.46	144.85	137.16	127.40	115.94	107.54	98.54	88.71	68.39	43.49	55.76	30.71	inf	109.63
	wet pond	50mm	342.35	312.95	283.00	255.89	228.37	203.50	183.02	167.90	152.77	165.89	230.81	161.64	inf	inf	inf	224.01

Table D.1 continued from previous page

ID	Measure	eff.depth	Event-based runoff depth (mm)															Avg.
			1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**15**	**20**	**30**	**40**	**50**	
	wet pond	100mm	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	448.02*
82	Gravel layers	5mm	1.89	1.83	1.77	1.79	1.78	1.75	1.74	1.72	1.76	1.74	1.82	1.93	1.87	2.45	1.29	1.81
	Gravel layers	10mm	3.60	3.43	3.38	3.30	3.25	3.14	3.10	3.22	3.15	3.24	3.67	3.50	3.91	3.50	1.86	3.28
	Gravel layers	20mm	13.63	13.25	12.92	12.77	13.04	12.25	11.61	12.56	12.18	11.91	13.22	12.52	9.77	6.88	3.85	11.49
	Gravel layers	30mm	61.15	55.77	50.82	51.86	56.56	51.89	47.68	45.44	43.93	43.35	37.27	32.01	16.25	17.32	8.35	41.31
	Gravel layers	40mm	184.76	175.31	154.96	144.76	138.06	127.69	116.27	107.92	98.79	88.87	68.25	43.11	55.84	30.74	inf	109.67
	Gravel layers	50mm	342.42	313.37	283.82	255.43	227.18	201.79	180.94	165.52	150.20	139.92	231.38	161.93	inf	inf	inf	221.16
	Gravel layers	100mm	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	442.32*
90	permeable pavement stor.	5mm	1.87	1.81	1.76	1.78	1.76	1.73	1.72	1.72	1.76	1.74	1.81	1.92	1.77	2.52	1.28	1.80
	permeable pavement stor.	10mm	3.52	3.49	3.36	3.35	3.22	3.13	3.15	3.18	3.19	3.22	3.58	3.32	4.00	3.44	1.81	3.26
	permeable pavement stor.	20mm	13.32	12.72	12.83	12.70	12.30	11.66	11.51	11.65	11.97	11.60	13.40	12.22	9.64	6.86	3.80	11.21
	permeable pavement stor.	30mm	54.28	53.58	56.57	51.23	48.85	49.84	47.21	46.00	42.10	38.45	36.83	31.83	16.22	18.38	8.42	39.99
	permeable pavement stor.	40mm	167.77	159.07	142.52	141.53	132.48	123.18	114.43	108.07	99.27	89.52	67.60	42.61	55.64	30.63	inf	105.31
	permeable pavement stor.	50mm	356.26	312.00	271.58	246.20	222.49	200.76	182.67	169.41	161.97	163.72	223.85	159.08	inf	inf	inf	222.50
	permeable pavement stor.	100mm	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	445*
45	Hollow roads	5mm	1.76	1.73	1.66	1.70	1.69	1.66	1.66	1.65	1.65	1.68	1.75	1.84	1.69	2.35	1.28	1.72
	Hollow roads	10mm	3.41	3.32	3.19	3.22	3.16	3.04	3.00	3.10	3.16	3.14	3.63	3.35	3.86	3.51	1.84	3.19
	Hollow roads	20mm	13.29	13.04	13.03	12.82	13.11	12.46	11.59	11.93	12.38	12.37	13.12	12.97	9.91	6.88	3.80	11.51
	Hollow roads	30mm	55.59	53.28	48.87	50.65	52.60	51.85	49.57	46.43	43.93	48.54	38.69	31.71	16.13	17.17	8.18	40.88
	Hollow roads	40mm	194.67	179.10	164.27	153.60	146.00	130.10	117.01	107.35	98.00	88.25	68.05	42.86	55.15	30.17	inf	112.47
	Hollow roads	50mm	335.89	323.19	292.84	260.42	230.65	204.06	182.27	166.14	150.24	133.75	233.91	161.43	82.17	inf	inf	212.07
	Hollow roads	100mm	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	inf	424.14

inf means infinity, but it does not means the measure's effectiveness is infinite. **inf** happens when a measure with a relatively large effective depth only generates uncontrolled runoff depth less than the specific runoff depth. Taking gravel layers with 50mm effective depth as an example, in this case, maximum event-based runoff depth is around 29mm (can be read from figure D.14c), event with runoff depth of 30mm or more does not happen by the 30-yr simulation results. Therefore, the return period increase factor (runoff frequency reduction factor) is calculated as inf. It actually cannot be infinite as we all know.

For the case where a measure with a large effective depth produces no uncontrolled runoff within the entire simulation, we calculate its effectiveness as doubling the factor of its last specification (50mm). The factor is marked with an asterisk *. Please note that the runoff reduction factor is not coming from pure science derivation, but it is an approximate indicator which can be used to describe how the measure alter the probability of runoff events. It is calculated from average.

Table D.2: Runoff reduction factors for measures with varied configuration modeled under baseline scenario

Baseline	5**mm**	10**mm**	20**mm**	30**mm**	40**mm**	50**mm**	100**mm**
RB	2.01	4.33	22.61	77.93	271.75	781.68	1563.36
GRE	1.57	1.76	1.99	2.17	2.33	2.45	3.27
GRD	4.06	7.67	30.43	107.45	280.02	471.13	942.26
PP	1.8	3.26	11.21	39.99	105.31	222.5	445
BS	1.87	3.47	12.27	35.7	61.99	106.66	121.16
WS	2.02	4.36	22.74	78.07	272.43	781.91	1563.82

Table D.3: Runoff reduction factors for measures with varied configuration modeled under G_H scenario

G_H	5**mm**	10**mm**	20**mm**	30**mm**	40**mm**	50**mm**	100**mm**
RB	1.94	3.95	18.78	62.15	195.61	664.32	1328.64
GRE	1.53	1.69	1.91	2.06	2.17	2.26	2.9
GRD	3.64	6.51	23.7	80.79	202.49	365.29	730.58
PP	1.74	3.03	10.04	32.63	80.09	183.91	367.82
BS	1.82	3.21	10.6	27.78	47.42	67.59	75.89
WS	1.96	3.97	18.82	62.21	195.97	664.73	1329.46

Table D.4: Runoff reduction factors for measures with varied configuration modeled under G_L scenario

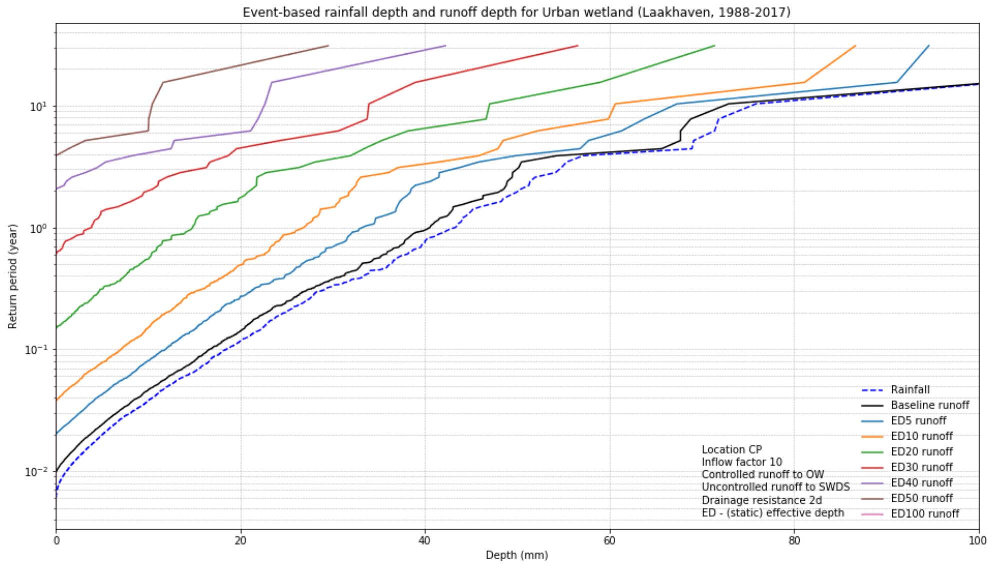
G_L	5**mm**	10**mm**	20**mm**	30**mm**	40**mm**	50**mm**	100**mm**
RB	1.98	3.99	18.79	61.5	182.03	629.97	1259.94
GRE	1.56	1.73	1.96	2.13	2.25	2.36	3.11
GRD	3.82	6.99	25.55	83.05	191.31	383.53	767.06
PP	1.76	3.06	9.93	32.15	80.74	175.45	350.9
BS	1.83	3.24	10.7	28.48	47.93	69.93	81.01
WS	1.99	4.02	18.89	61.59	182.35	630.35	1260.7

Table D.5: Runoff reduction factors for measures with varied configuration modeled under W_H scenario

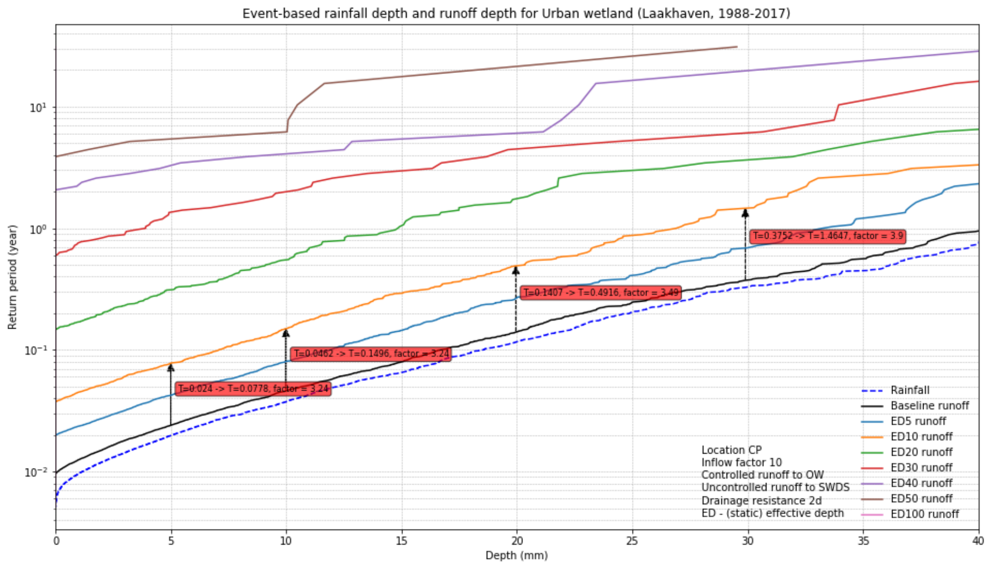
W_H	5**mm**	10**mm**	20**mm**	30**mm**	40**mm**	50**mm**	100**mm**
RB	1.87	3.62	15.77	48.94	140.02	379.85	759.7
GRE	1.49	1.64	1.82	1.94	2.02	2.1	2.56
GRD	3.26	5.58	18.57	61.37	171.84	343.6	687.2
PP	1.69	2.87	8.86	26.32	70.4	158.94	317.88
BS	1.77	3.05	9.28	22.02	36.41	44.12	48.61
WS	1.88	3.63	15.85	49.05	140.11	380.28	760.56

Table D.6: Runoff reduction factors for measures with varied configuration modeled under W_L scenario

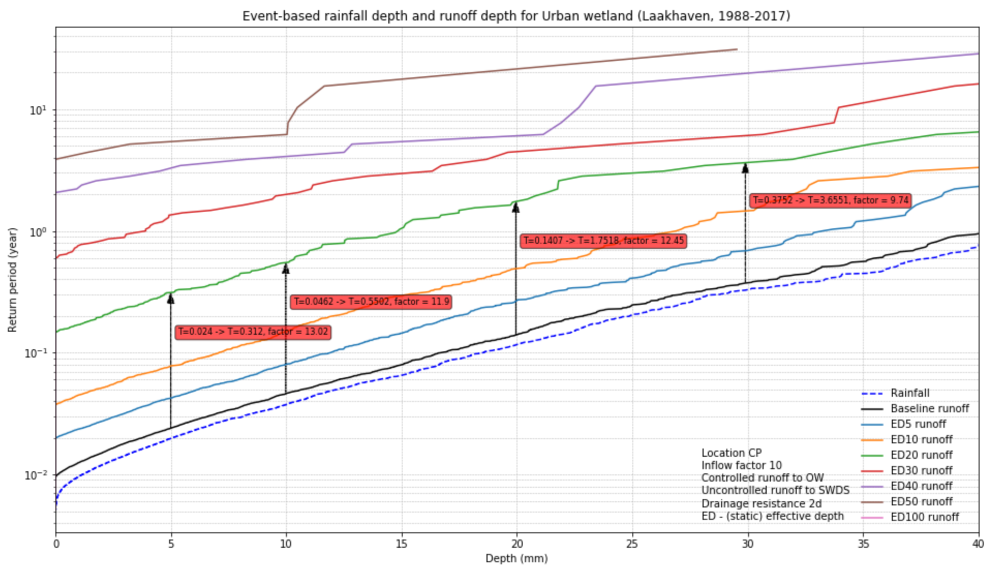
W_L	5**mm**	10**mm**	20**mm**	30**mm**	40**mm**	50**mm**	100**mm**
RB	1.88	3.74	16.27	47.87	124.82	365.96	731.92
GRE	1.53	1.7	1.93	2.09	2.19	2.31	3.02
GRD	3.66	6.61	23.26	78.19	178.54	345.67	691.34
PP	1.68	2.92	9.2	26.66	66.83	153	306
BS	1.76	3.1	9.78	22.66	35.08	44.31	47.65
WS	1.89	3.76	16.31	47.94	125	366.14	732.28



(a) Return period of event-based rainfall depth and runoff depth for Urban wetland

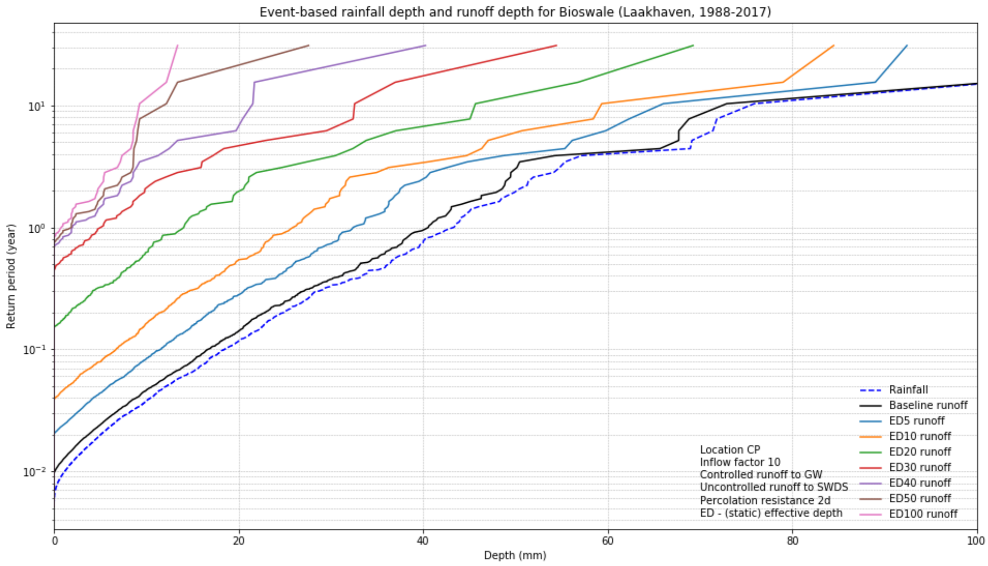


(b) Runoff frequency reduction factor for Urban wetland with 10 mm effective depth

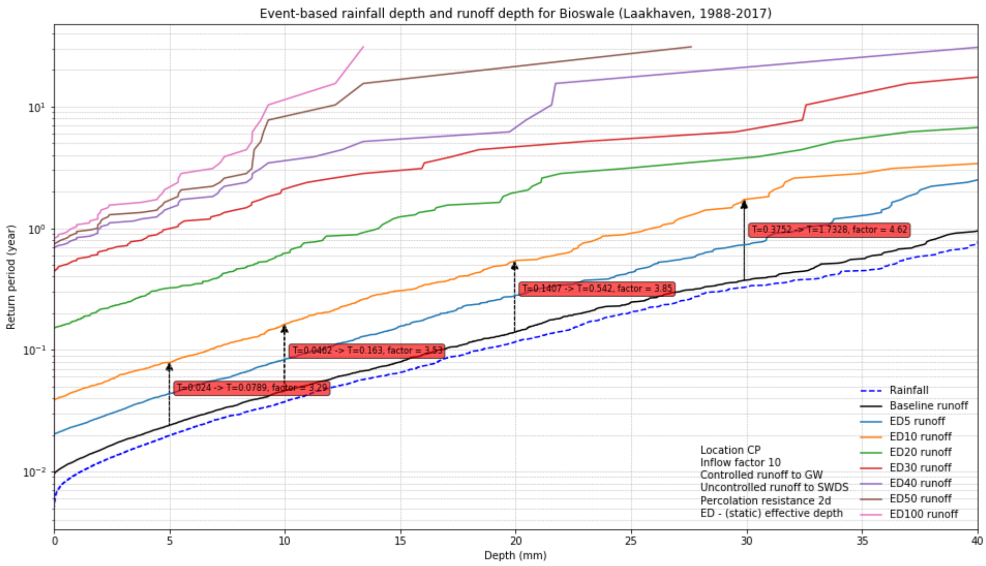


(c) Runoff frequency reduction factor for Urban wetland with 20 mm effective depth

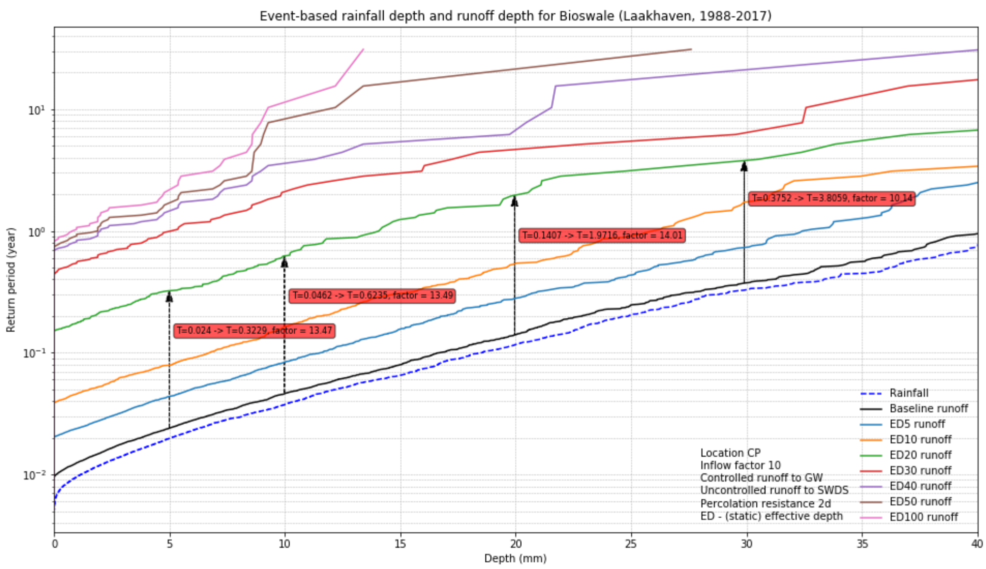
Figure D.1: Runoff frequency reduction factor for Urban wetland with different effective depth specifications



(a) Return period of event-based rainfall depth and runoff depth for Bioswale

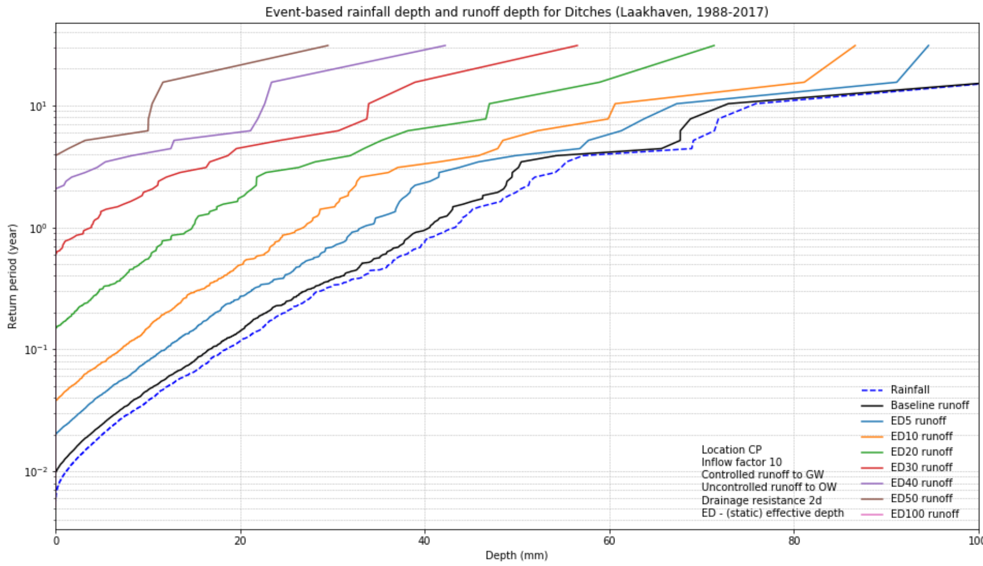


(b) Runoff frequency reduction factor for Bioswale with 10 mm effective depth

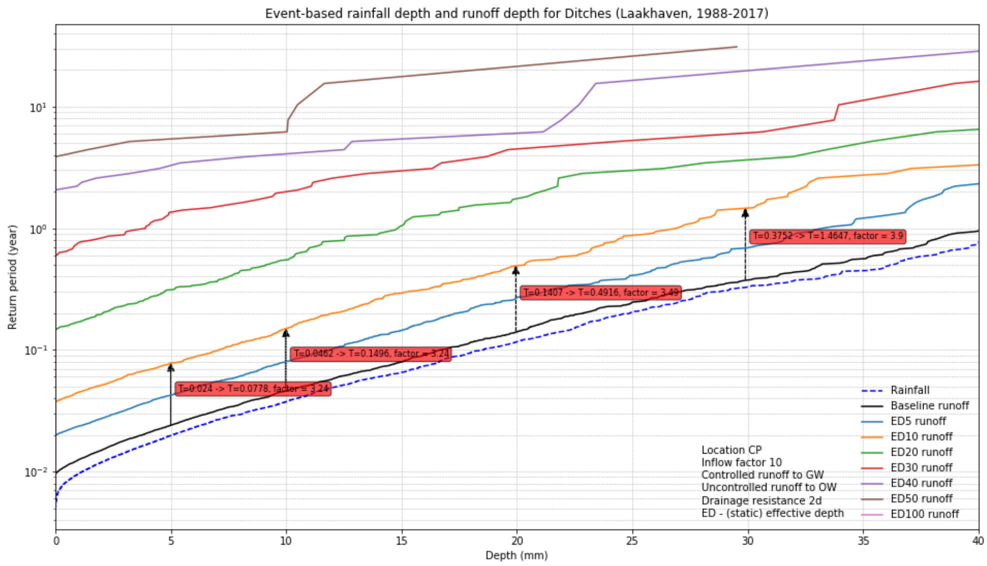


(c) Runoff frequency reduction factor for Bioswale with 20 mm effective depth

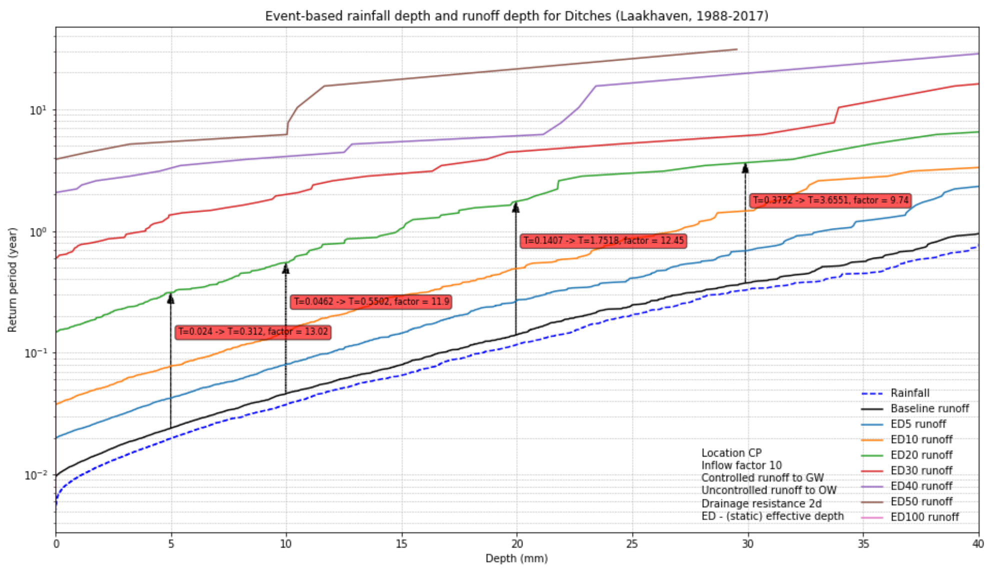
Figure D.2: Runoff frequency reduction factor for Bioswale with different effective depth specifications



(a) Return period of event-based rainfall depth and runoff depth for Ditches

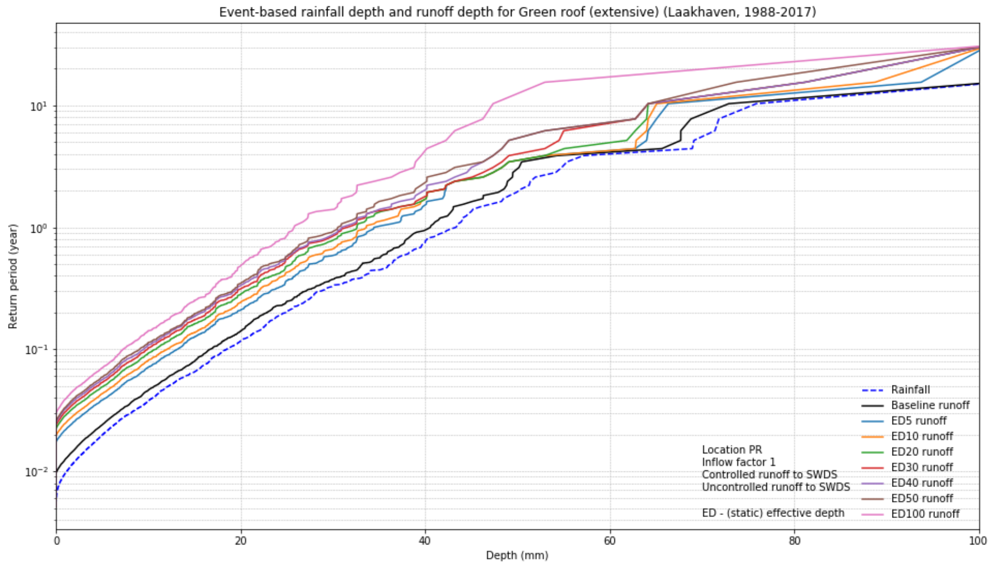


(b) Runoff frequency reduction factor for Ditches with 10 mm effective depth

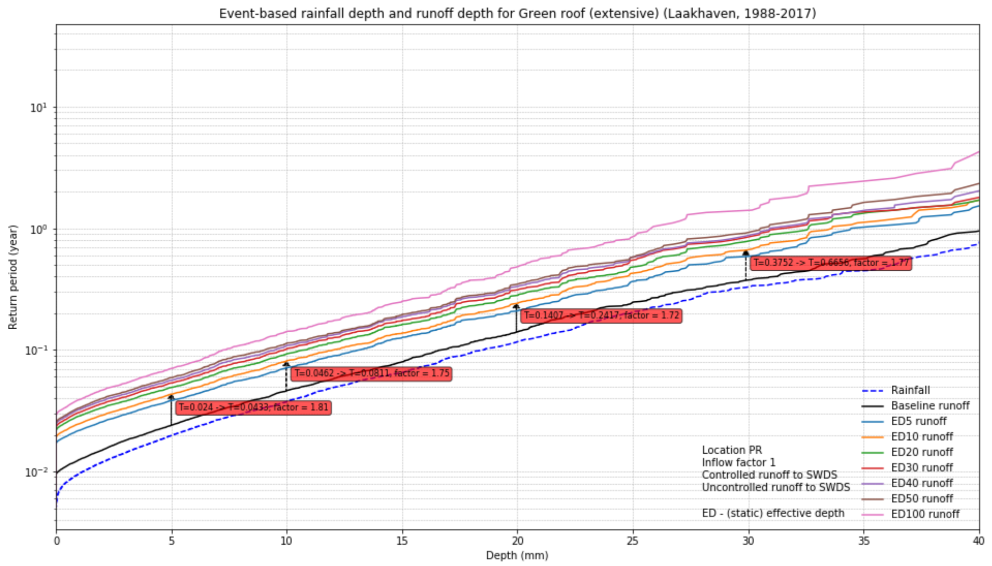


(c) Runoff frequency reduction factor for Ditches with 20 mm effective depth

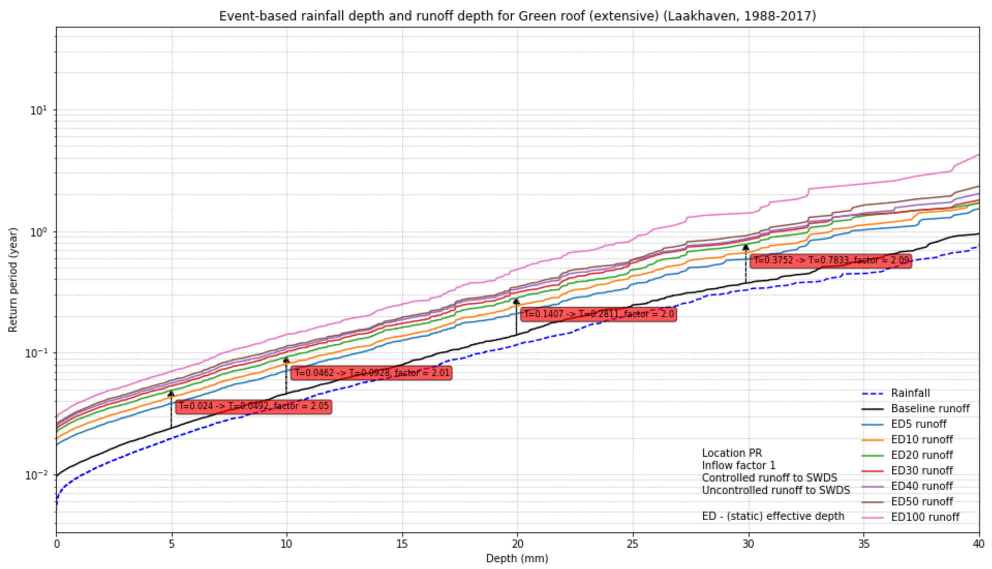
Figure D.3: Runoff frequency reduction factor for Ditches with different effective depth specifications



(a) Return period of event-based rainfall depth and runoff depth for Green roof (extensive)

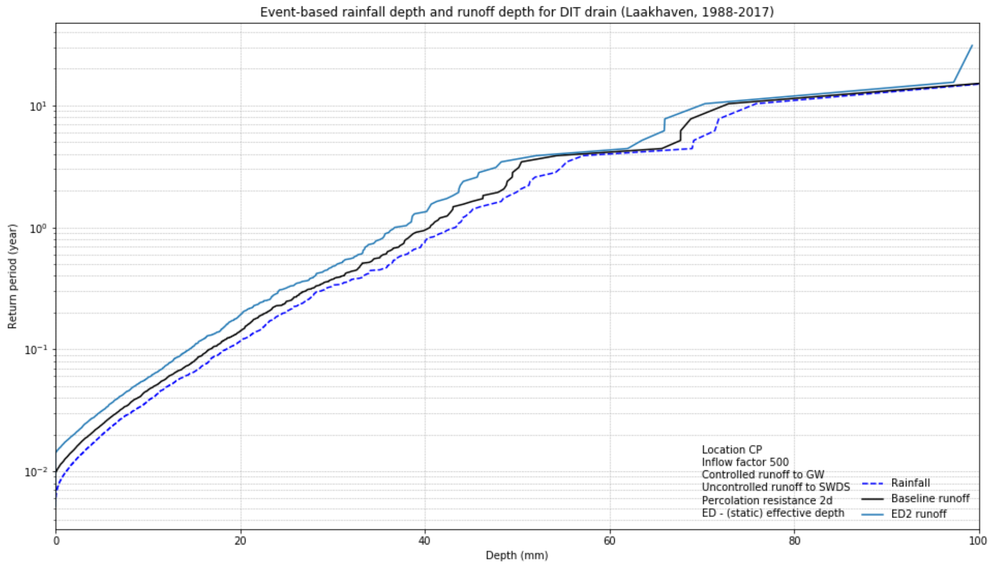


(b) Runoff frequency reduction factor for Green roof (extensive) with 10 mm effective depth

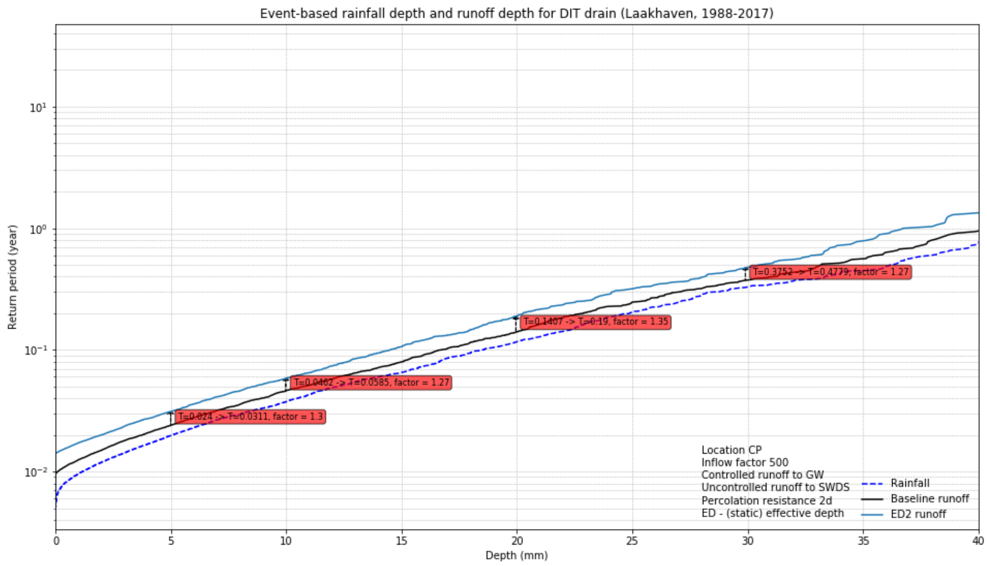


(c) Runoff frequency reduction factor for Green roof (extensive) with 20 mm effective depth

Figure D.4: Runoff frequency reduction factor for Green roof (extensive) with different effective depth specifications

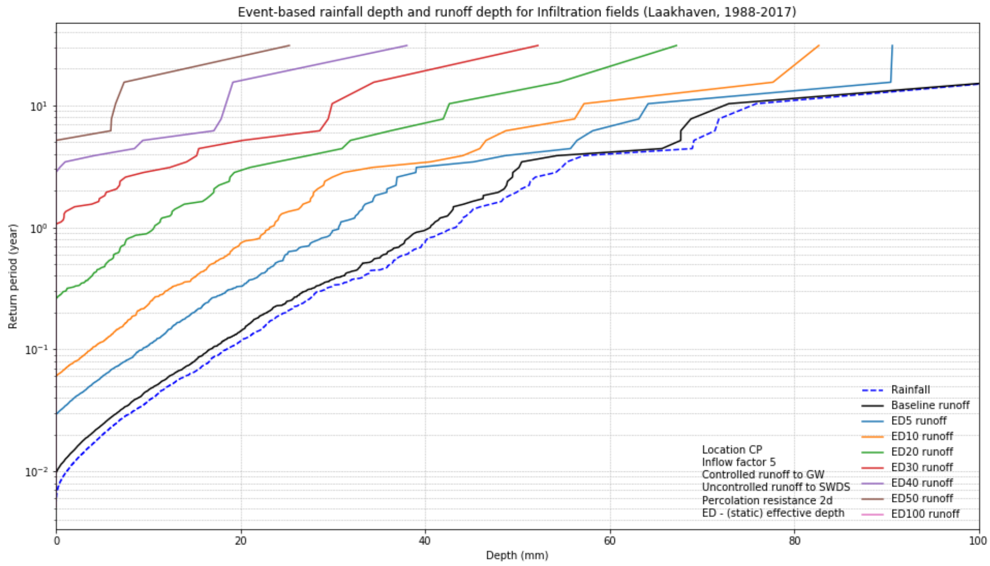


(a) Return period of event-based rainfall depth and runoff depth for DIT drain

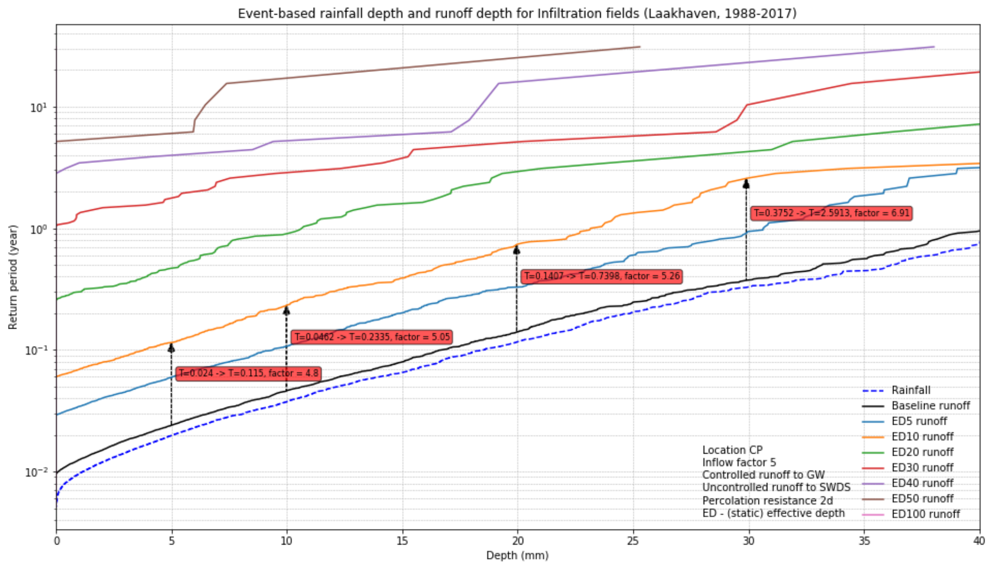


(b) Runoff frequency reduction factor for DIT drain with 2 mm effective depth

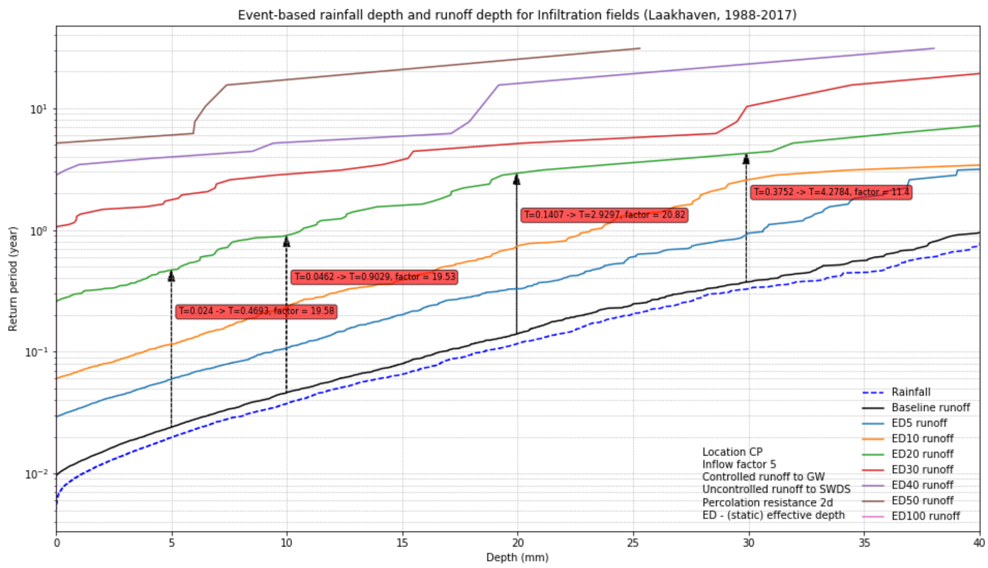
Figure D.5: Runoff frequency reduction factor for DIT drain with different effective depth specifications



(a) Return period of event-based rainfall depth and runoff depth for Infiltration fields

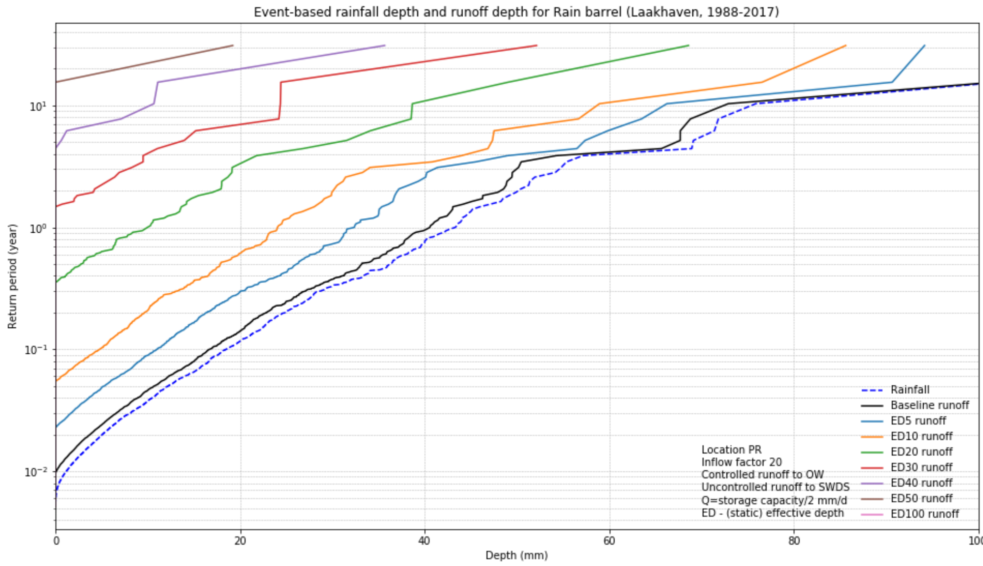


(b) Runoff frequency reduction factor for Infiltration fields with 10 mm effective depth

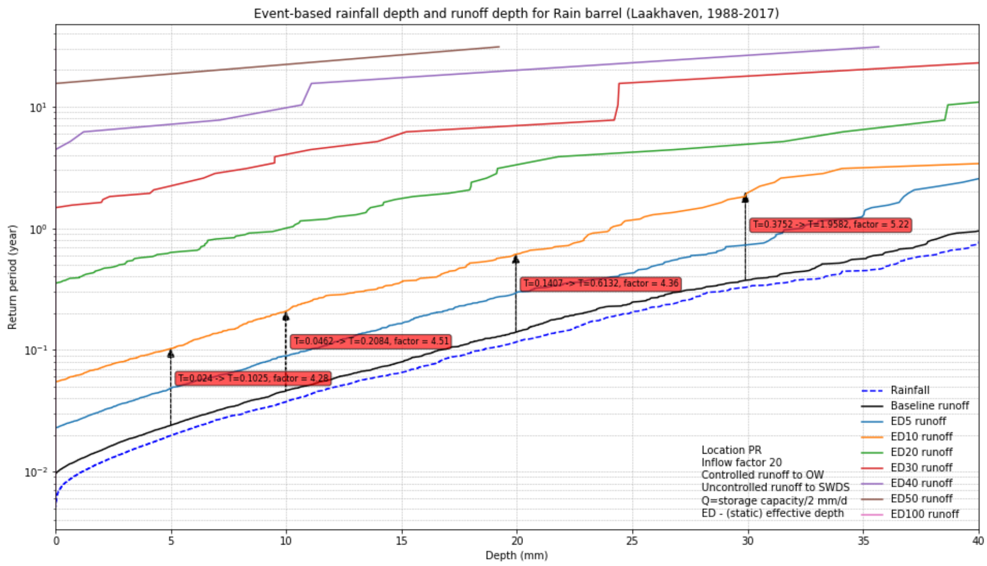


(c) Runoff frequency reduction factor for Infiltration fields with 20 mm effective depth

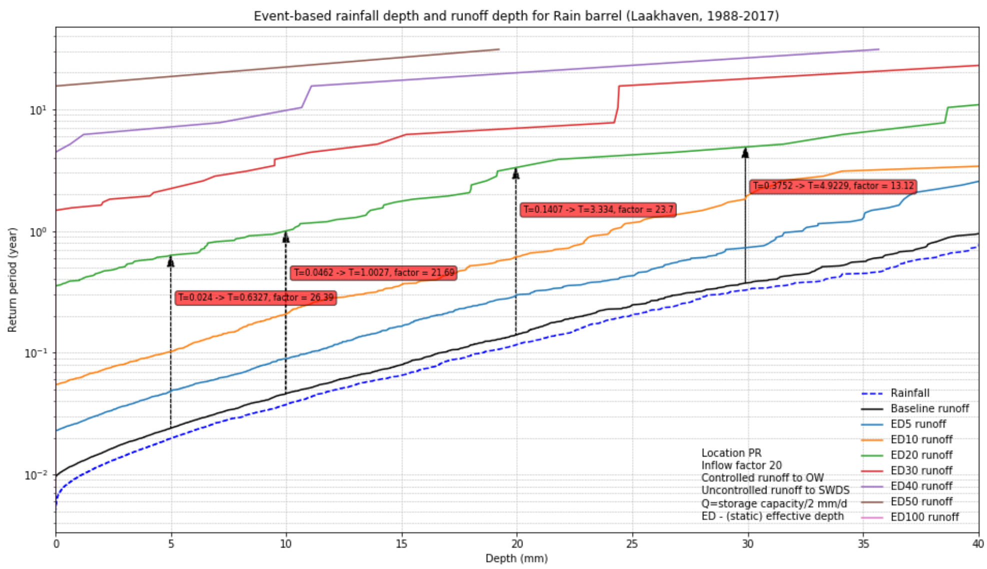
Figure D.6: Runoff frequency reduction factor for Infiltration fields with different effective depth specifications



(a) Return period of event-based rainfall depth and runoff depth for Rain barrel

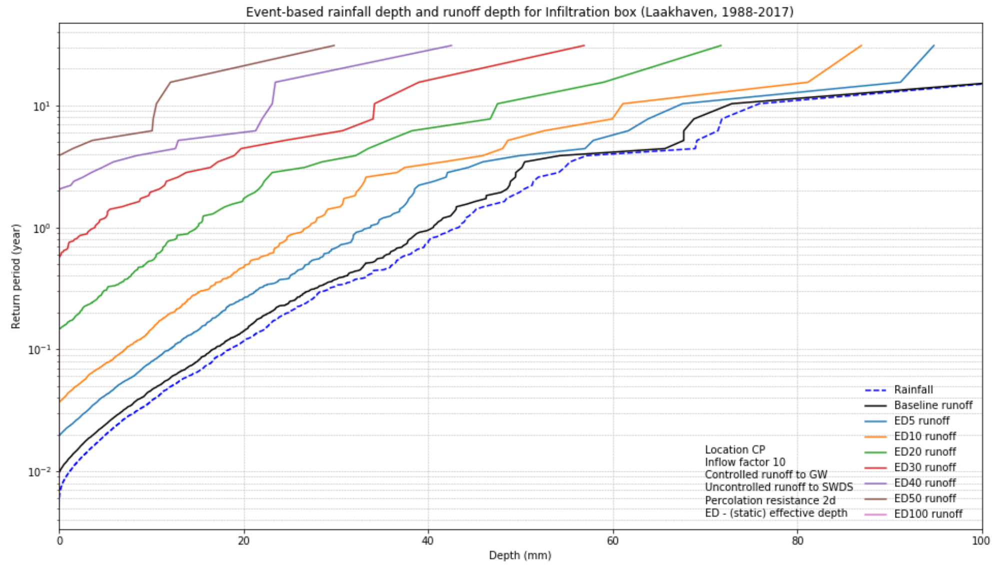


(b) Runoff frequency reduction factor for Rain barrel with 10 mm effective depth

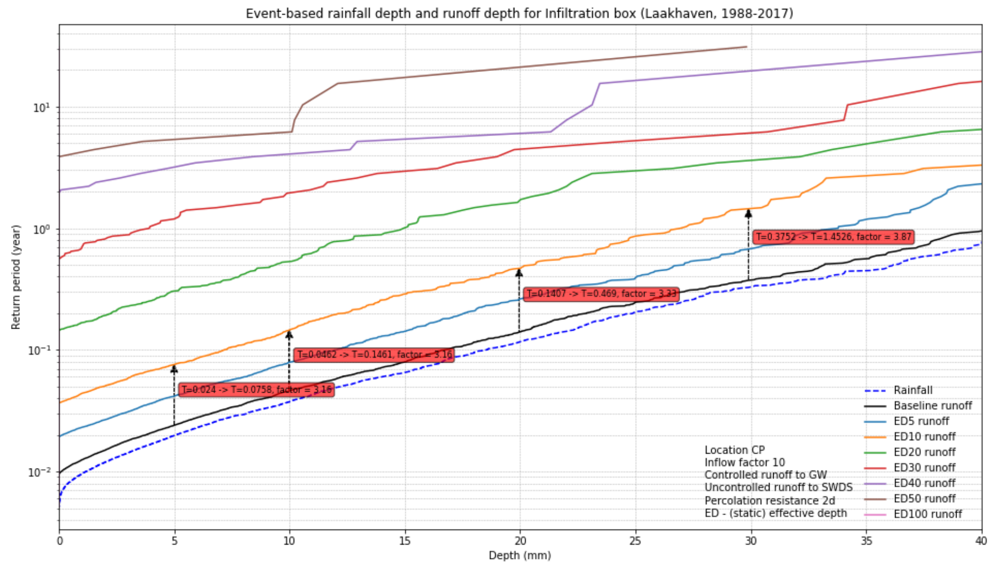


(c) Runoff frequency reduction factor for Rain barrel with 20 mm effective depth

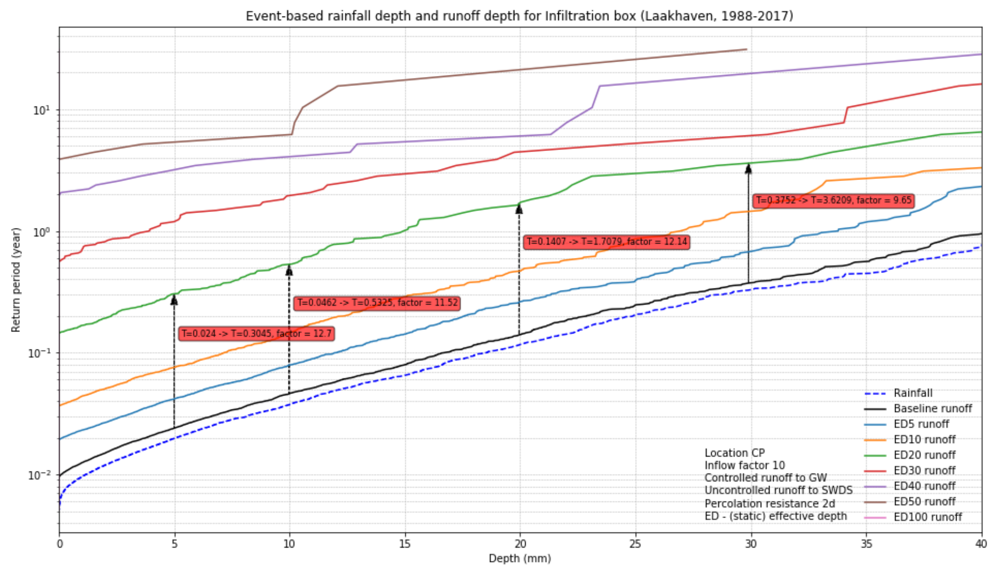
Figure D.7: Runoff frequency reduction factor for Rain barrel with different effective depth specifications



(a) Return period of event-based rainfall depth and runoff depth for Infiltration box

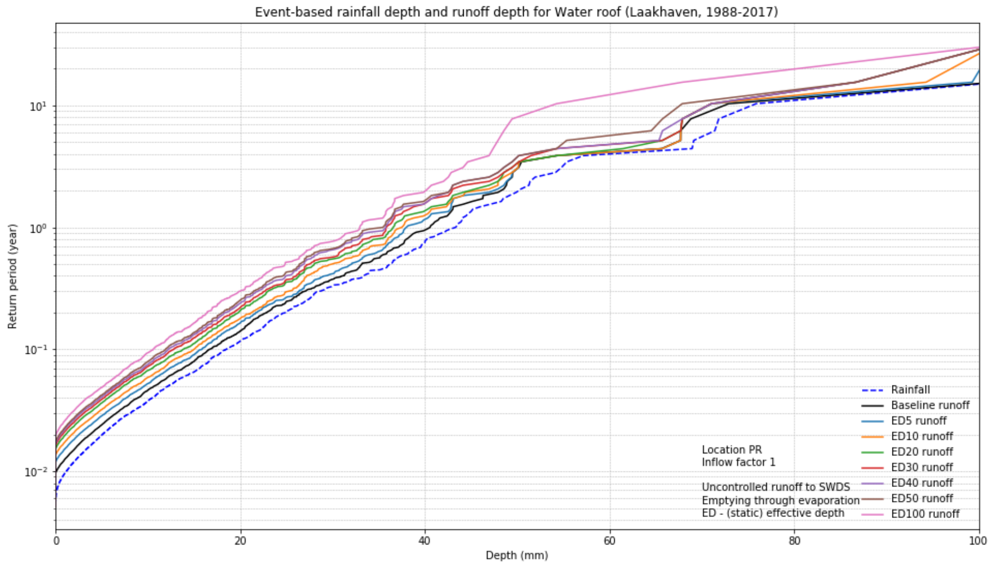


(b) Runoff frequency reduction factor for Infiltration box with 10 mm effective depth

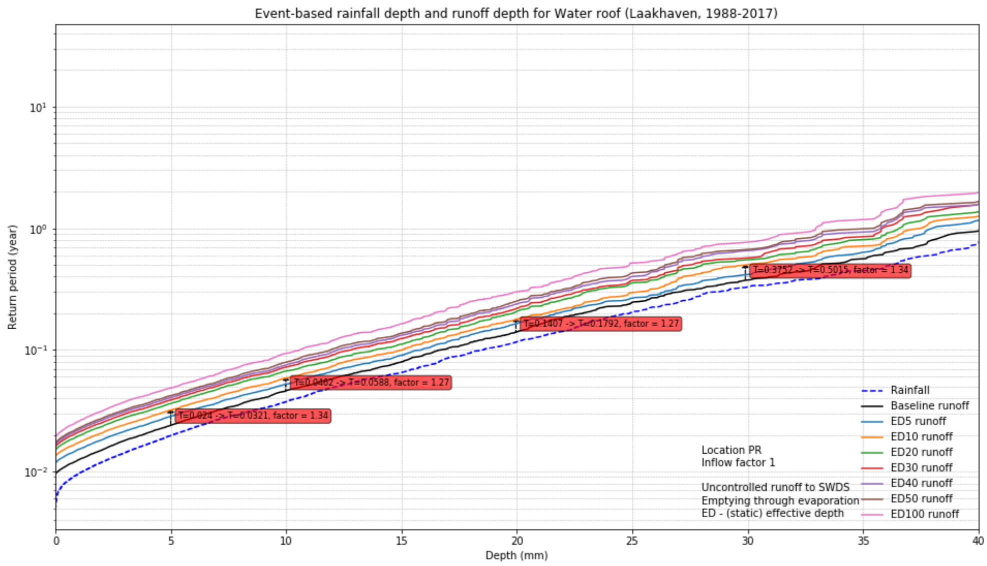


(c) Runoff frequency reduction factor for Infiltration box with 20 mm effective depth

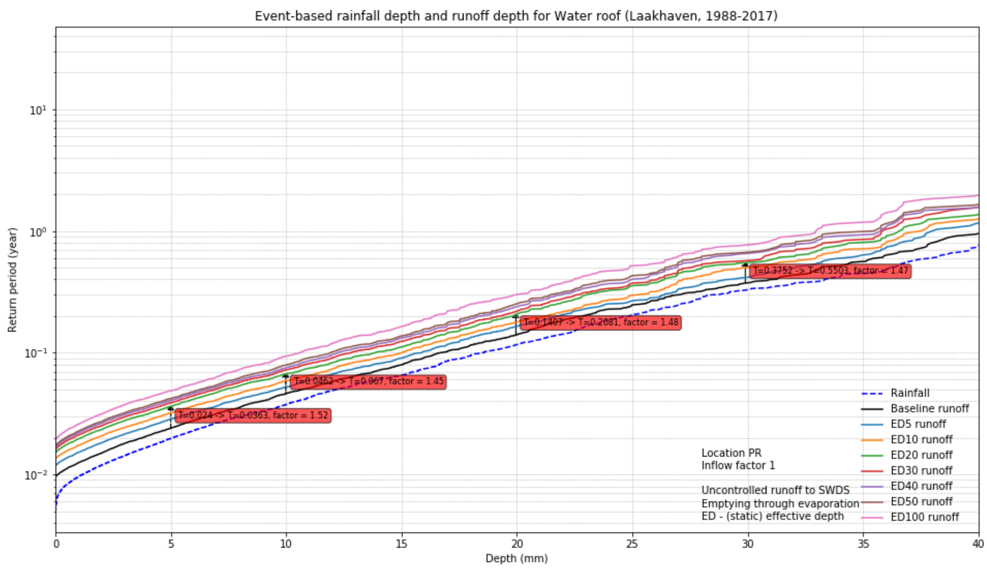
Figure D.8: Runoff frequency reduction factor for Infiltration box with different effective depth specifications



(a) Return period of event-based rainfall depth and runoff depth for Water roof

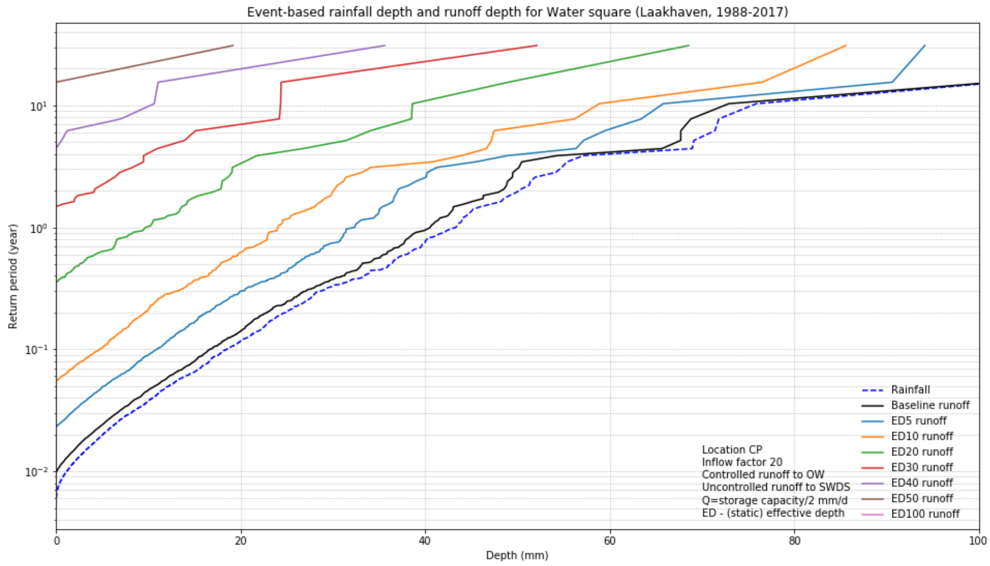


(b) Runoff frequency reduction factor for Water roof with 10 mm effective depth

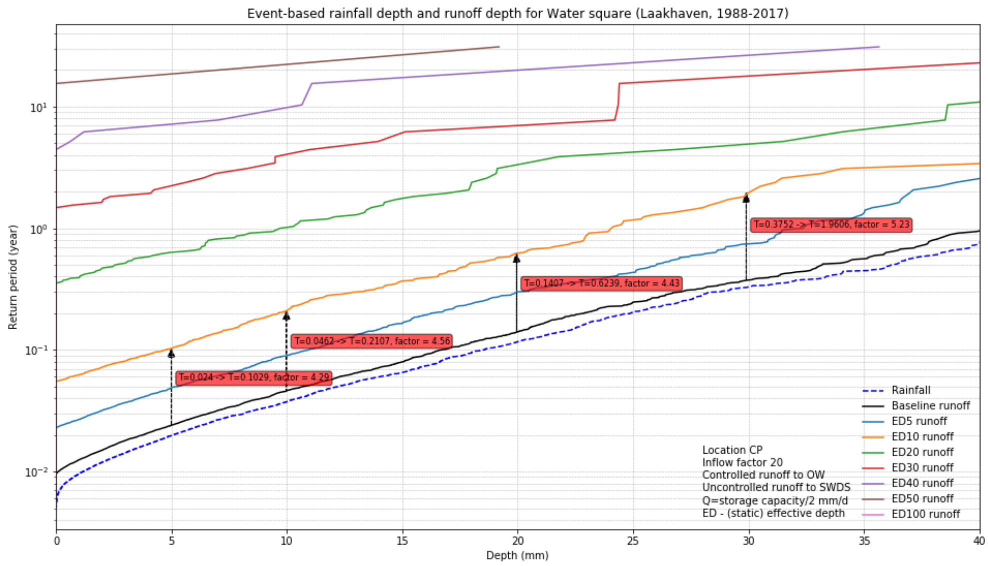


(c) Runoff frequency reduction factor for Water roof with 20 mm effective depth

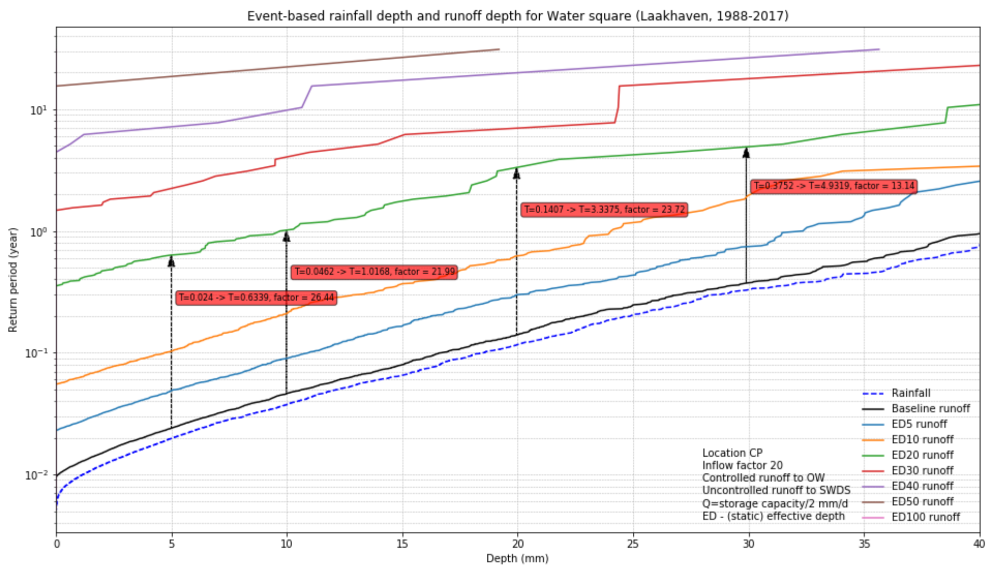
Figure D.9: Runoff frequency reduction factor for Water roof with different effective depth specifications



(a) Return period of event-based rainfall depth and runoff depth for Water square

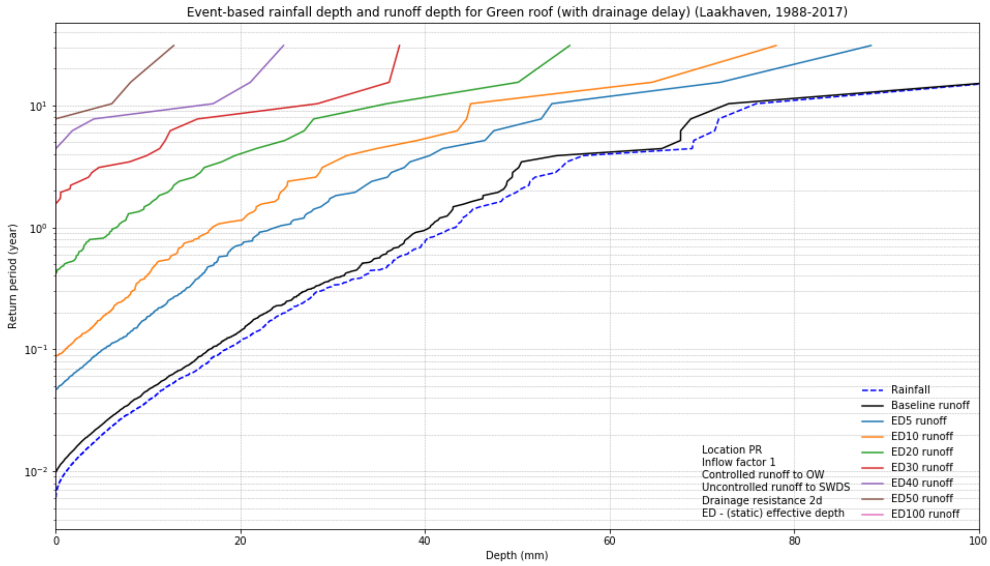


(b) Runoff frequency reduction factor for Water square with 10 mm effective depth

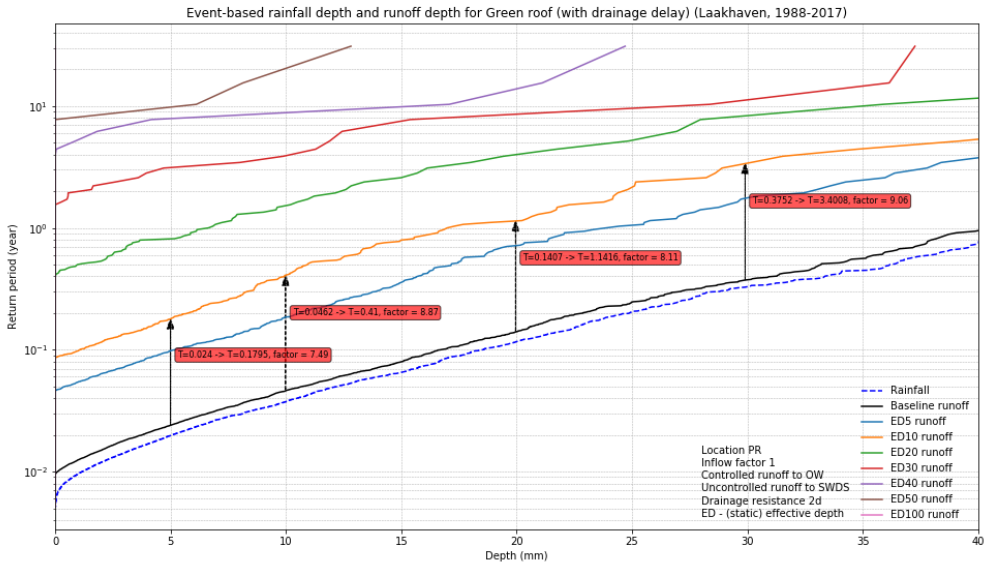


(c) Runoff frequency reduction factor for Water square with 20 mm effective depth

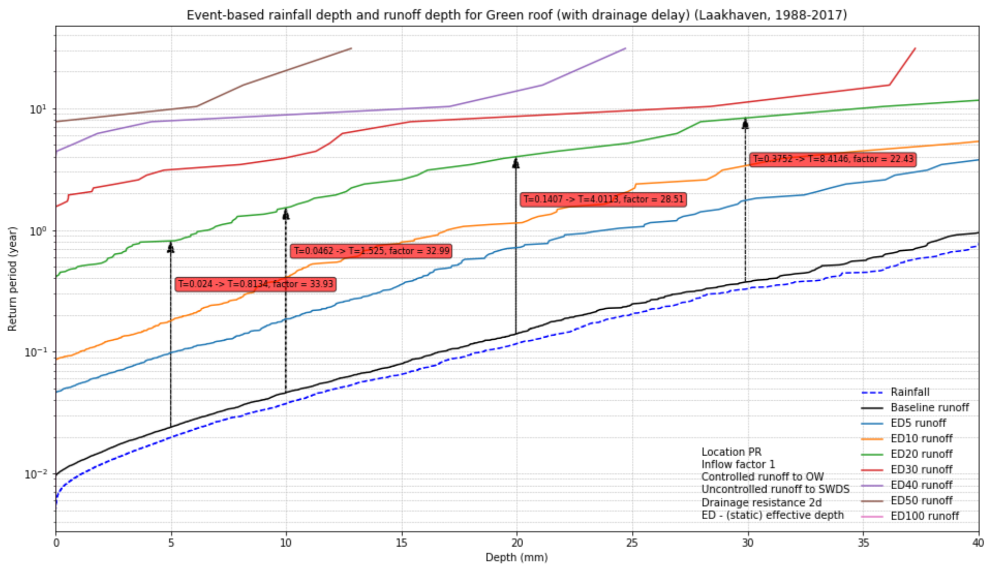
Figure D.10: Runoff frequency reduction factor for Water square with different effective depth specifications



(a) Return period of event-based rainfall depth and runoff depth for Green roof (with drainage delay)

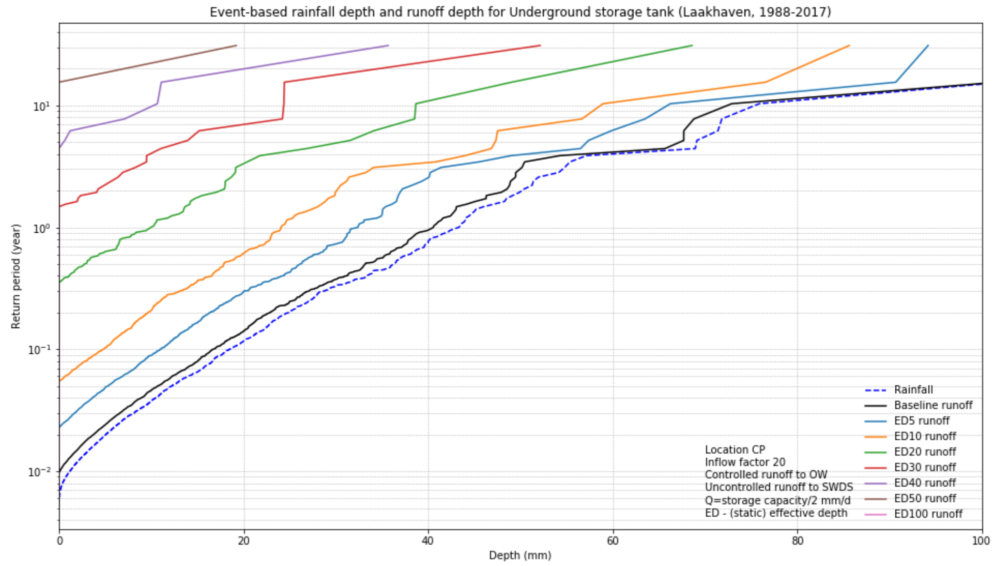


(b) Runoff frequency reduction factor for Green roof (with drainage delay) with 10 mm effective depth

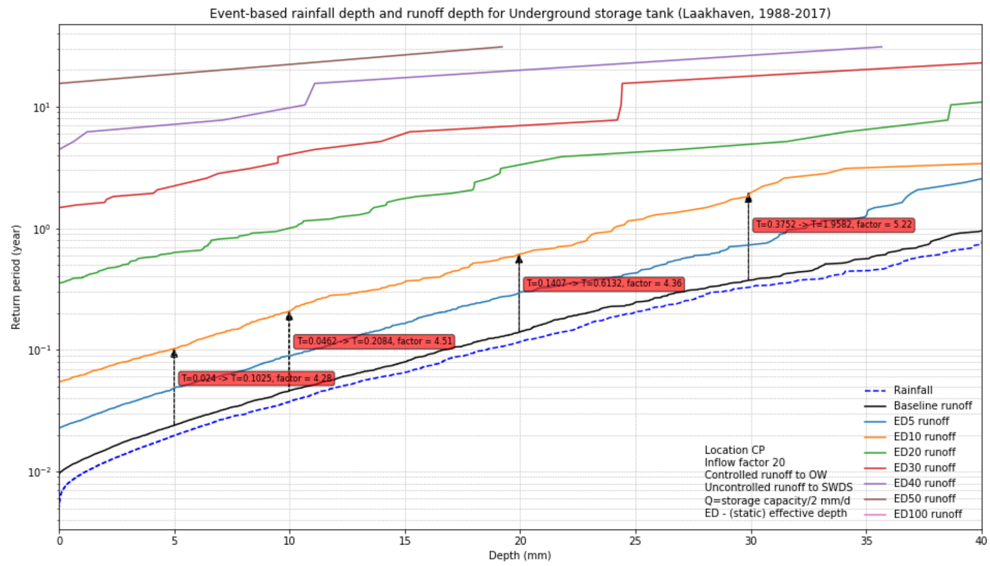


(c) Runoff frequency reduction factor for Green roof (with drainage delay) with 20 mm effective depth

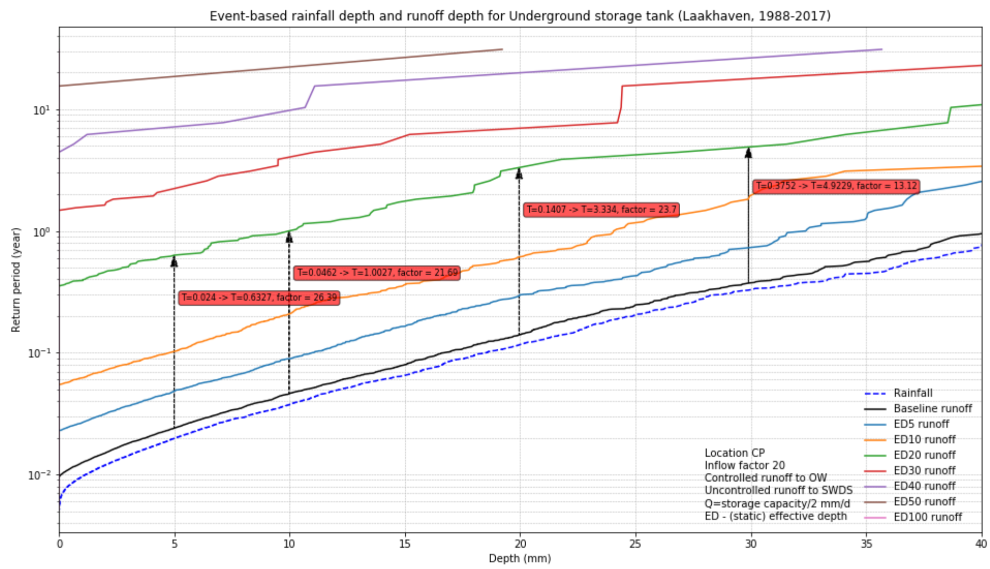
Figure D.11: Runoff frequency reduction factor for Green roof (with drainage delay) with different effective depth specifications



(a) Return period of event-based rainfall depth and runoff depth for Underground storage tank

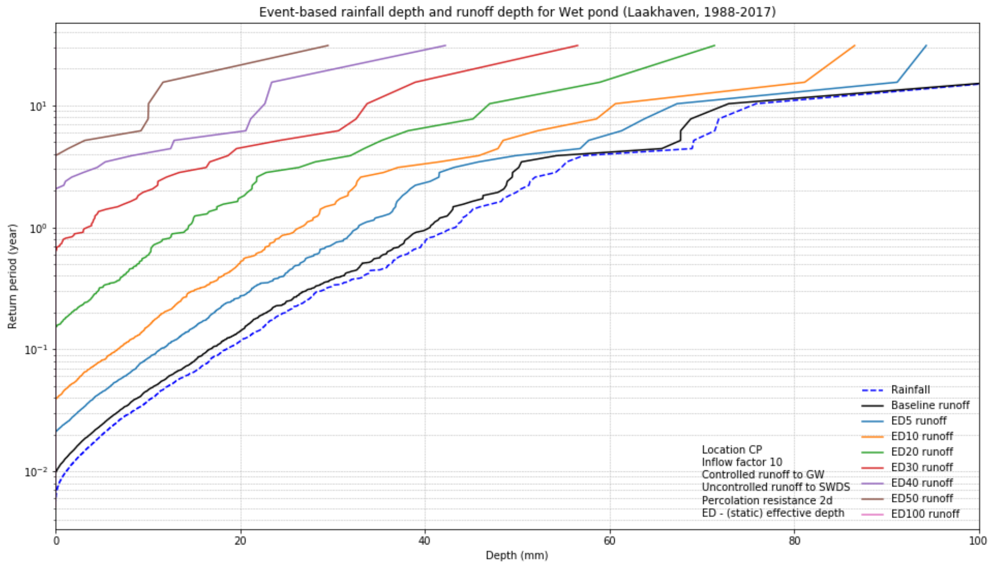


(b) Runoff frequency reduction factor for Underground storage tank with 10 mm effective depth

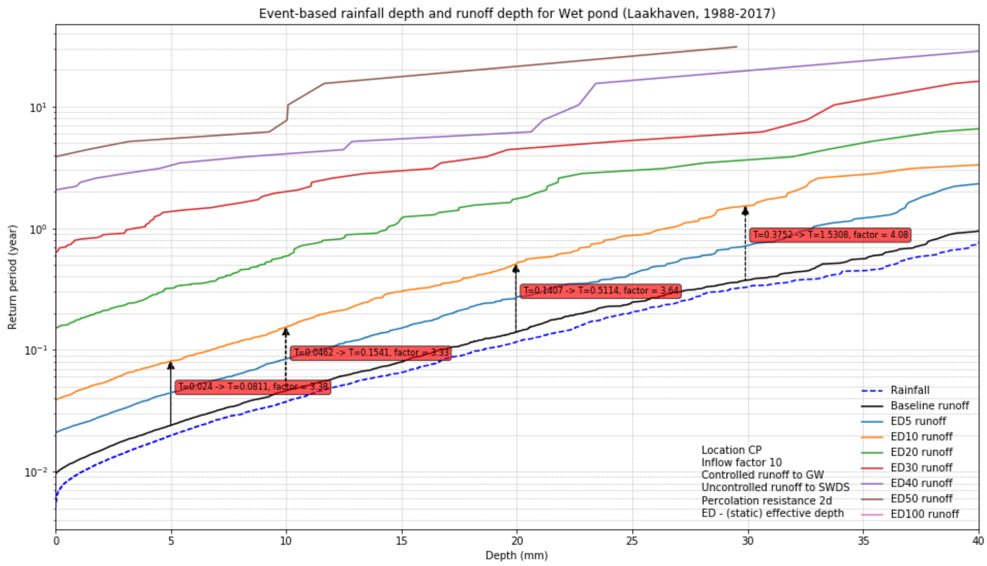


(c) Runoff frequency reduction factor for Underground storage tank with 20 mm effective depth

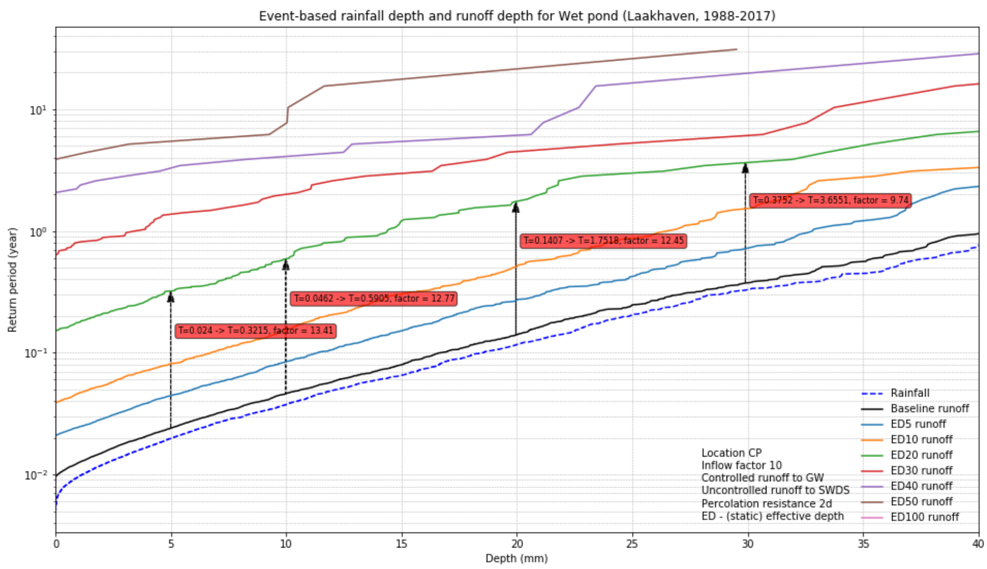
Figure D.12: Runoff frequency reduction factor for Underground storage tank with different effective depth specifications



(a) Return period of event-based rainfall depth and runoff depth for Wet pond

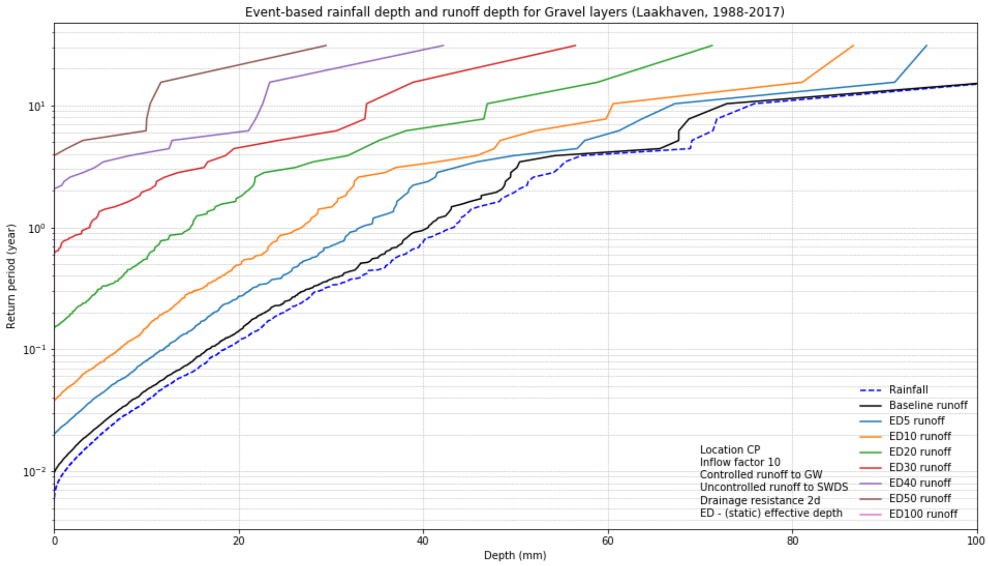


(b) Runoff frequency reduction factor for Wet pond with 10 mm effective depth

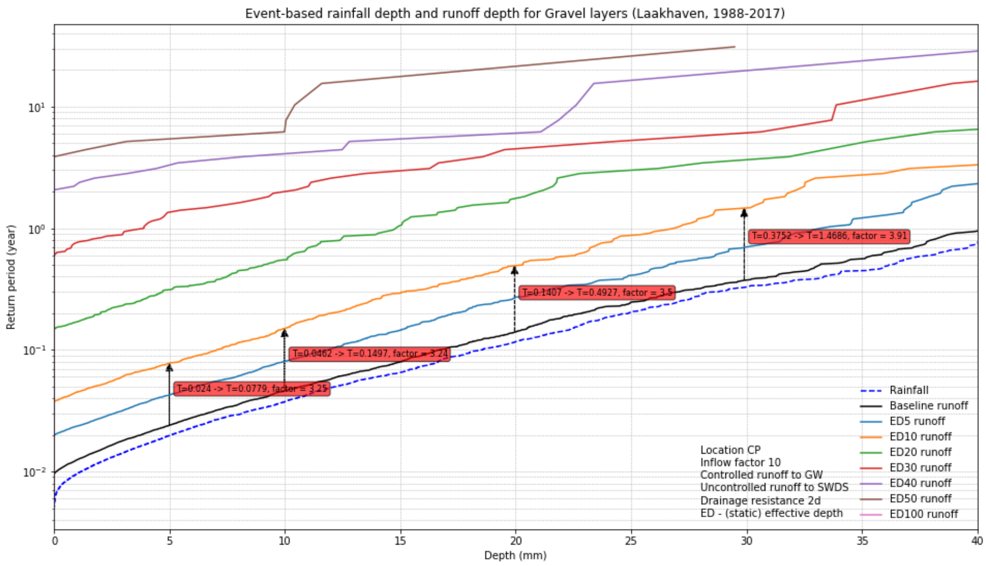


(c) Runoff frequency reduction factor for Wet pond with 20 mm effective depth

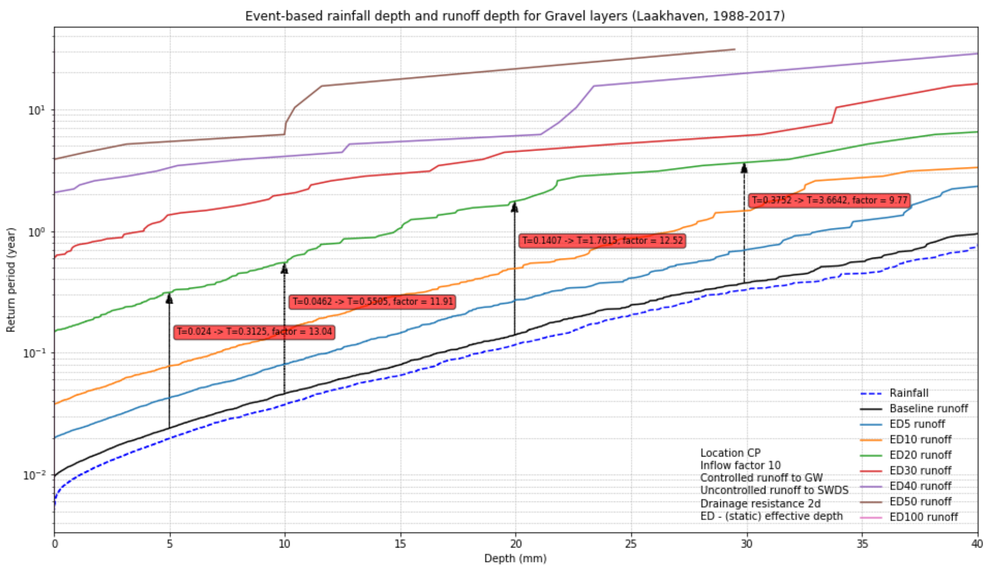
Figure D.13: Runoff frequency reduction factor for Wet pond with different effective depth specifications



(a) Return period of event-based rainfall depth and runoff depth for Gravel layers

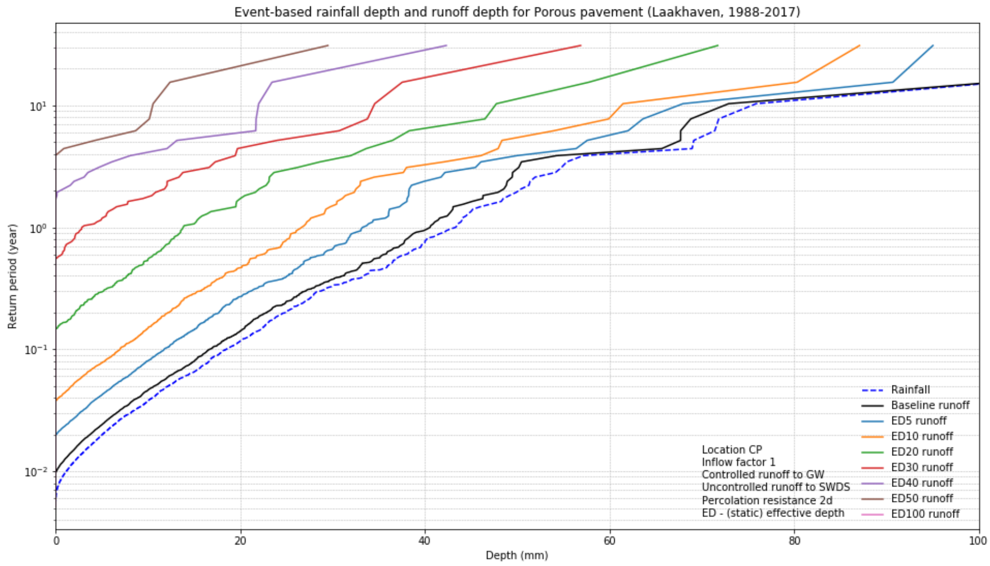


(b) Runoff frequency reduction factor for Gravel layers with 10 mm effective depth

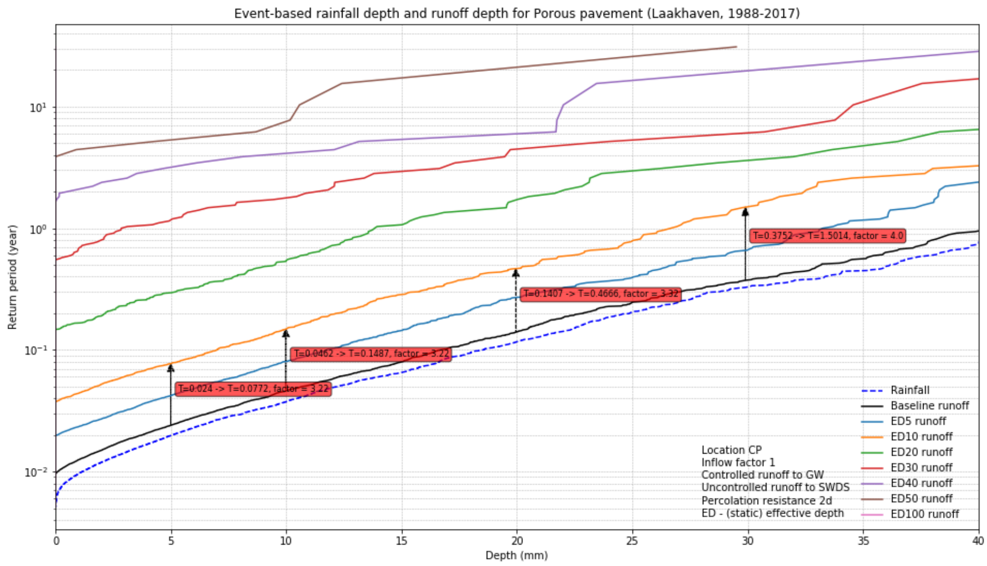


(c) Runoff frequency reduction factor for Gravel layers with 20 mm effective depth

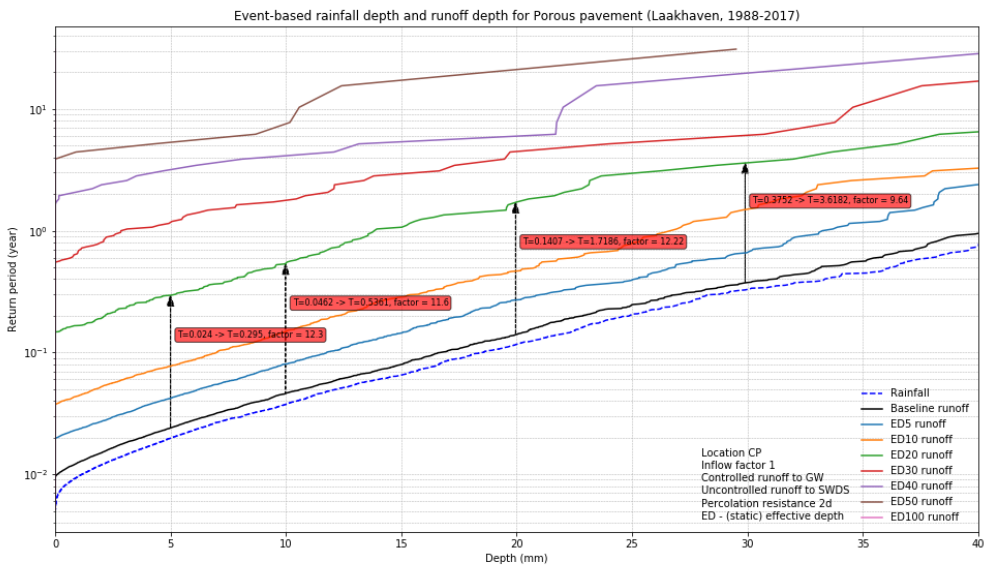
Figure D.14: Runoff frequency reduction factor for Gravel layers with different effective depth specifications



(a) Return period of event-based rainfall depth and runoff depth for Porous pavement

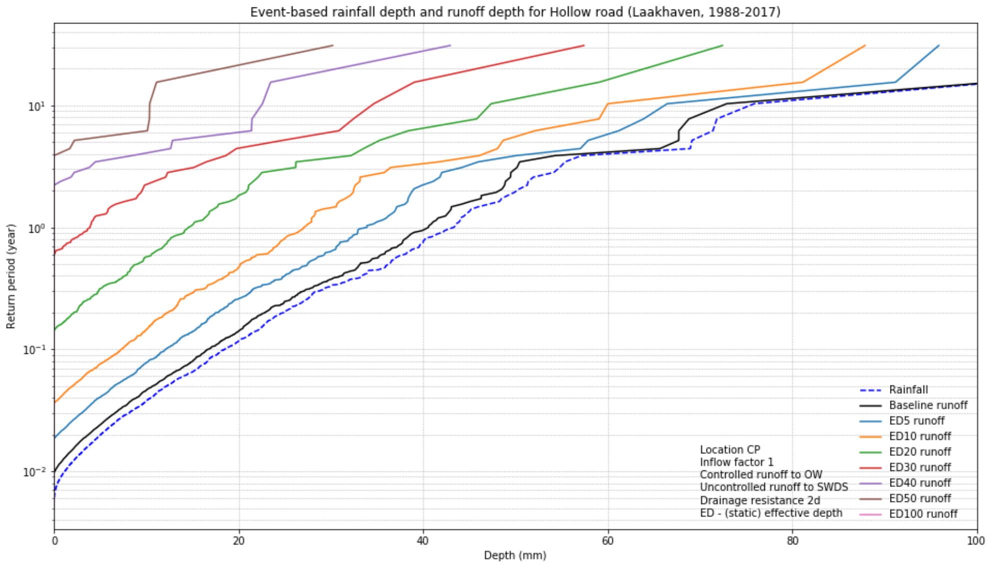


(b) Runoff frequency reduction factor for Porous pavement with 10 mm effective depth

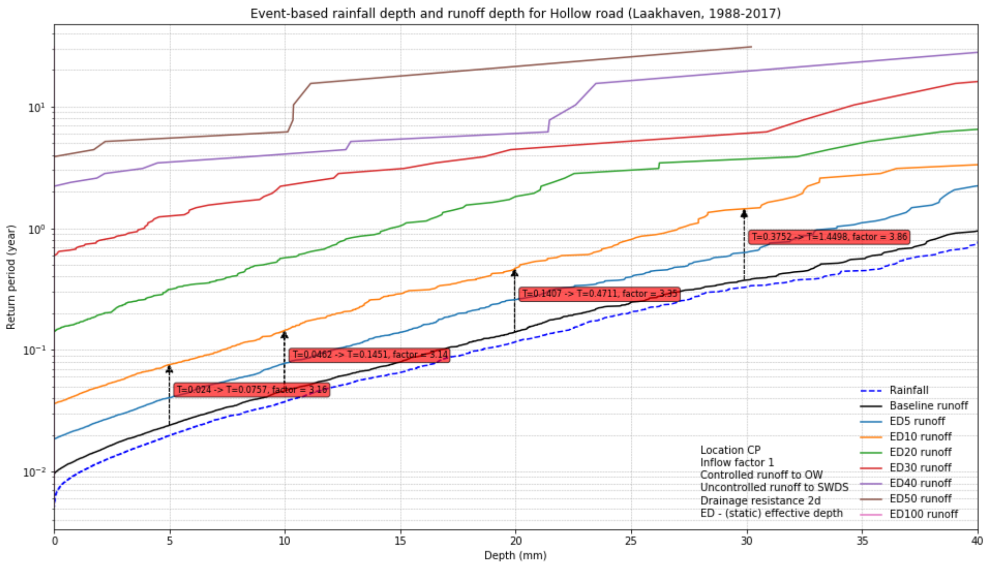


(c) Runoff frequency reduction factor for Porous pavement with 20 mm effective depth

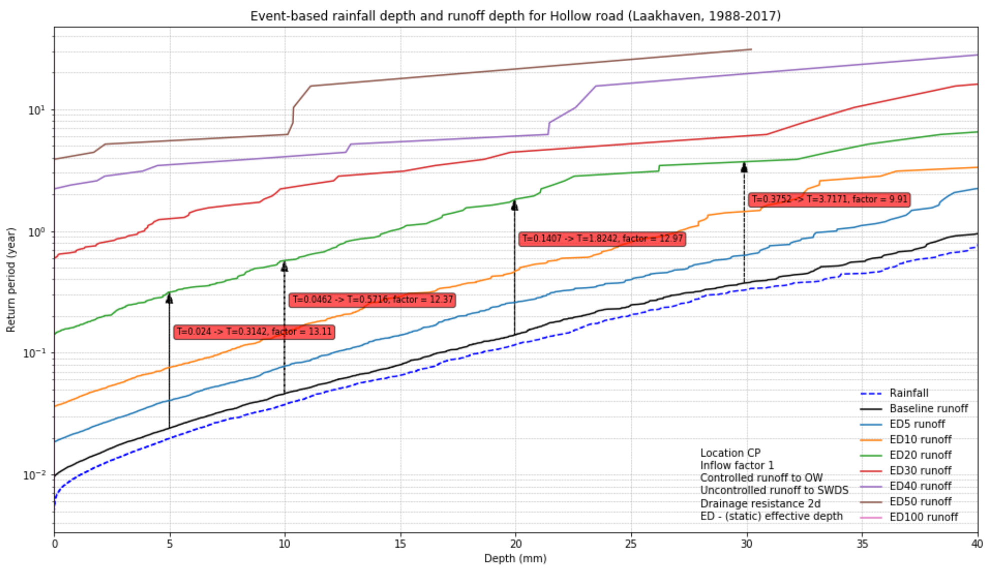
Figure D.15: Runoff frequency reduction factor for Porous pavement with different effective depth specifications



(a) Return period of event-based rainfall depth and runoff depth for Hollow road



(b) Runoff frequency reduction factor for Hollow road with 10 mm effective depth



(c) Runoff frequency reduction factor for Hollow road with 20 mm effective depth

Figure D.16: Runoff frequency reduction factor for Hollow road with different effective depth specifications

D.1 Conversion from measure inflow area to entire area

Runoff frequency reduction factor is calculated with the Urbanwb model. As stated above, it indicates how the frequency of floods is altered by the implementation of adaptation measures. However, this factor only describes a measure's effect of reducing runoff frequency over the measure inflow area. And the measure inflow area is usually partial of the entire area as shown in the figure D.17. The measure inflow area theoretically can have nothing to do with the measure area — runoff from far away even outside the study area can be directed to a centralized measure through channels. But here it is assumed that the measure area is encompassed by the measure inflow area with an inflow factor [1] greater or equal to 1 and thus is not plotted in the figure D.17.

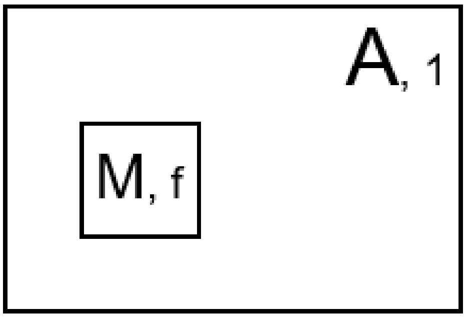


Figure D.17: Illustration of the entire area and the measures inflow area, where A denotes the entire area, the entire area excluding the measure inflow area has the runoff frequency reduction factor of 1, M denotes the measure inflow area, and f is runoff frequency reduction factor over the measure inflow area, which is directly calculated with the Urbanwb Model.

Previously, a simple formula was applied to do the straightforward conversion as follows:

$$f_{tot} = \frac{M \cdot f + (A - M) \cdot 1}{A}$$

,where A is the area of the entire study area, M is area of the measure inflow area, f is the calculated runoff frequency reduction factor of a measure over the measure inflow area, f_{tot} is the runoff frequency reduction factor over the entire area after conversion. However, this method was later found inappropriate under some extreme conditions, for instance, a tiny fraction of the entire area (1%) is applied with an extremely effective measure with a fairly great reduction factor (10000) over the measure inflow area, then the runoff frequency reduction factor over the entire area converted by the above formula can be unreasonably large (100.99), which is apparently illogical.

Therefore, after careful reconsideration, a new formula was proposed to convert the runoff frequency reduction factor over the measure inflow area to that for the entire area as below:

$$f_{tot} = e^{\frac{A}{M} ln f} \qquad (*)$$

,where A is area of the entire study area, M is area of the measure inflow area, f is the calculated runoff frequency reduction factor over the measure inflow area, f_{tot} is runoff frequency reduction factor over the entire area after conversion. The mathematical derivation

[1] inflow factor = $\frac{\text{measure inflow area}}{\text{measure area}}$, where the measure area is the built-up surface area of a measure and the measure inflow area is the area where the runoff from which flows into the measure, *i.e.* runoff inflow area to the measure.

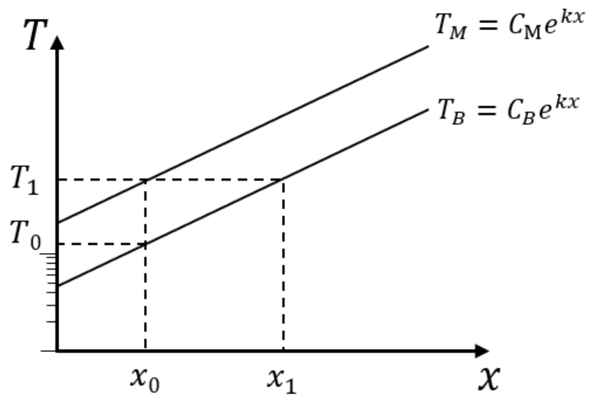


Figure D.18: Simplification graph of runoff depth and return period in a semi-logarithmic graph, x denotes runoff depth (in mm) and T denotes the corresponding return time (in year). Ignoring the extremely small events, the points are roughly fit into straight lines since the return period is exponential related to the event-based runoff depth.

of the new formula is provided below. Figure D.18 shows the simplification of the semi-log scale graph of return period and runoff depth like figure 3.24. In this figure, T_B is the curve for the runoff over the entire area under baseline situation without applied measure, while T_M is the curve for the runoff over the measure inflow area under the situation with applied measure. It is assumed that the curves in this semi-log scale graph obtained by the plotting position method roughly approximate straight lines. Therefore, the runoff return time T (in year) is an exponential function of the event-based runoff depth x (in mm), which reversely indicates that the runoff value x is a natural logarithmic function of the return time T:

$$T = C_1 \cdot e^{C_2 x}$$

$$\mathrm{x} = \frac{1}{C_2} \cdot \ln \frac{T}{C_1}$$

After many modeling experiments, it is found out that the curves are roughly parallel in many cases. Therefore, since two simplification curves are parallel, the C_2 is equal and thus replaced with k in the expressions:

$$T_B = C_B \cdot e^{kx}$$

$$T_M = C_M \cdot e^{kx}$$

For any given runoff value x, runoff frequency reduction factor is a constant and therefore calculated as:

$$f = \frac{T_M}{T_B} = \frac{C_M \cdot \cancel{e^{kx}}}{C_B \cdot \cancel{e^{kx}}} = \frac{C_M}{C_B}$$

In the figure D.18, for a certain runoff value x_0, the return time for the baseline case (situation without applied measure) is $T_0 = T_B|_{x=x_0}$, however, under the situation with measure applied the return time of the same runoff depth is $T_1 = C_M \cdot e^{kx_0}$. For return time T_1, the corresponding runoff value under the baseline situation is thus calculated from $T_1 = C_M \cdot e^{kx_0} = C_B \cdot e^{kx_1}$. Therefore, for any given return period T', in terms of the entire measure inflow area, the runoff value for the baseline case is always $\frac{1}{k}\ln f$ larger than the runoff value when the measure is applied:

$$x_1 = x_0 + \frac{1}{k}\ln f (x_0 > 0)$$

Considering a $T = T'$ event happens to the entire study area that causes the runoff over the entire area under the current situation without measure is x', then the runoff on the measure inflow area if measure applied would be $x' - \frac{1}{k}\ln f$. Therefore, the runoff averaged over the entire area is:

$$\text{Runoff} = \frac{(x' - \frac{1}{k}\ln f)\cdot M + x'\cdot(A-M)}{A} = \frac{\cancel{x'\cdot M} - \frac{1}{k}\ln f\cdot M + x'\cdot A - \cancel{x'\cdot M}}{A} = x' - \frac{M}{A}\cdot\frac{1}{k}\ln f$$

This indicates for a given return time T', the runoff value over the entire area is reduced by a fix amount which is related to the area ratio of the measure inflow area M over the entire area A, as shown in the figure D.19 below:

$$(T', x') \Rightarrow (T', x' - \frac{M}{A}\cdot\frac{1}{k}\ln f)$$

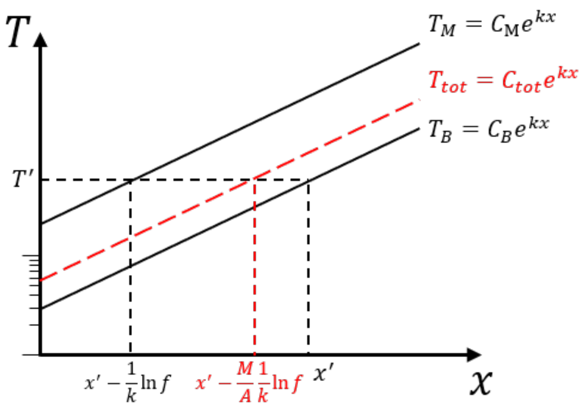


Figure D.19: Simplification of runoff depth and return period in a semi-logarithmic graph, x' denotes any given runoff depth (in mm) and T' denotes the return time corresponding to x' (in year), A is the entire area, M is the measure inflow area, T_M is the curve for the measure inflow area, T_B is the curve for the runoff over the entire area under the baseline case without measure and for the runoff over the entire area excluding the measure inflow area under the case with applied measure. T_{tot} is the curve for the runoff averaged over the entire area under the situation with applied measure.

Therefore, the runoff frequency reduction factor over the entire area is calculated as following:

$$f_{tot} = \frac{T'}{T_B|_{x=x'-\frac{M}{A}\cdot\frac{1}{k}\ln f}} = \frac{T_B|_{x=x'}}{T_B|_{x=x'-\frac{M}{A}\cdot\frac{1}{k}\ln f}} = \frac{C_B\cdot e^{kx'}}{C_B\cdot e^{k(x'-\frac{M}{A}\cdot\frac{1}{k}\ln f)}} = e^{\frac{M}{A}\ln f} = f^{\frac{M}{A}}$$

,where f_{tot} is the runoff frequency reduction factor over the entire area with applied measure, A is the entire area, M is the measure inflow area, and f is the runoff frequency reduction factor over the measure inflow area. For now, the formula to do the conversion of the runoff frequency reduction factor from over the measure inflow area to over the entire area is updated with the new one, which has been mathematically proven more reasonable than the old formula. Another step forward is pushed by asking "What if the entire area contains unpaved land surface where the majority of water infiltrates and naturally drains instead of running off?" To answer this question, Vergroesen (2019) adapted the above formula by including the rest of the entire area excluding the paved area, like unpaved area and surface water. As shown in the figure D.20, compared to the figure D.17, now the entire area is made up of total paved area where the runoff and drainage through sewer system is dominant and the rest of the area where the infiltration and natural drainage is more prevalent. Runoff from unpaved area is also possible provided that hortonian overland flow and saturation overland flow happen or runoff from the paved area is partially disconnected to the sewer system and flows to the unpaved land surface. Runoff percentage from the rest of the area is estimated by analyzing the output time series of the Urbanwb model.

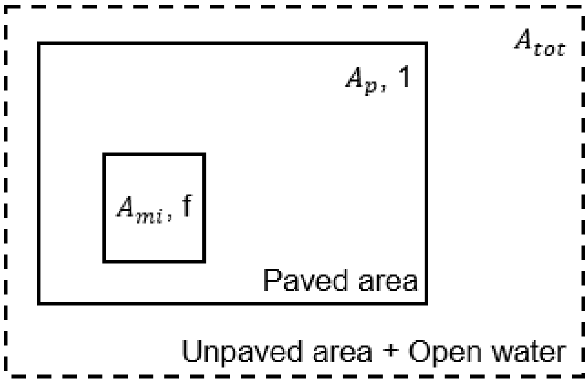


Figure D.20: Illustration of the entire area, the entire paved area, the rest area and the measures inflow area, where A_{tot} denotes the entire area, A_p denotes the entire paved area, A_{mi} denotes the measure inflow area, and therefore $A_{tot} - A_p$ is the rest of the area containing unpaved land surface and open water.

Therefore, by including the rest of the area, a more comprehensive formula is proposed by Vergroesen (2019) to calculate the runoff frequency reduction factor over the total study area composed of paved area, unpaved area and open water as below:

$$F_{tot} = \frac{A_p \cdot e^{\left(\frac{A_{mi} \cdot ln(Fmeas)}{A_p}\right)} + \frac{Perc_{RA}}{100} \cdot \left(A_{tot} - A_p\right) \cdot 1}{A_p + \frac{Perc_{RA}}{100} \cdot \left(A_{tot} - A_p\right)} \quad (**)$$

where, F_{tot} is the runoff frequency reduction factor for the total area, F_{meas} is the factor for the measure inflow area, A_{tot} denotes the total area, A_p denotes the paved area, A_{mi} denotes the measure inflow area, $Perc_{RA}$ denotes the runoff from the rest of the area (*i.e.* $A_{tot} - A_p$), which is estimated as a percentage from the runoff from the paved area. Please note that both new formulas (*) and (**), though better than the old formula, are imperfect and have a certain degree of simplification. For example, the relationship between return time and runoff value are not strictly exponential-related, the curves are only roughly parallel to each other and the small fraction of water on the open paved land surface that infiltrates to the ground is not taken into account in the formula. To sum up, it is one of the findings of the undertaken thesis to improve the conversion of a measure's effectiveness of reducing runoff frequency on the runoff inflow area to the measure to the effectiveness over the entire area. Table D.7 below shows the comparisons between the old formulas and two new formulas. As can been seen from the table, under Case1 and Case2 — extreme

Table D.7: Comparisons between three formulas that convert the runoff reduction factors over the total area from the factors over the measure inflow area

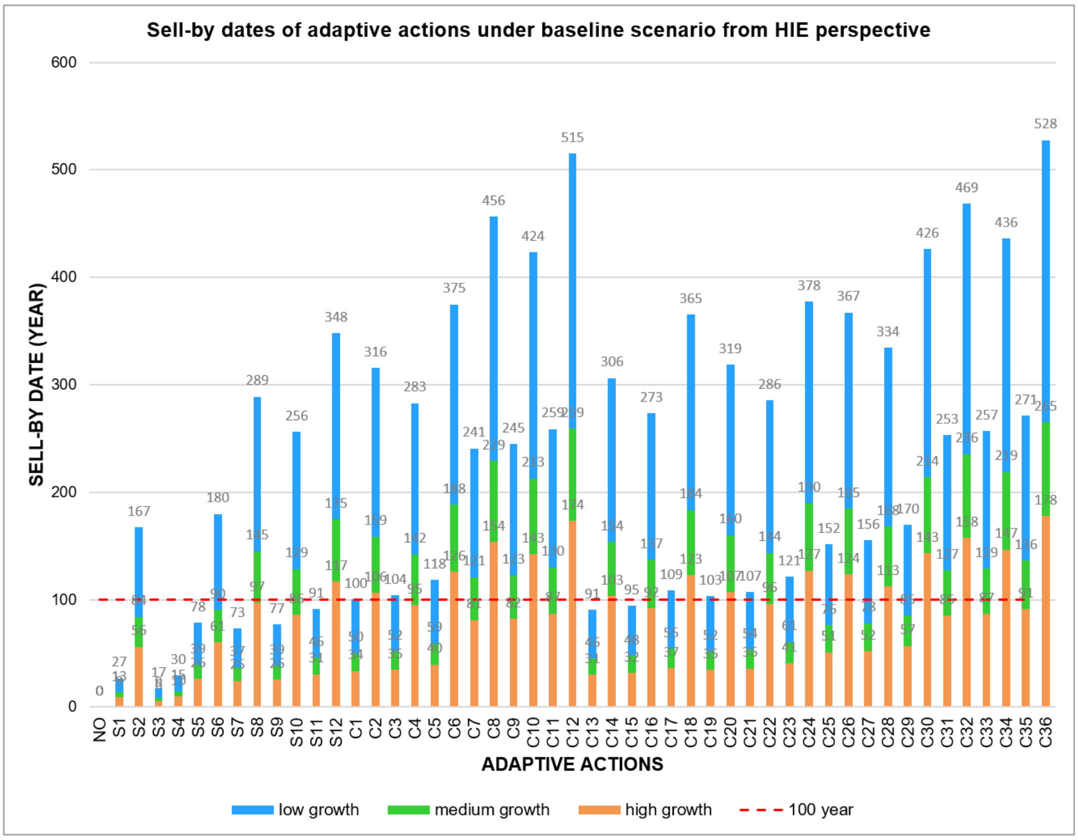
Case with different setup	Case1	Case2	Case3	Case4	Case5
Measure inflow area (m^2), A_{mi}	1	1	20	20	50
Paved area (m^2), A_P	50	50	50	50	50
Total area (m^2), A_{tot}	100	100	100	100	100
Rest area runoff is x% of the paved runoff, Per_{RA}	10	10	10	0	100
Runoff frequency reduction factor over the measure Inflow area, f_{mi}	100	10000	5	10	100
Factor over the entire area calculated by the old formula, f_{tot}	1.99	100.99	1.8	2.8	50.5
Factor over the entire area calculated by the new formula (*), f_{tot}	1.0965	1.2023	1.9037	2.5119	100.0000
Factor over the entire area calculated by the new formula (**), F_{tot}	1.0877	1.1839	1.8215	2.5119	50.5000

cases, the factor calculated with the old formula is too large, which is obviously unreasonable, whereas the factors calculated with two new formulas seem more realistic, and the difference between old and new factors is pretty large. Under Case3 and Case4 — ordinary cases, three formulas have similar resultant values, and runoff from the rest of the area if defined a small value will reduce the calculated f_{tot} a little bit. Under Case5 in which runoff from the rest area (unpaved) is considerably large, it will influence the difference in the f_{tot} calculated by two new formulas quite a lot.

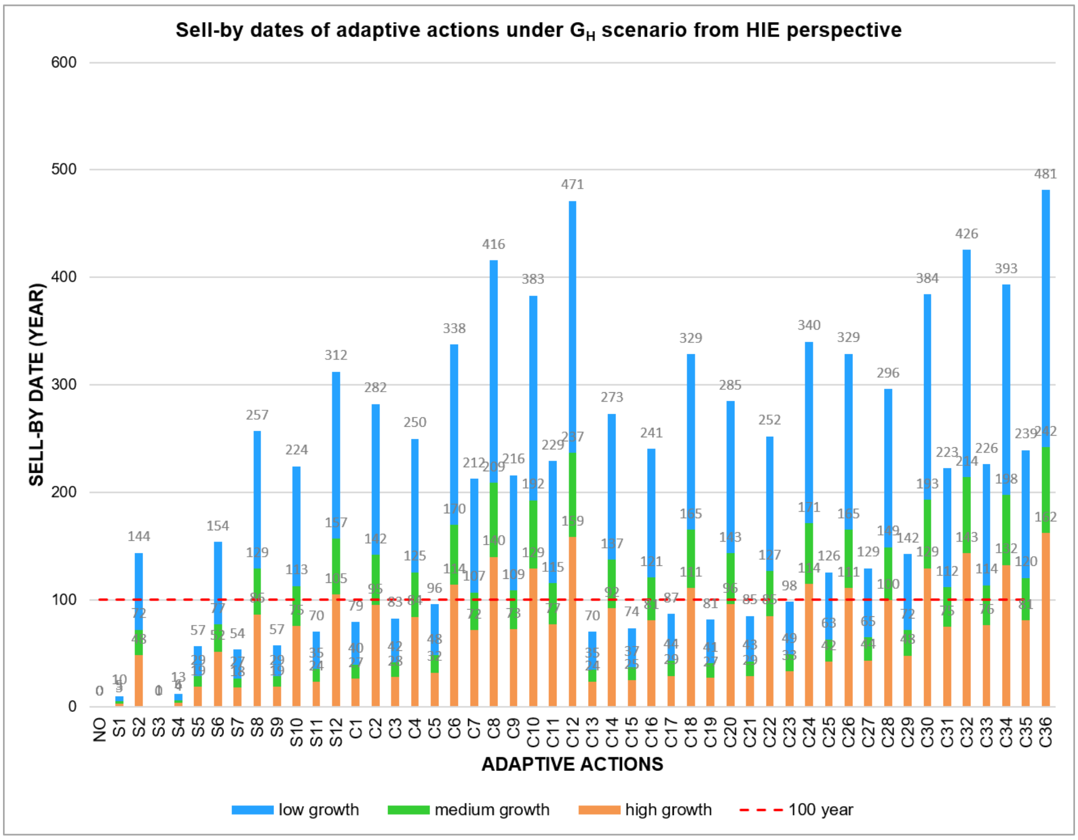
For the undertaken study, we assume that the soil on the unpaved land surface has been well-amended and vegetated. Therefore, it has relatively high infiltration capacity and interception capacity, and runoff from the paved area is 100% connected to the sewer system without overland flowing to the unpaved surface. After simulation, there is only small groundwater flooding on the unpaved area that generates negligible runoff. Therefore, in our conversion, the Per_{RA} is set zero and thus the formula (*) and (**) have the same results.

Appendix E

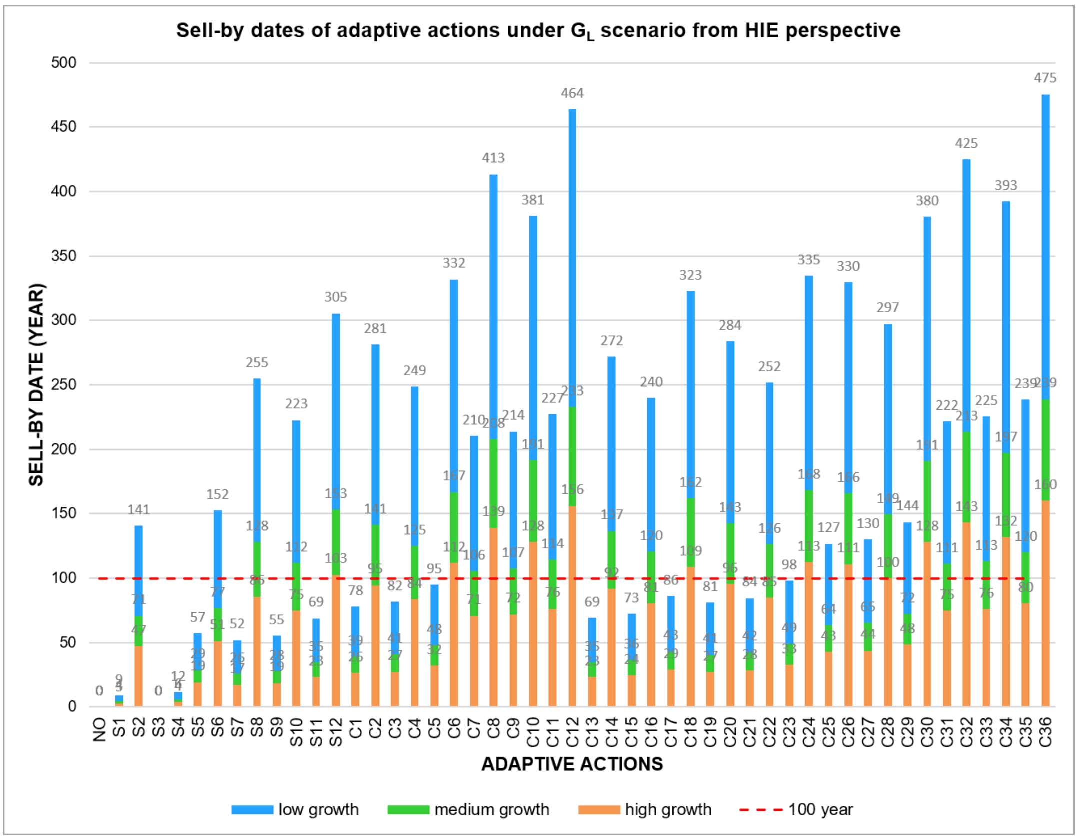
Sell-by dates of adaptation actions



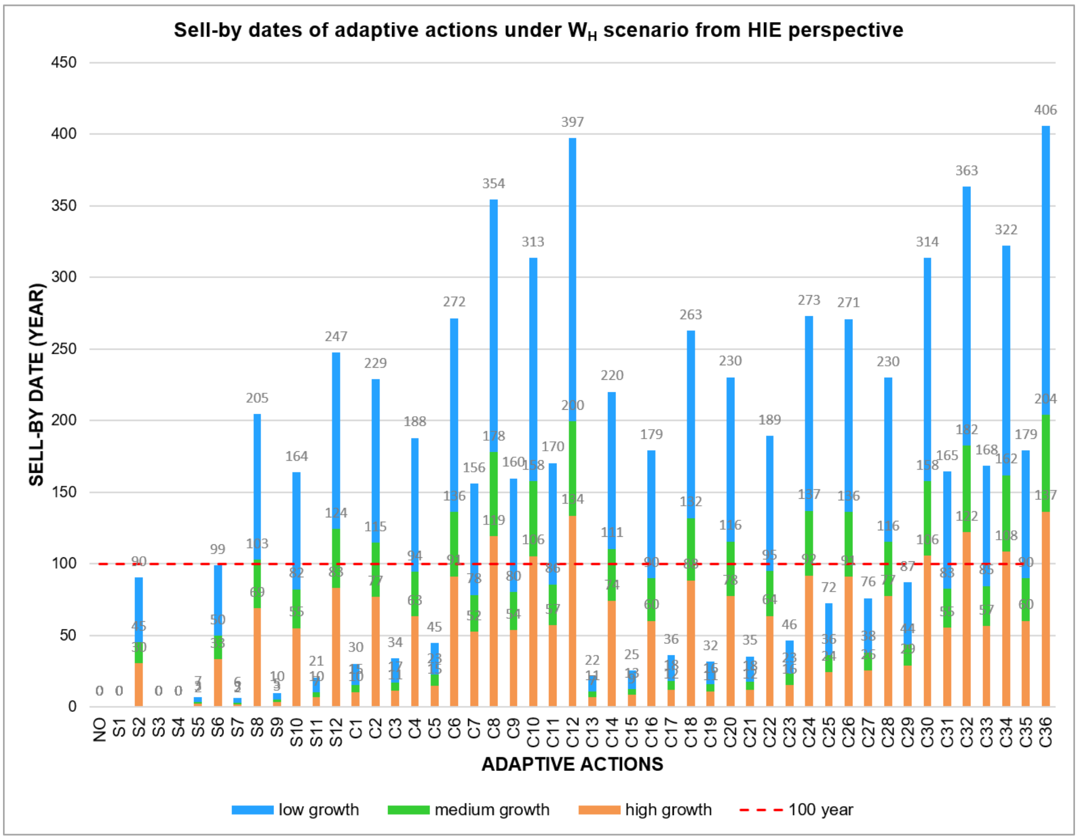
(a) Sell-by dates of policy options under baseline climate scenario in a *Hierarchist* future



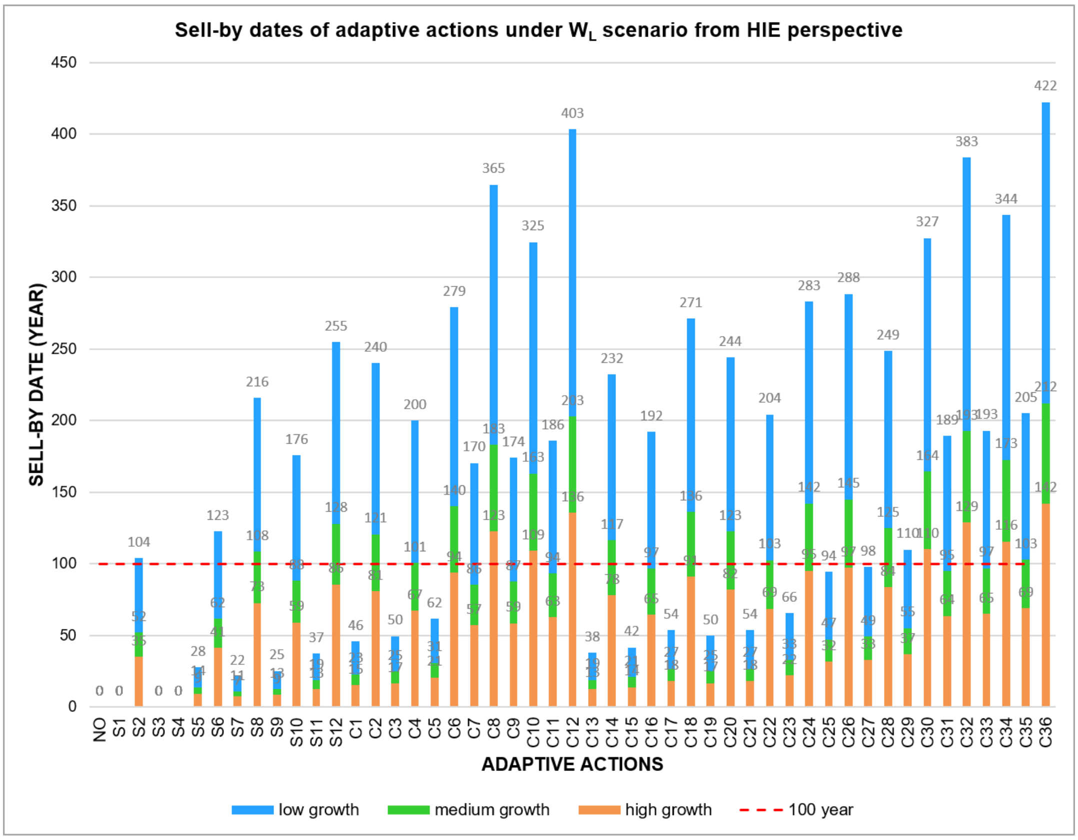
(b) Sell-by dates of policy options under G_H climate scenario in a *Hierarchist* future



(c) Sell-by dates of policy options under G_L climate scenario in a *Hierarchist* future

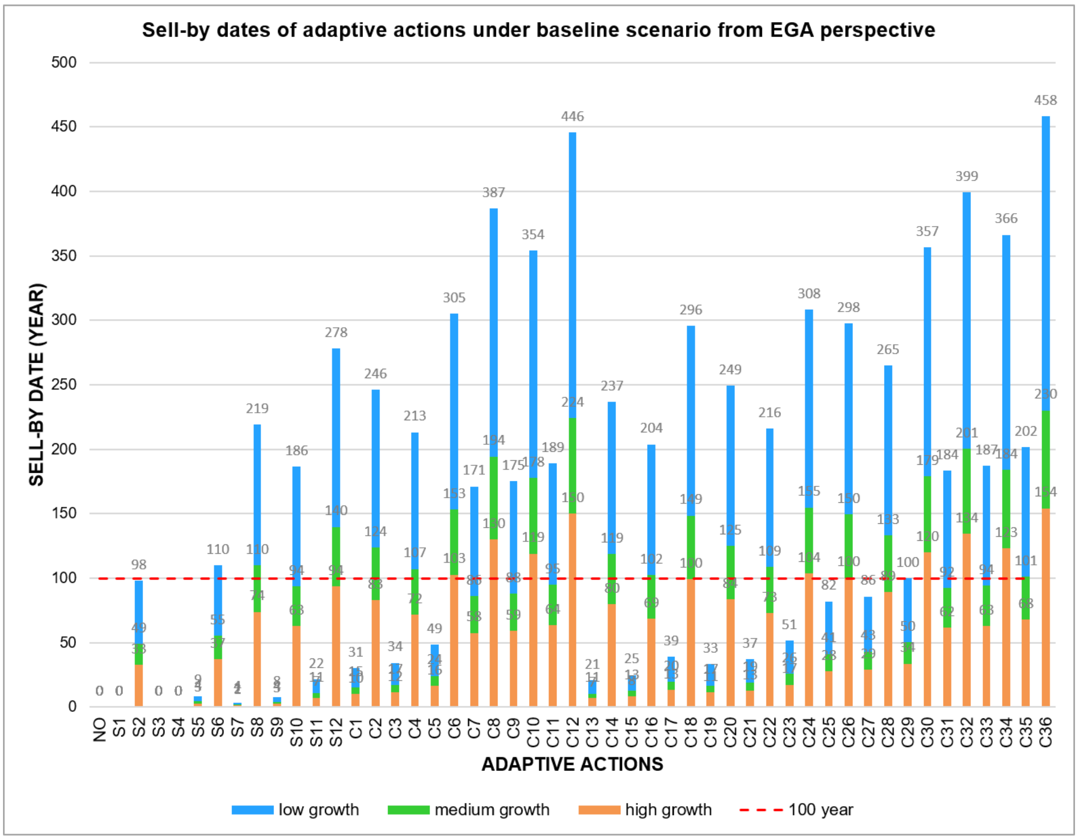


(d) Sell-by dates of policy options under W_H climate scenario in a *Hierarchist* future

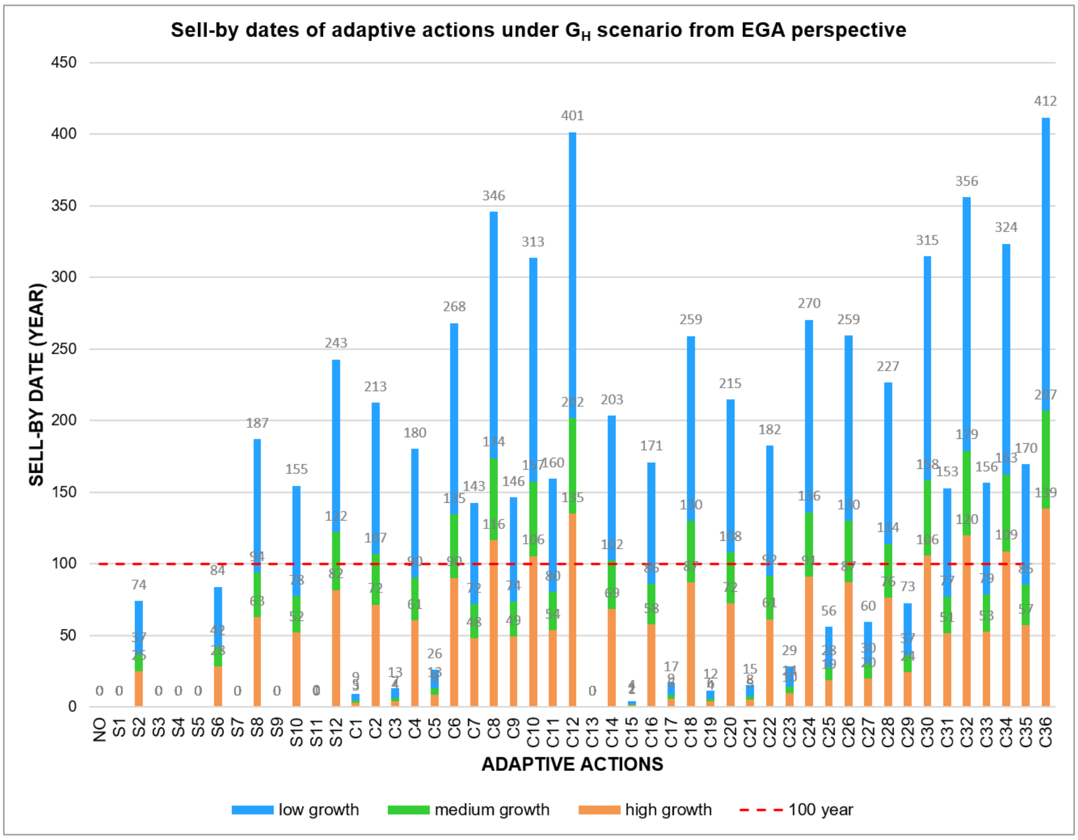


(e) Sell-by dates of policy options under W_L climate scenario in a *Hierarchist* future

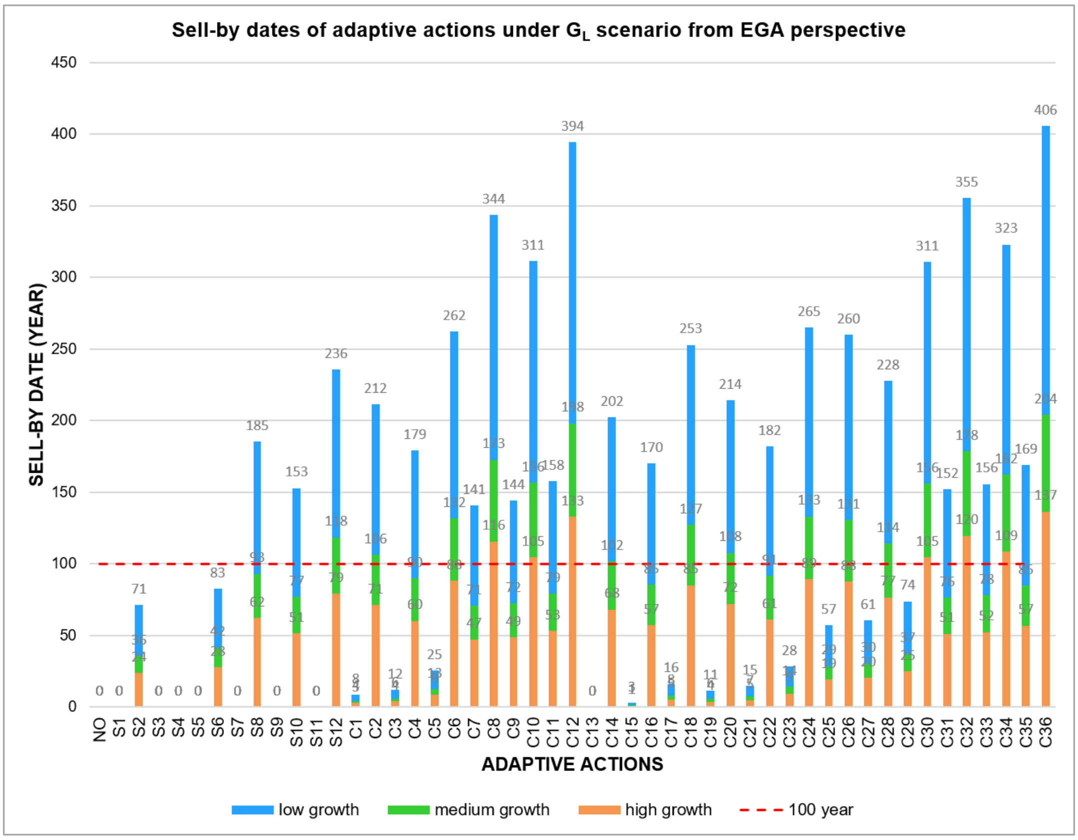
Figure E.1: Sell-by dates of policy options under different climatic and socio-economic scenario in a *Hierarchist* future



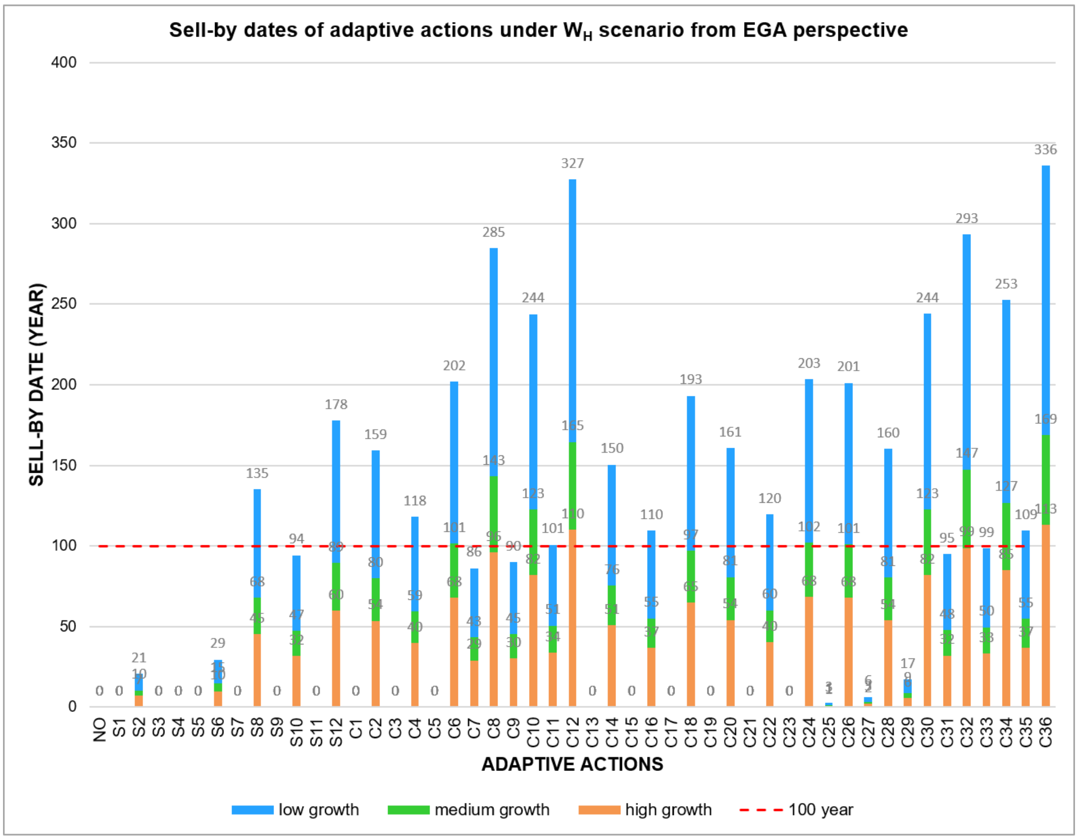
(a) Sell-by dates of policy options under baseline climate scenario in a *Egalitarian* future



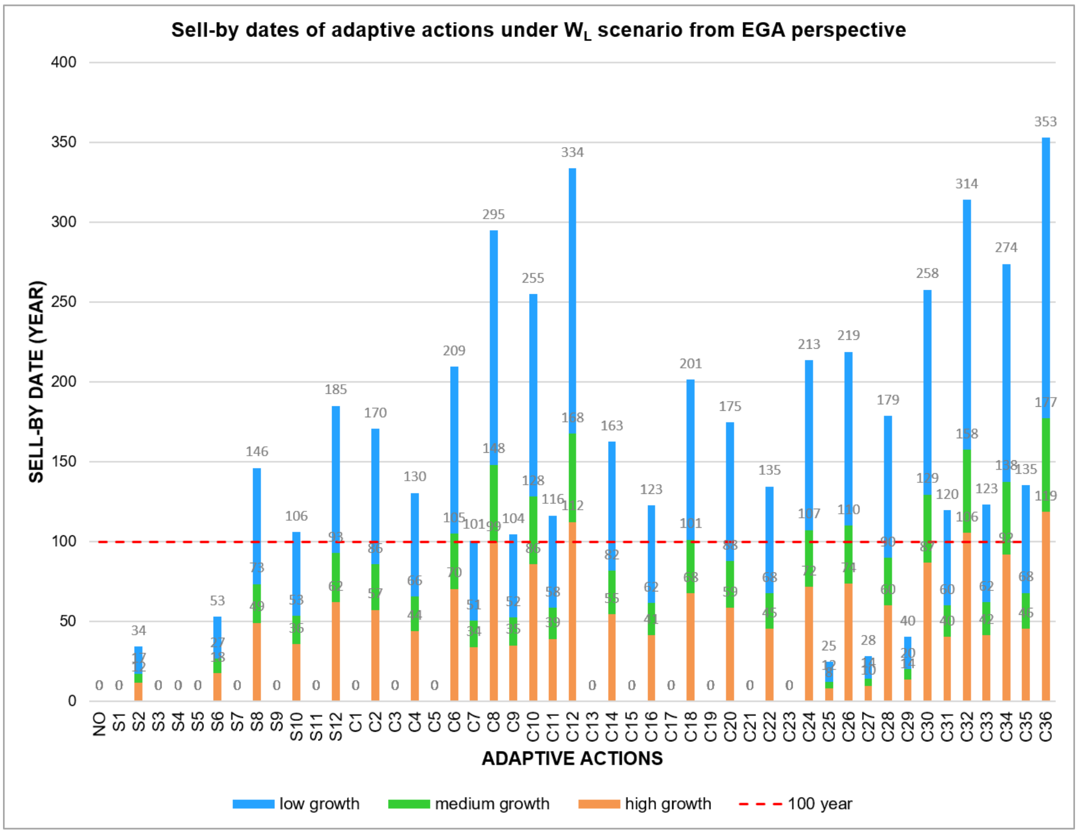
(b) Sell-by dates of policy options under G_H climate scenario in a *Egalitarian* future



(c) Sell-by dates of policy options under G_L climate scenario in a *Egalitarian* future

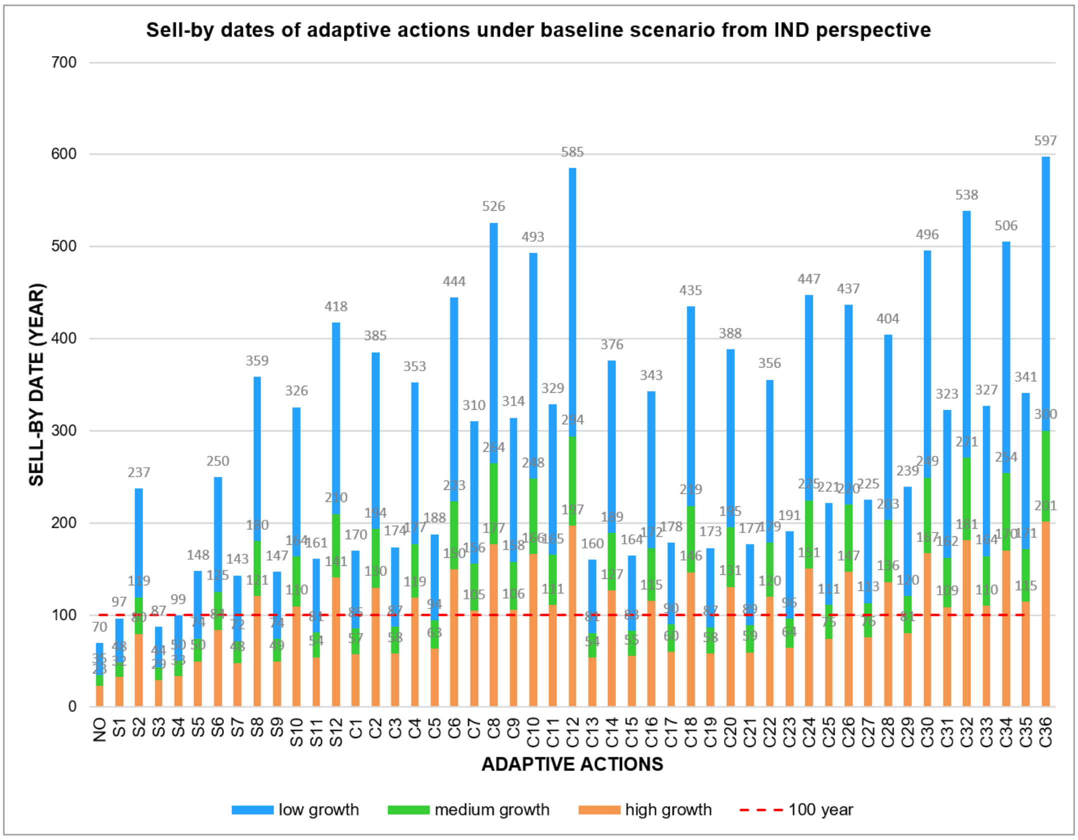


(d) Sell-by dates of policy options under W_H climate scenario in a *Egalitarian* future

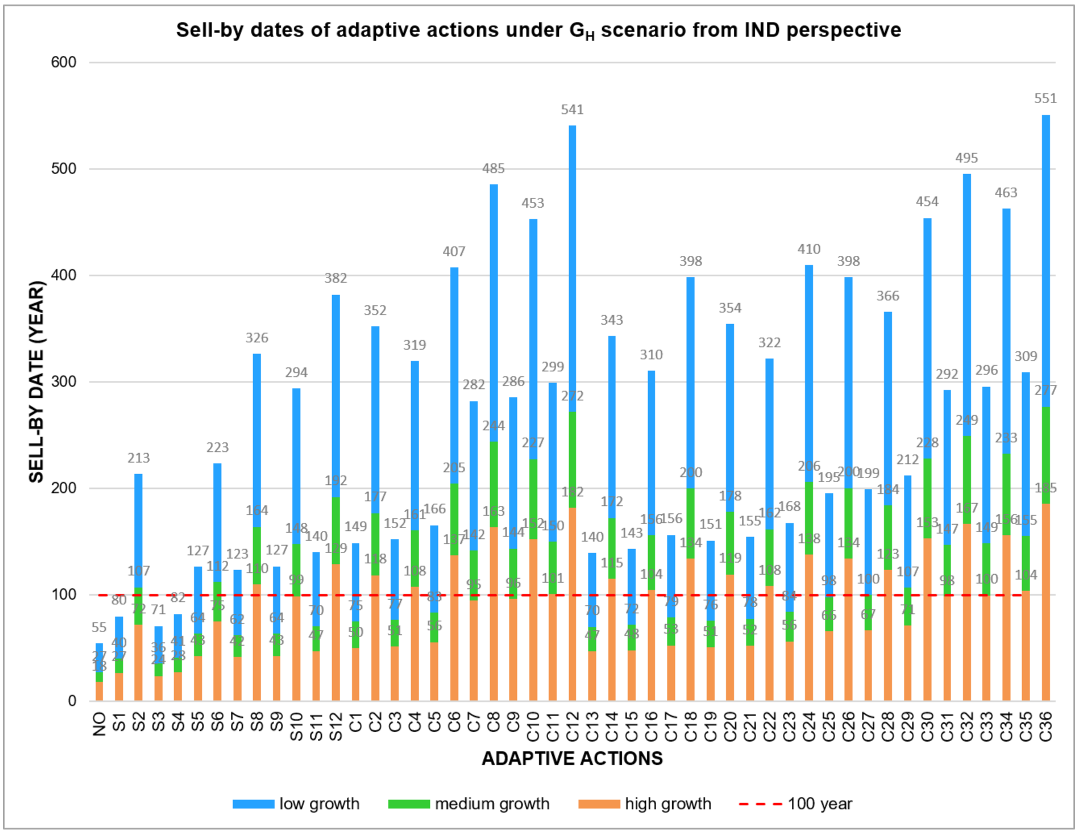


(e) Sell-by dates of policy options under W_L climate scenario in a *Egalitarian* future

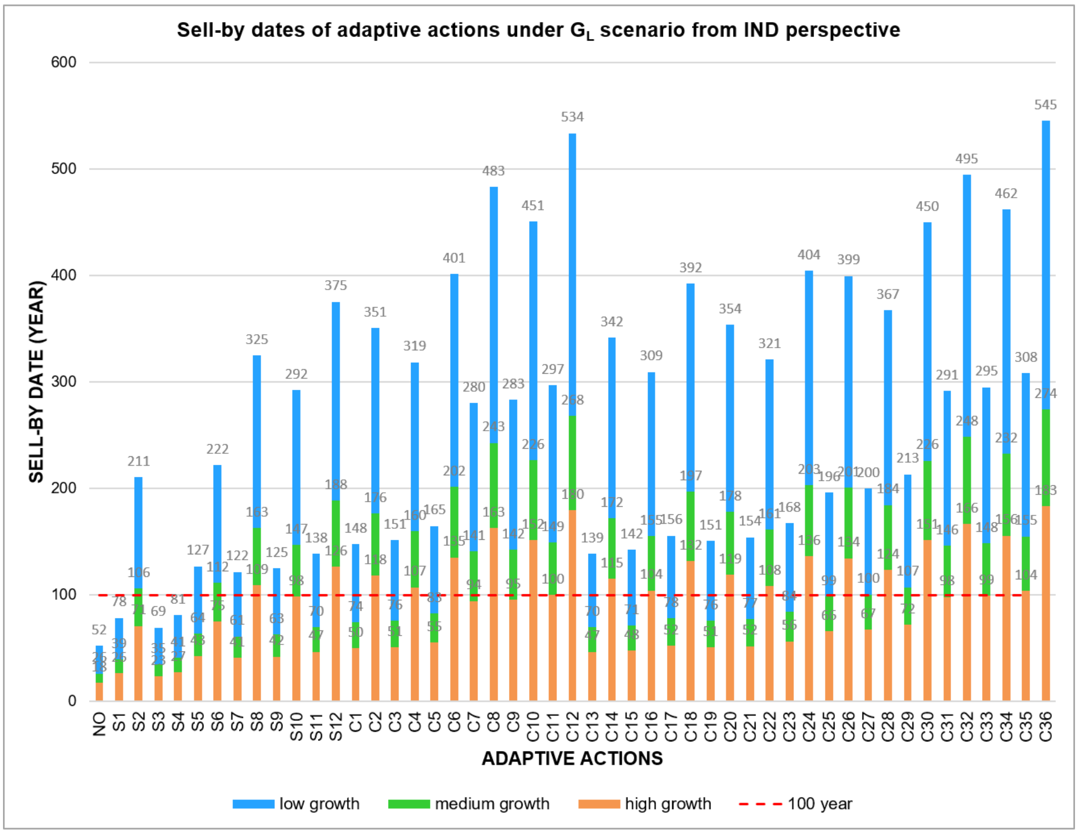
Figure E.2: Sell-by dates of policy options under different climatic and socio-economic scenario in a *Egalitarian* future



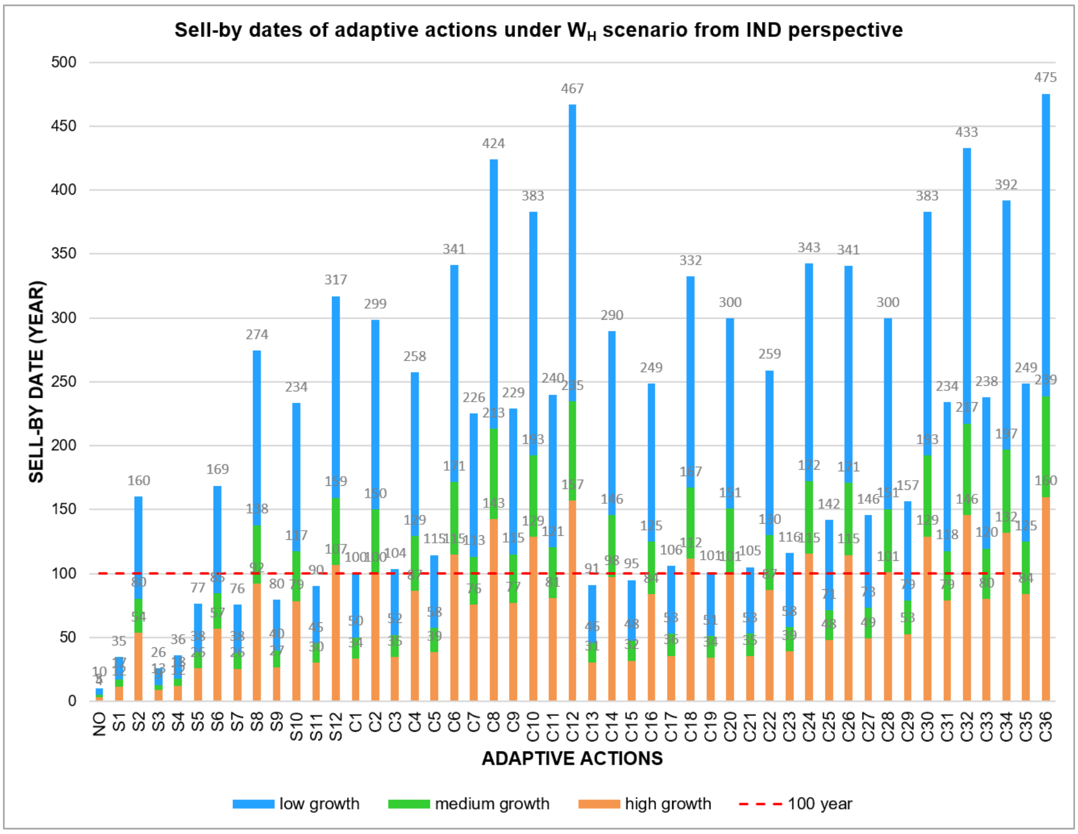
(a) Sell-by dates of policy options under baseline climate scenario in a *Individualist* future



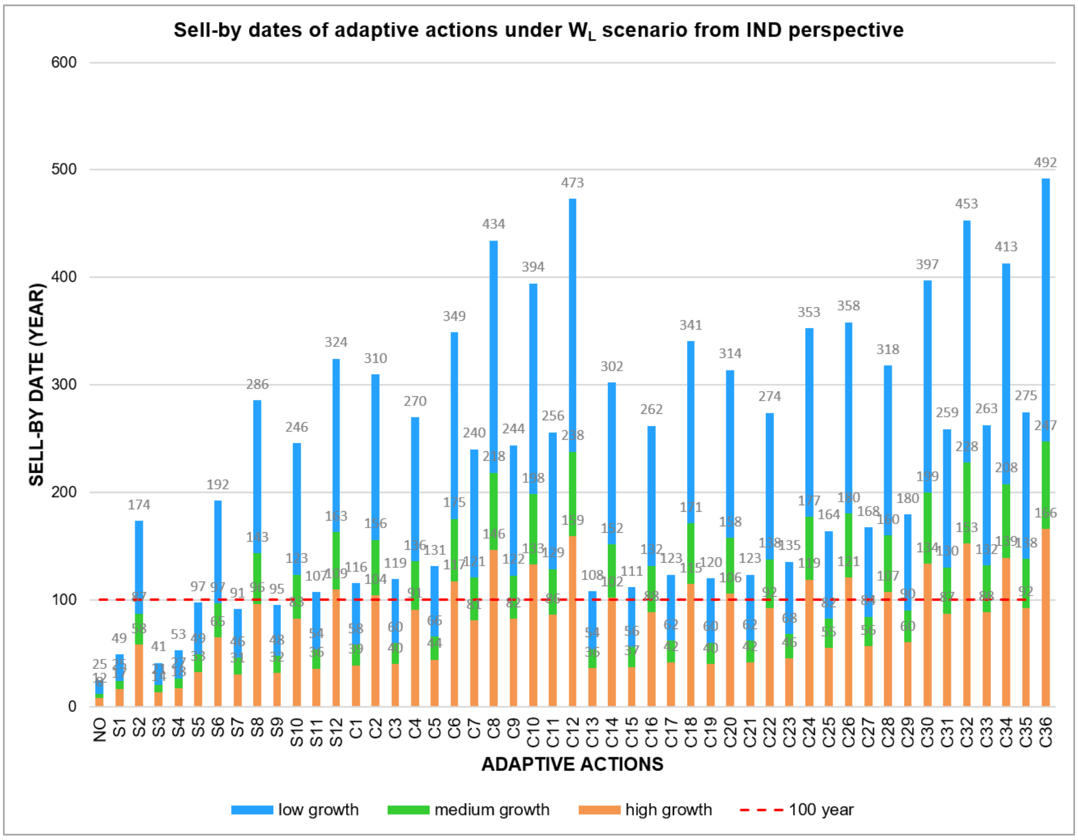
(b) Sell-by dates of policy options under G_H climate scenario in a *Egalitarian* future



(c) Sell-by dates of policy options under G_L climate scenario in a *Individualist* future



(d) Sell-by dates of policy options under W_H climate scenario in a *Individualist* future

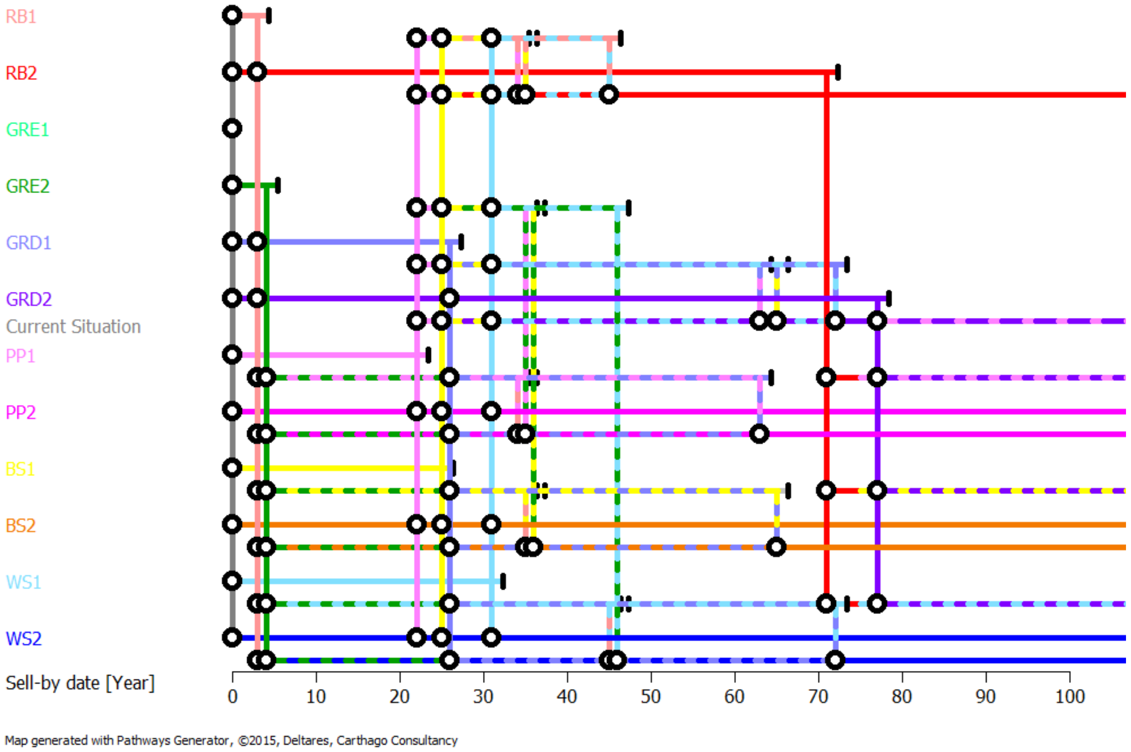


(e) Sell-by dates of policy options under W_L climate scenario in a *Individualist* future

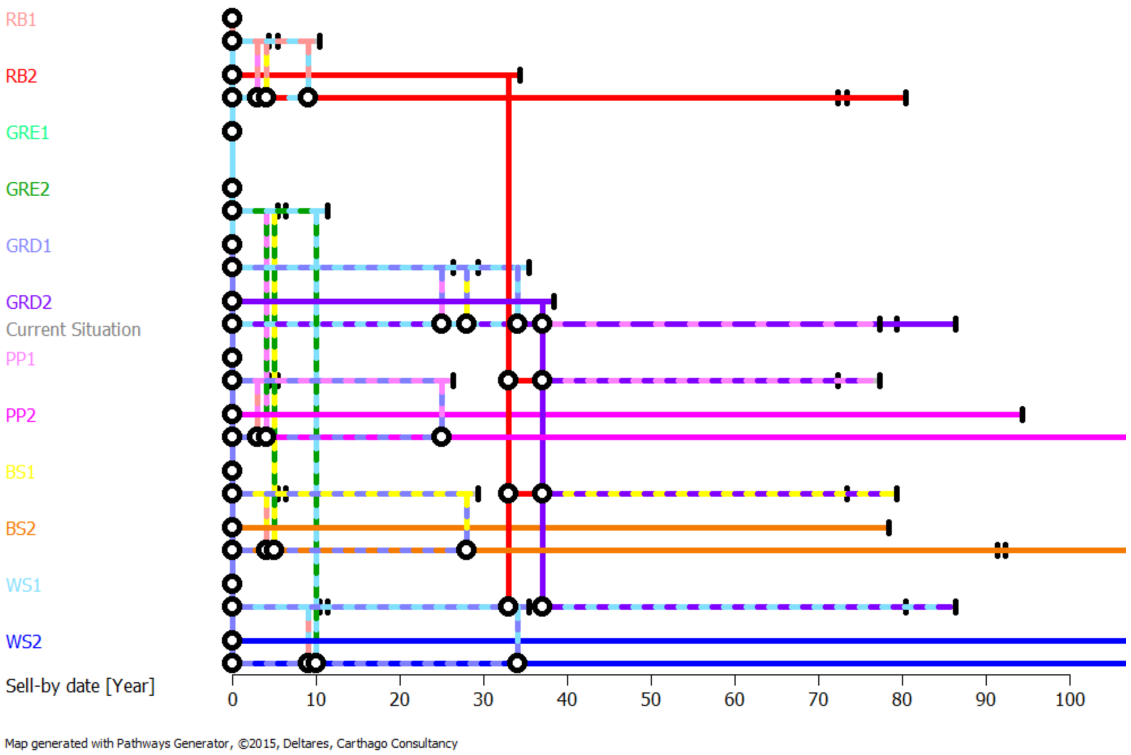
Figure E.3: Sell-by dates of policy options under different climatic and socio-economic scenario in a *Individualist* future

Appendix F

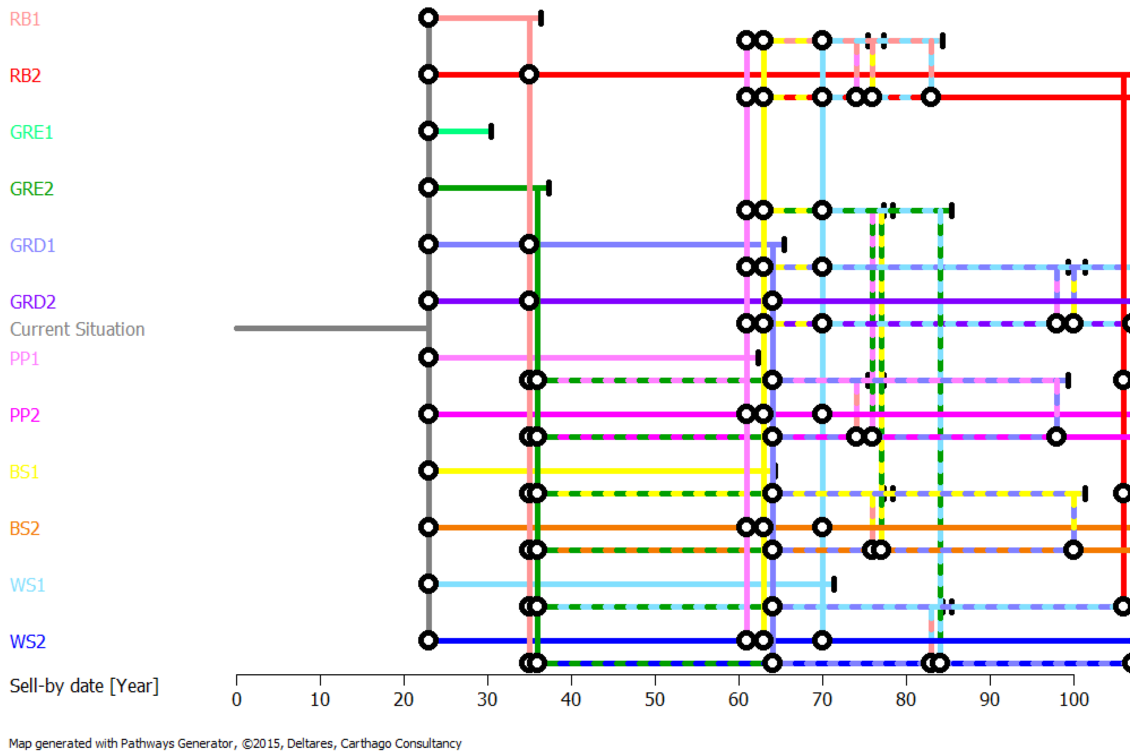
Adaptation Pathways map based on median values



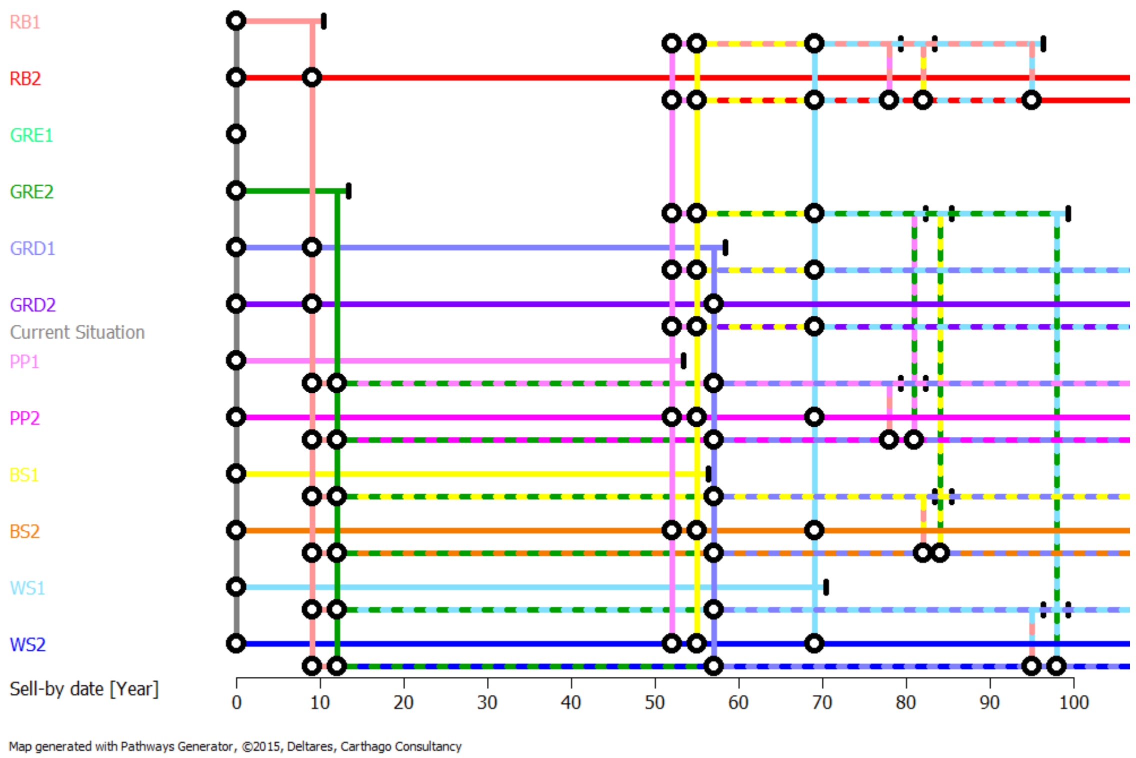
(a) Adaptation Pathways map based on median values of all realizations for *Hierarchist* perspective



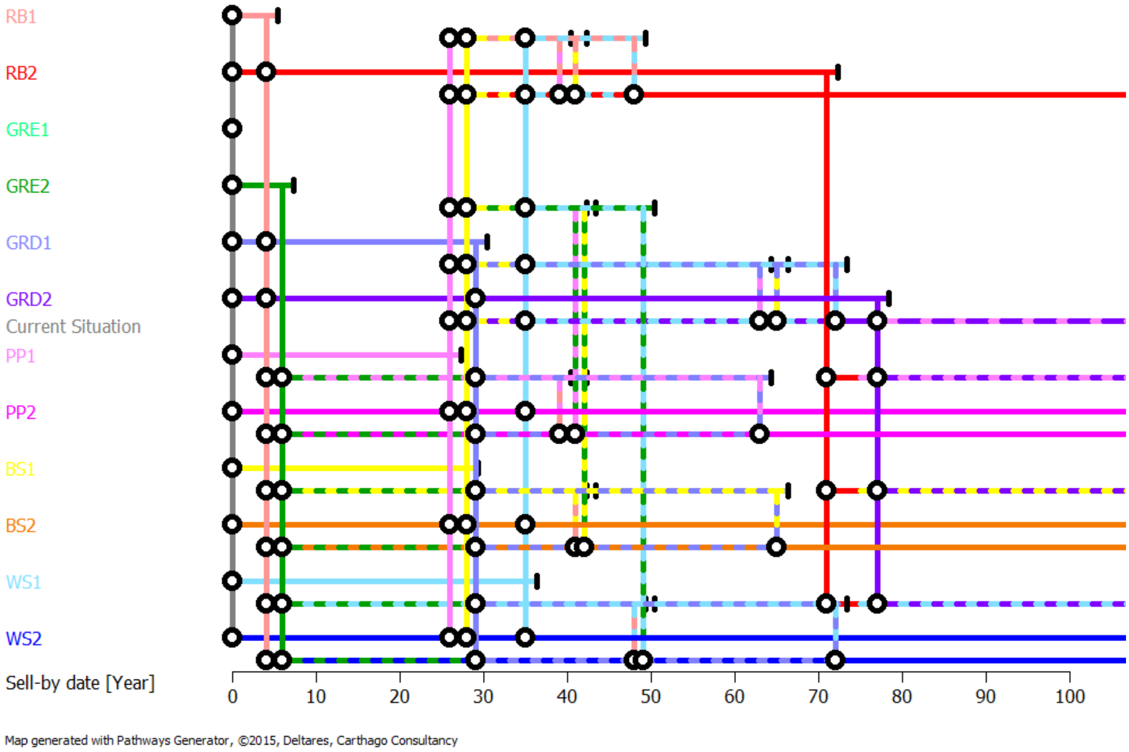
(b) Adaptation Pathways map based on median values of all realizations for *Egalitarian* perspective



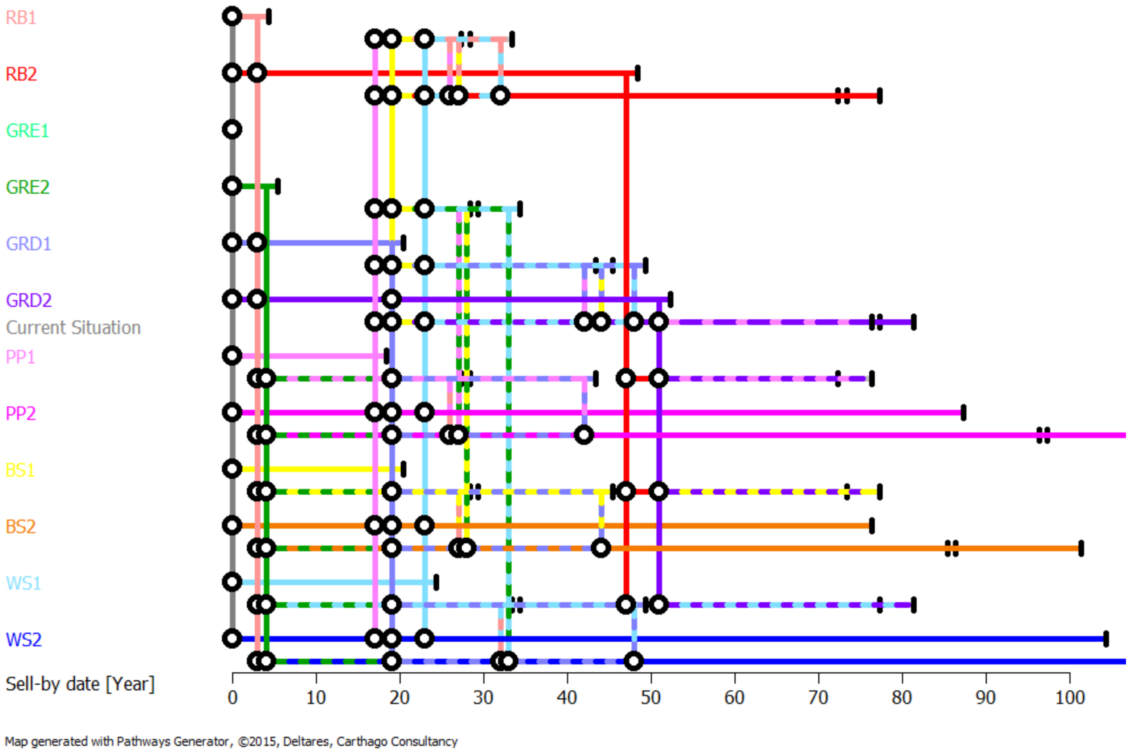
(c) Adaptation Pathways map based on median values of all realizations for *Individualist* perspective



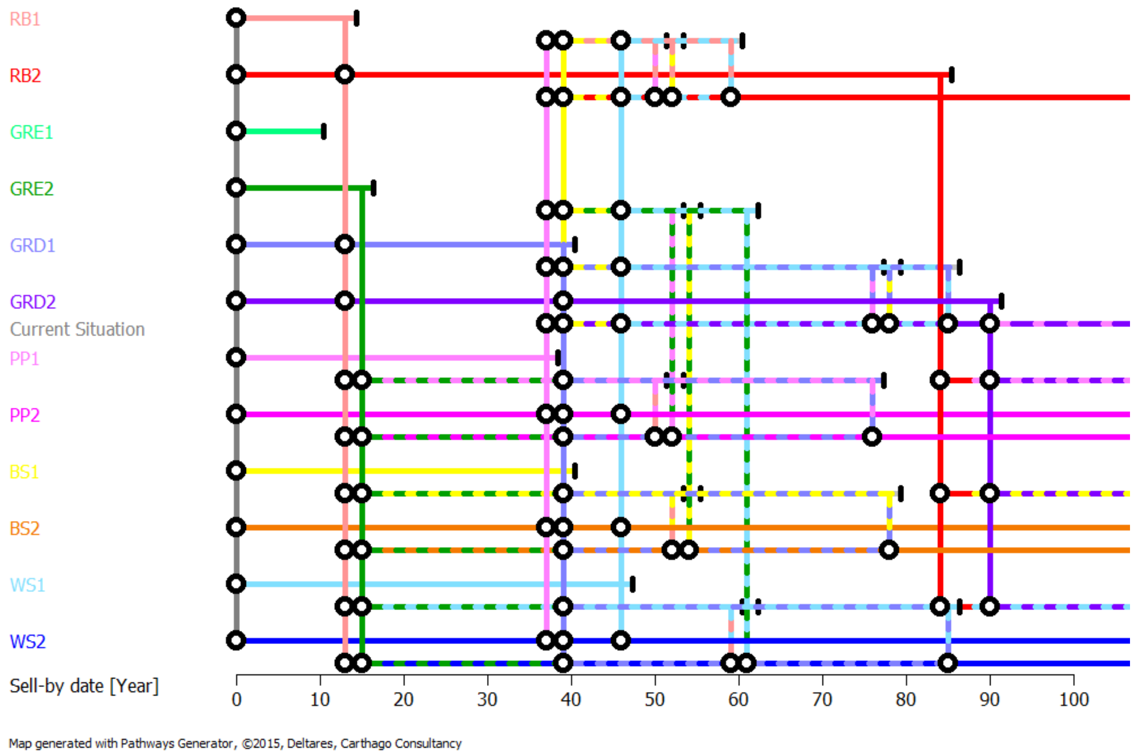
(d) Adaptation Pathways map based on the median values of all realizations for the low growth socio-economic scenario



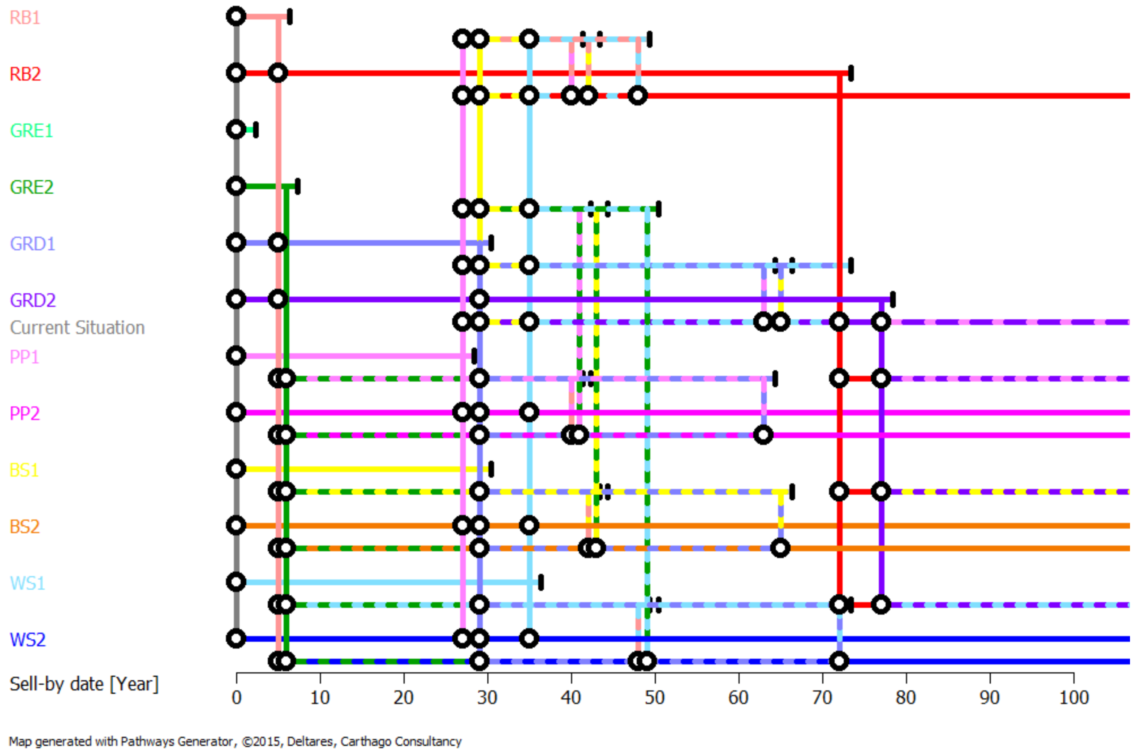
(e) Adaptation Pathways map based on the median values of all realizations for the medium growth socio-economic scenario



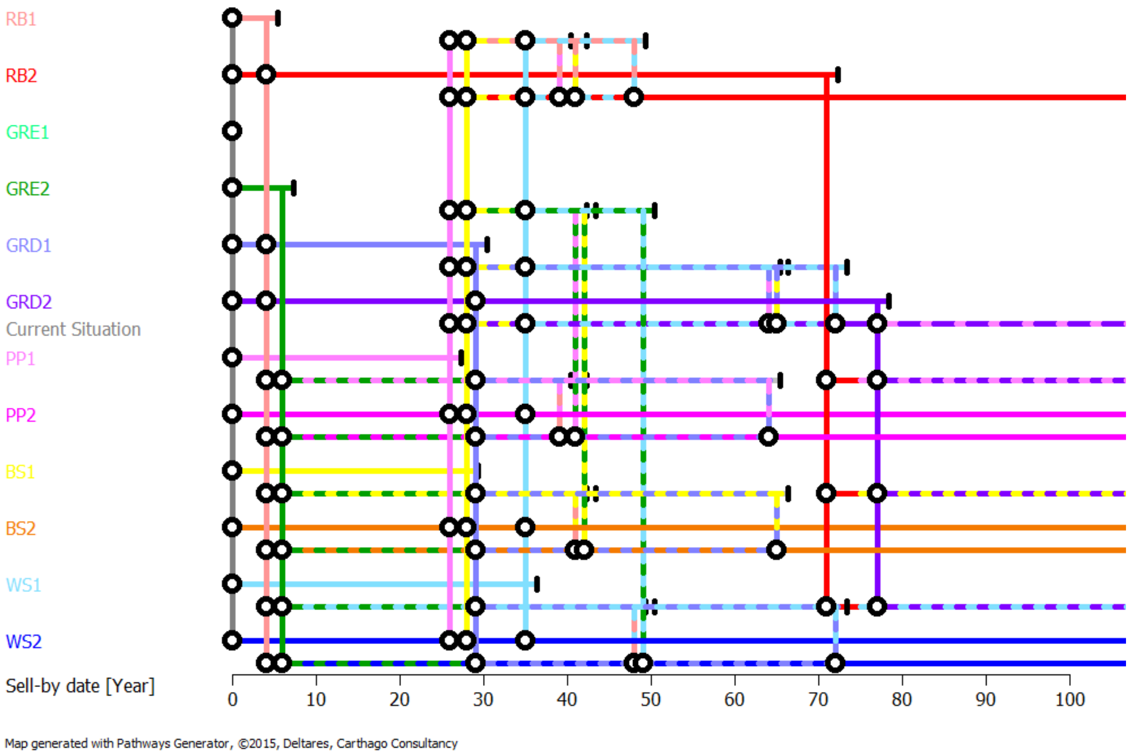
(f) Adaptation Pathways map based on the median values of all realizations for the high growth socio-economic scenario



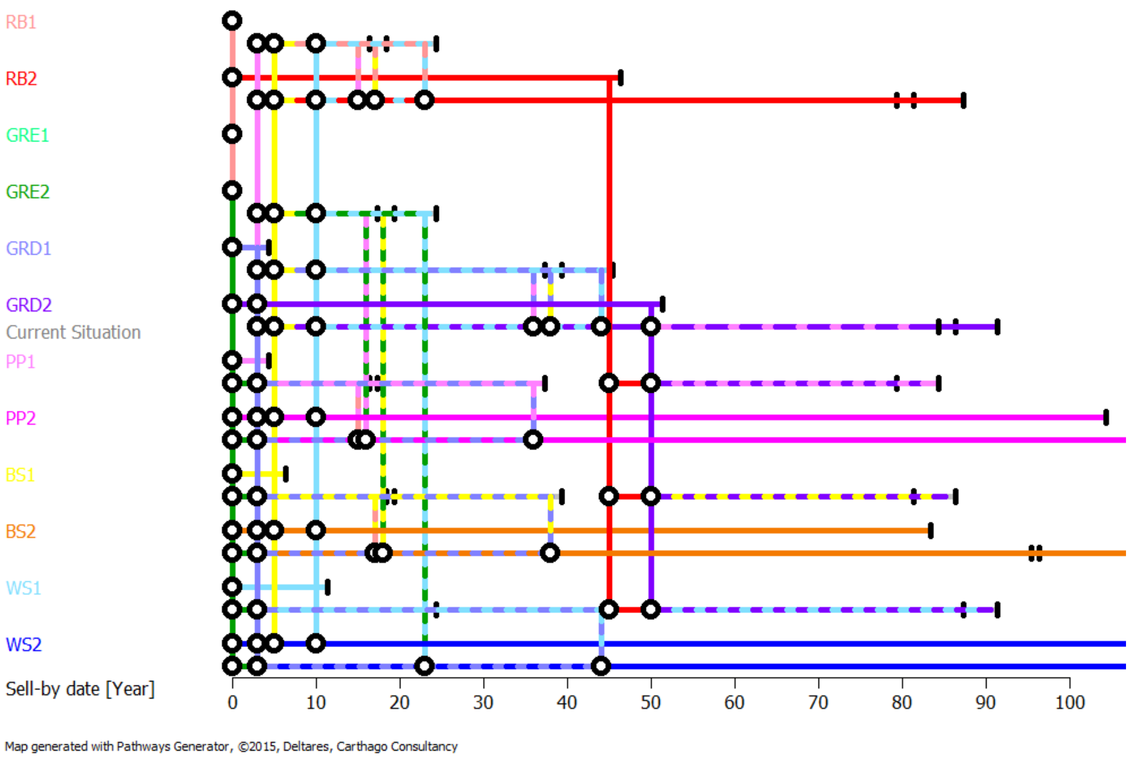
(g) Adaptation Pathways map based on the median values of all realizations for the baseline climate scenario



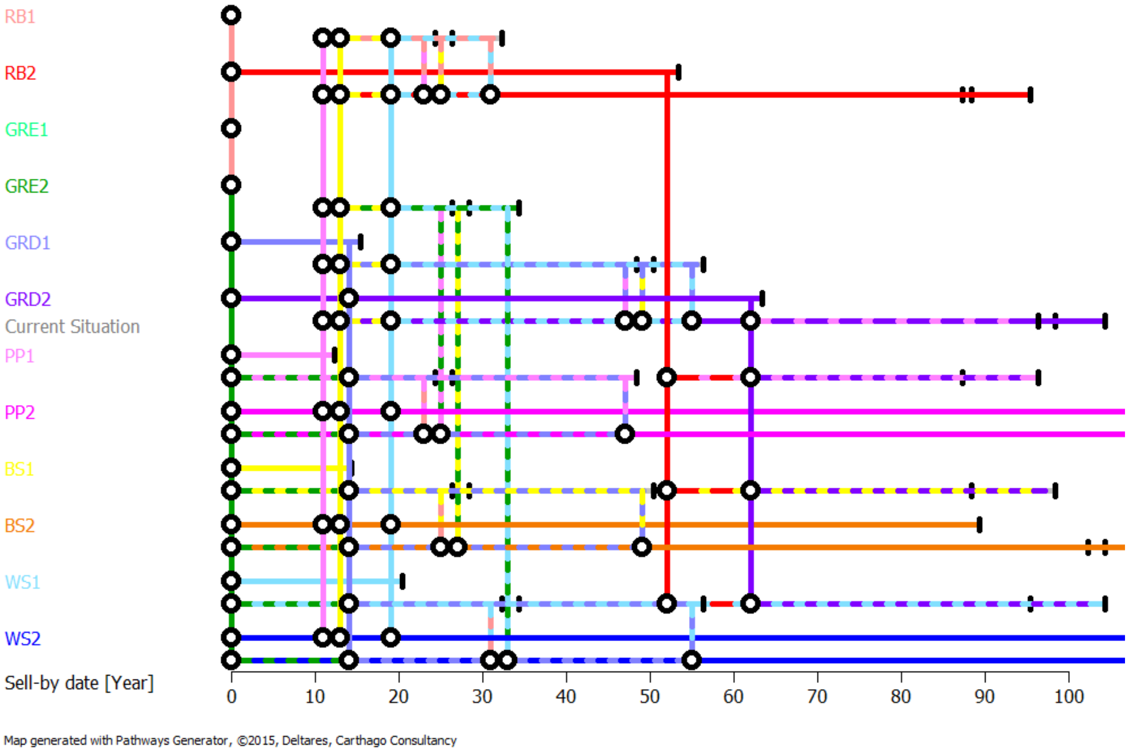
(h) Adaptation Pathways map based on the median values of all realizations for the G_H climate scenario



(i) Adaptation Pathways map based on the median values of all realizations for the G_L climate scenario



(j) Adaptation Pathways map based on the median values of all realizations for the W_H climate scenario



(k) Adaptation Pathways map based on the median values of all realizations for the W_L climate scenario

Figure F.1: Adaptation Pathways maps based on the median values of all realizations for a certain condition

ID	Scenario0	HIE median	EGA median	IND median	Low growth median	Medium growth median	High growth median	Baseline climate median	GH climate median	GL climate median	WH climate median	WL climate median	Dynamic robust strategies
1													
2													
3				1	1								
4													
5													
6													
7				1	1								
8													
9	1	1	0	1	1	1	0	1	1	1	1	1	
10													
11	1	1	0	1	1	1	0	1	1	1	0	0	
12													
13	1	1	1	1	1	1	1	1	1	1	1	1	1
14				1	1								
15													
16				1	1								
17	1	1	1	1	1	1	1	1	1	1	1	1	1
18	1	1	1	1	1	1	1	1	1	1	1	1	1
19	1	1	1	1	1	1	1	1	1	1	1	1	1
33													
34	1	1	1	1	1	1	1	1	1	1	1	1	1
35	1	1	1	1	1	1	1	1	1	1	1	1	1
36													
37	1	1	1	1	1	1	1	1	1	1	1	1	1
38	1	1	1	1	1	1	1	1	1	1	1	1	1
39													
40	1	1	1	1	1	1	1	1	1	1	1	1	1
41	1	1	1	1	1	1	1	1	1	1	1	1	1
20				1	1								
21	1	1	1	1	1	1	1	1	1	1	1	1	1
22	1	1	1	1	1	1	1	1	1	1	1	1	1
23	1	1	1	1	1	1	1	1	1	1	1	1	1
27					1								
28	1	1	1	1	1	1	1	1	1	1	1	1	1
29	1	1	1	1	1	1	1	1	1	1	1	1	1
24				1	1								
25	1	1	1	1	1	1	1	1	1	1	1	1	1
26	1	1	1	1	1	1	1	1	1	1	1	1	1
30				1	1								
31	1	1	1	1	1	1	1	1	1	1	1	1	1
32	1	1	1	1	1	1	1	1	1	1	1	1	1
44													
43	1	1	1	1	1	1	0	1	1	1	1	1	
45	1	1	1	1	1	1	0	1	1	1	1	1	
46													
47	1	1	0	1	1	1	0	1	1	1	0	1	
48	1	1	0	1	1	1	0	1	1	1	0	1	
49													
50	1	1	1	1	1	1	1	1	1	1	1	1	1
51	1	1	1	1	1	1	1	1	1	1	1	1	1
52													
53	1	1	1	1	1	1	1	1	1	1	1	1	1
54	1	1	1	1	1	1	1	1	1	1	1	1	1

(a) The applicability of actions or pathways with ID from 1 to 54 based on the median values of all realizations for different conditions

ID	Scenario0	HIE median	EGA median	IND median	Low growth median	Medium growth median	High growth median	Baseline climate median	GH climate median	GL climate median	WH climate median	WL climate median	Dynamic robust strategies
55					1								
56	1	1	1	1	1	1	1	1	1	1	1	1	1
57	1	1	1	1	1	1	1	1	1	1	1	1	1
58													
59	1	1	1	1	1	1	0	1	1	1	1	1	
60	1	1	0	1	1	1	0	1	1	1	1	1	
62	1	1	0	1	1	1	0	1	1	1	1	1	
61	1	1	1	1	1	1	1	1	1	1	1	1	1
64													
63	1	1	1	1	1	1	1	1	1	1	1	1	1
65	1	1	1	1	1	1	1	1	1	1	1	1	1
78				1	1								
79	1	1	1	1	1	1	1	1	1	1	1	1	1
80	1	1	1	1	1	1	1	1	1	1	1	1	1
81													
82	1	1	0	1	1	1	0	1	1	1	0	1	
66	1	1	0	1	1	1	0	1	1	1	0	0	
67	1	1	0	1	1	1	0	1	1	1	1	1	
68	1	1	1	1	1	1	1	1	1	1	1	1	1
69													
70	1	1	1	1	1	1	1	1	1	1	1	1	1
71	1	1	1	1	1	1	1	1	1	1	1	1	1
72				1	1								
73	1	1	1	1	1	1	1	1	1	1	1	1	1
74	1	1	1	1	1	1	1	1	1	1	1	1	1
75													
76	1	1	1	1	1	1	1	1	1	1	1	1	1
77	1	1	1	1	1	1	1	1	1	1	1	1	1
83	1	1	0	1	1	1	0	1	1	1	1	1	
84	1	1	0	1	1	1	0	1	1	1	1	1	
85	1	1	1	1	1	1	1	1	1	1	1	1	1
86	1	1	1	1	1	1	1	1	1	1	1	1	1
87	1	1	1	1	1	1	1	1	1	1	1	1	1
88	1	1	1	1	1	1	1	1	1	1	1	1	1
89	1	1	1	1	1	1	1	1	1	1	1	1	1
90	1	1	1	1	1	1	1	1	1	1	1	1	1
91	1	1	1	1	1	1	1	1	1	1	1	1	1
92	1	1	1	1	1	1	1	1	1	1	1	1	1
93	1	1	1	1	1	1	1	1	1	1	1	1	1
94				1	1								
95	1	1	1	1	1	1	1	1	1	1	1	1	1
96	1	1	1	1	1	1	1	1	1	1	1	1	1
97	1	1	1	1	1	1	1	1	1	1	1	1	1
98				1	1								
99	1	1	1	1	1	1	1	1	1	1	1	1	1
100	1	1	1	1	1	1	1	1	1	1	1	1	1
101					1								
102	1	1	1	1	1	1	1	1	1	1	1	1	1
103	1	1	1	1	1	1	1	1	1	1	1	1	1
104				1	1								
105	1	1	1	1	1	1	1	1	1	1	1	1	1
106	1	1	1	1	1	1	1	1	1	1	1	1	1
SUM	69	69	58	81	84	69	55	69	69	69	64	67	55

(b) The applicability of actions or pathways with ID from 55 to 106 based on the median values of all realizations for different conditions

Figure F.2: The applicability of 106 actions or pathways based on the median values of all realizations for different conditions

ID	Color	Action or Pathway	Type of pathway	Scenario0	HIE-median	EGA-median	IND-median	LowGrowth	MediumG	HighG	BaselineClimate	GH	GL	WH	WL
-->1		Current Situation		0	0	0	23	0	0	0	0	0	0	0	0
2		RB1		13	3	0	35	9	4	3	13	5	4	0	0
3		RB2		84	71	33	106	141	71	47	84	72	71	45	52
4		GRE1		9	0	0	29	0	0	0	9	1	0	0	0
5		GRE2		15	4	0	36	12	6	4	15	6	6	0	0
6		GRD1		39	26	0	64	57	29	19	39	29	29	3	14
7		GRD2		90	77	37	112	152	77	51	90	77	77	50	62
8		PP1		37	22	0	61	52	26	17	37	27	26	3	11
9		PP2		145	128	93	163	255	128	86	145	129	128	103	108
10		BS1		39	25	0	63	55	28	19	39	29	28	5	13
11		BS2		129	112	77	147	223	112	75	129	113	112	82	88
12		WS1		46	31	0	70	69	35	23	46	35	35	10	19
13		WS2		175	153	118	188	305	153	103	175	157	153	124	128
14		RB1 + RB2	Sequence	84	71	33	106	141	71	47	84	72	71	45	52
15		RB1 + GRD1	Sequence	39	26	0	64	57	29	19	39	29	29	3	14
16		RB1 + GRD2	Sequence	90	77	37	112	152	77	51	90	77	77	50	62
17		RB2 + PP1	Combine	121	106	71	141	210	106	71	121	107	106	78	86
18		RB2 + BS1	Combine	123	107	72	142	214	107	72	123	109	107	80	87
19		RB2 + WS1	Combine	130	114	79	149	227	114	76	130	115	114	86	94
33		RB1 + PP1	Combine	50	34	3	74	78	39	26	50	40	39	15	23
34		RB1 + PP2	Combine	159	141	106	176	281	141	95	159	142	141	115	121
35		RB1 + PP1 + RB1 + PP2	Sequence	159	141	106	176	281	141	95	159	142	141	115	121
36		RB1 + BS1	Combine	52	35	4	76	82	41	27	52	42	41	17	25
37		RB1 + BS2	Combine	142	125	90	160	249	125	84	142	125	125	94	101
38		RB1 + BS1 + RB1 + BS2	Sequence	142	125	90	160	249	125	84	142	125	125	94	101
39		RB1 + WS1	Combine	59	45	9	83	95	48	32	59	48	48	23	31
40		RB1 + WS2	Combine	188	167	132	202	332	167	112	188	170	167	136	140
41		RB1 + WS1 + RB1 + WS2	Sequence	188	167	132	202	332	167	112	188	170	167	136	140
20		GRD1 + GRD2	Sequence	90	77	37	112	152	77	51	90	77	77	50	62
21		GRD2 + PP1	Combine	127	111	76	146	222	111	75	127	112	111	83	95
22		GRD2 + BS1	Combine	129	113	78	148	225	113	76	129	114	113	85	97
23		GRD2 + WS1	Combine	136	120	85	155	239	120	80	136	120	120	90	103
27		GRD1 + PP1	Combine	76	63	25	98	126	63	42	76	63	64	36	47
28		GRD1 + PP2	Combine	185	165	130	200	329	165	111	185	165	166	136	145
29		GRD1 + PP1 + GRD1 + PP2	Sequence	185	165	130	200	329	165	111	185	165	166	136	145

(a) Descriptions of the sequences of actions and pathways (1-29), and the corresponding sell-by dates under different conditions

ID	Color	Action or Pathway	Type of pathway	Scenario0	HIE-median	EGA-median	IND-median	LowGrowth	MediumG	HighG	BaselineClimate	GH	GL	WH	WL
24		GRD1 + BS1	Combine	78	65	28	100	129	65	44	78	65	65	38	49
25		GRD1 + BS2	Combine	168	149	114	184	296	149	100	168	149	149	116	125
26		GRD1 + BS1 + GRD1 + BS2	Sequence	168	149	114	184	296	149	100	168	149	149	116	125
30		GRD1 + WS1	Combine	85	72	34	107	142	72	48	85	72	72	44	55
31		GRD1 + WS2	Combine	214	191	156	226	380	191	128	214	193	191	158	164
32		GRD1 + WS1 + GRD1 + WS2	Sequence	214	191	156	226	380	191	128	214	193	191	158	164
44		GRE2 + PP1	Combine	52	35	4	76	81	41	27	52	41	41	16	25
43		GRE2 + PP2	Combine	160	143	108	178	284	143	96	160	143	143	116	123
45		GRE2 + PP1 + GRE2 + PP2	Sequence	160	143	108	178	284	143	96	160	143	143	116	123
46		GRE2 + BS1	Combine	54	36	5	77	84	42	28	54	43	42	18	27
47		GRE2 + BS2	Combine	144	126	91	161	252	126	85	144	127	126	95	103
48		GRE2 + BS1 + GRE2 + BS2	Sequence	144	126	91	161	252	126	85	144	127	126	95	103
49		GRE2 + WS1	Combine	61	46	10	84	98	49	33	61	49	49	23	33
50		GRE2 + WS2	Combine	190	168	133	203	335	168	113	190	171	168	137	142
51		GRE2 + WS1 + GRE2 + WS2	Sequence	190	168	133	203	335	168	113	190	171	168	137	142
52		PP1 + RB1	Combine	50	34	3	74	78	39	26	50	40	39	15	23
53		PP1 + RB2	Combine	121	106	71	141	210	106	71	121	107	106	78	86
54		PP1 + RB1 + PP1 + RB2	Sequence	121	106	71	141	210	106	71	121	107	106	78	86
55		PP1 + GRD1	Combine	76	63	25	98	126	63	42	76	63	64	36	47
56		PP1 + GRD2	Combine	127	111	76	146	222	111	75	127	112	111	83	95
57		PP1 + GRD1 + PP1 + GRD2	Sequence	127	111	76	146	222	111	75	127	112	111	83	95
58		PP1 + GRE2	Combine	52	35	4	76	81	41	27	52	41	41	16	25
59		PP1 + GRE2 + GRE2 + PP2	Sequence	160	143	108	178	284	143	96	160	143	143	116	123
60		PP1 + PP2	Sequence	145	128	93	163	255	128	86	145	129	128	103	108
62		PP1 + BS2	Sequence	129	112	77	147	223	112	75	129	113	112	82	88
61		PP1 + WS2	Sequence	175	153	118	188	305	153	103	175	157	153	124	128
64		BS1 + RB1	Combine	52	35	4	76	82	41	27	52	42	41	17	25
63		BS1 + RB2	Combine	123	107	72	142	214	107	72	123	109	107	80	87
65		BS1 + RB1 + BS1 + RB2	Sequence	123	107	72	142	214	107	72	123	109	107	80	87
78		BS1 + GRD1	Combine	78	65	28	100	129	65	44	78	65	65	38	49
79		BS1 + GRD2	Combine	129	113	78	148	225	113	76	129	114	113	85	97
80		BS1 + GRD1 + BS1 + GRD2	Sequence	129	113	78	148	225	113	76	129	114	113	85	97
81		BS1 + GRE2	Combine	54	36	5	77	84	42	28	54	43	42	18	27
82		BS1 + GRE2 + GRE2 + BS2	Sequence	144	126	91	161	252	126	85	144	127	126	95	103
66		BS1 + BS2	Sequence	129	112	77	147	223	112	75	129	113	112	82	88

(b) Descriptions of the sequences of actions and pathways (24-66), and the corresponding sell-by dates under different conditions

ID	Color	Action or Pathway	Type of pathway	Scenario0	HIE-median	EGA-median	IND-median	LowGrowth	MediumG	HighG	BaselineClimate	GH	GL	WH	WL
67		BS1 + PP2	Sequence	145	128	93	163	255	128	86	145	129	128	103	108
68		BS1 + WS2	Sequence	175	153	118	188	305	153	103	175	157	153	124	128
69		WS1 + RB1	Combine	59	45	9	83	95	48	32	59	48	48	23	31
70		WS1 + RB2	Combine	130	114	79	149	227	114	76	130	115	114	86	94
71		WS1 + RB1 + WS1 + RB2	Sequence	130	114	79	149	227	114	76	130	115	114	86	94
72		WS1 + GRD1	Combine	85	72	34	107	142	72	48	85	72	72	44	55
73		WS1 + GRD2	Combine	136	120	85	155	239	120	80	136	120	120	90	103
74		WS1 + GRD1 + WS1 + GRD2	Sequence	136	120	85	155	239	120	80	136	120	120	90	103
75		WS1 + GRE2	Combine	61	46	10	84	98	49	33	61	49	49	23	33
76		WS1 + GRE2 + GRE2 + WS2	Sequence	190	168	133	203	335	168	113	190	171	168	137	142
77		WS1 + WS2	Sequence	175	153	118	188	305	153	103	175	157	153	124	128
83		WS1 + PP2	Sequence	145	128	93	163	255	128	86	145	129	128	103	108
84		WS1 + BS2	Sequence	129	112	77	147	223	112	75	129	113	112	82	88
85		GRD1 + GRD2 + GRD2 + PP1	Combine	127	111	76	146	222	111	75	127	112	111	83	95
86		GRD1 + GRD2 + GRD2 + BS1	Combine	129	113	78	148	225	113	76	129	114	113	85	97
87		GRD1 + GRD2 + GRD2 +	Combine	136	120	85	155	239	120	80	136	120	120	90	103
88		RB1 + RB2 + PP1	Combine	121	106	71	141	210	106	71	121	107	106	78	86
89		RB1 + RB2 + BS1	Combine	123	107	72	142	214	107	72	123	109	107	80	87
90		RB1 + RB2 + WS1	Combine	130	114	79	149	227	114	76	130	115	114	86	94
91		RB1 + GRD2 + PP1	Combine	127	111	76	146	222	111	75	127	112	111	83	95
92		RB1 + GRD2 + BS1	Combine	129	113	78	148	225	113	76	129	114	113	85	97
93		RB1 + GRD2 + WS1	Combine	136	120	85	155	239	120	80	136	120	120	90	103
94		RB1 + GRD1 + GRD1 + GRD2	Sequence	90	77	37	112	152	77	51	90	77	77	50	62
95		RB1 + GRD1 + GRD1 + GRD2	Combine	127	111	76	146	222	111	75	127	112	111	83	95
96		RB1 + GRD1 + GRD1 + GRD2	Combine	129	113	78	148	225	113	76	129	114	113	85	97
97		RB1 + GRD1 + GRD1 + GRD2	Combine	136	120	85	155	239	120	80	136	120	120	90	103
98		RB1 + GRD1 + BS1	Combine	78	65	28	100	129	65	44	78	65	65	38	49
99		RB1 + GRD1 + BS2	Combine	168	149	114	184	296	149	100	168	149	149	116	125
100		RB1 + GRD1 + BS1 + RB1 +	Sequence	168	149	114	184	296	149	100	168	149	149	116	125
101		RB1 + GRD1 + PP1	Combine	76	63	25	98	126	63	42	76	63	64	36	47
102		RB1 + GRD1 + PP2	Combine	185	165	130	200	329	165	111	185	165	166	136	145
103		RB1 + GRD1 + PP1 + RB1 +	Sequence	185	165	130	200	329	165	111	185	165	166	136	145
104		RB1 + GRD1 + WS1	Combine	85	72	34	107	142	72	48	85	72	72	44	55
105		RB1 + GRD1 + WS2	Combine	214	191	156	226	380	191	128	214	193	191	158	164
106		RB1 + GRD1 + WS1 + RB1 +	Sequence	214	191	156	226	380	191	128	214	193	191	158	164

(c) Descriptions of the sequences of actions and pathways (67-106), and the corresponding sell-by dates under different conditions

Figure F.3: Descriptions of the sequences of all actions and pathways, and the corresponding sell-by dates under different conditions

Appendix G

Comparisons of case studies

G.1 Hypothetic Waas case study

G.1.1 Study area

Waas case is a hypothetic case study whereby the Adaptation Pathway approach was officially proposed by Haasnoot et al. (2012). The study investigated two adaptive planning for two different purposes — flood management planning and low flow management planning. Only the former one is relevant to the topic of the undertaken thesis and thus is introduced in this section. According to Haasnoot et al. (2012), the methodology of Waas case study was based on a conceptual framework (Haasnoot et al., 2011) and a technological framework (Offermans et al., 2011). In the following section, we briefly introduce this methodology as a typical prototype of the top-down approach implementation.

According to Haasnoot et al. (2012), Waas study area was "inspired by a river reach in the Rhine delta of the Netherlands (the river Waal)". The study area was set up with a highly schematized river and floodplain with realistic characteristics. Figure G.1 below shows the 3-D schematic drawing of Waas case study area — Protected from the river by the embankments, a large city, and several small villages were scattered in the five dike rings over the floodplain which was composed of various land use configurations. Haasnoot et al. (2012) made an assumption that in the past 25 years this region had suffered two flood events which brought about total damage of 2.81 billion Euros. Furthermore, they introduced the Perspectives method included with three active stereotypical perspectives in the water field — *Hierarchist*, *Egalitarian* and *Individualist* (Middelkoop et al., 2004; Offermans et al., 2011), which were derived from the Cultural Theory concept (Thompson et al., 1990). And, it was assumed that, in the aftermath of the second flood event, people began to realize that the absolute controlling might eventually fail to warrant safety as a result of climate change, therefore, people's perspective started to shift from completely *Hierarchist* — who believes controlling nature and government accountability, to *Hierarchist* with partial *Egalitarian* — who values the environment and equity. Different perspectives led to different acceptable thresholds and thus the timing of adaptation policies. Past floods together with the increasing pressure on the spatial adaptation induced by climate change and socio-economic developments gave the impetus to develop additional adaptation policies to enhance the study area's resistance to possible adverse impacts in the future. Haasnoot et al. (2012) mainly elaborated this discussion from a *Hierarchist*'s point of view by setting the cumulative flood damage being no more than 2500M Euros as the perspective-based adaptation objective.

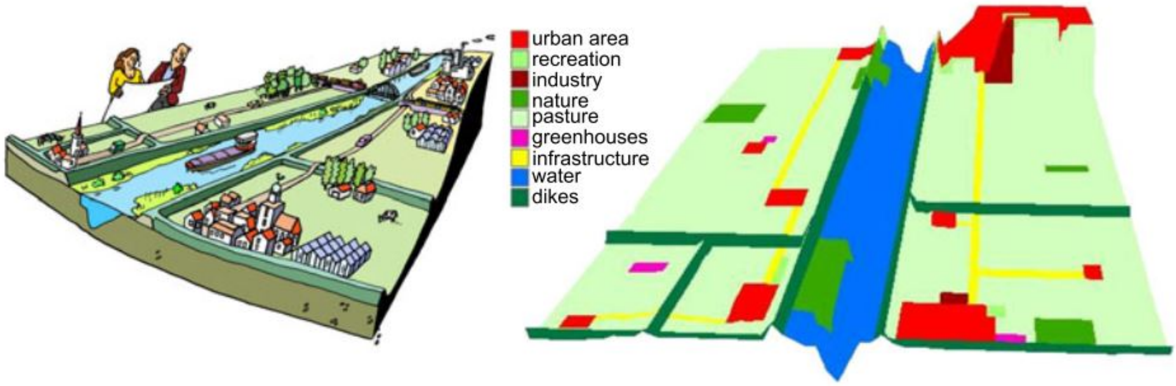


Figure G.1: 3-D schematic drawing of the study area of Waas case, reprinted from Haasnoot et al. (2012)

G.1.2 Scenarios, Policy options, Assessment model, and Sell-by date

The approach applied in Waas case is a typical top-down approach since multiple transient climate scenarios were applied as the forcing to the assessment model to do numerous transient runs. Based on three climate scenarios of KNMI'06 scenarios (Van den Hurk et al., 2007) namely "no climate change" scenario, "G scenario", and "W_p scenario", with the help of the KNMI Rainfall Generator (Buishand and Brandsma, 1996) and a transient delta approach (Lenderink et al., 2007), an ensemble of thirty 100-year time series of precipitation and evaporation representing thirty transient climate scenarios was generated by Haasnoot et al. (2012). Each of the three basic climate scenarios had ten different realizations of precipitation and evaporation as the simulation of natural climate variability. The method of synthesizing this type of transient time-dependent scenario and its usage were later summarized by Haasnoot et al. (2015).

Haasnoot et al. (2012) later employed these synthetic time series as the forcing to a HBV-SOBEK-coupled hydrological model developed for the Rhine (Te Linde et al., 2010) to produce discharge data for the Rhine at Lobith, which acted as the upstream boundary conditions for the Integrated Assessment Meta Model (*abbr.* IAMM). The IAMM was one example of "Fast Simple Models" (Van Grol et al., 2006), since it was capable of rapidly simulating, representing dominant processes without unnecessary details and supporting the incorporation and evaluation of individual policy options. Resulting discharges were then translated into water levels with the stage-discharge ($H-Q$) relations derived from a 1-D SOBEK hydrodynamic model for the river Waal. The resulting water levels were then translated into impacts (damages) with the impact model composed of a digital elevation map (DEM), dike failure probability model (Van Velzen, 2008) and depth-damage functions (De Bruijn, 2008; Haasnoot et al., 2009; Kok, 2004). In the case of a dike failure, total flood damage for the entire area was calculated as the sum of flood damage in cells for all land use sectors. Cumulative flood damage throughout the simulation (damage per year) was applied as the performance indicator for each policy option and used in the subsequent calculations of the sell-by date of policy options. Figure G.2 shows the above-mentioned cause-effect relations for the fluvial flooding management embedded in the IAMM (marked

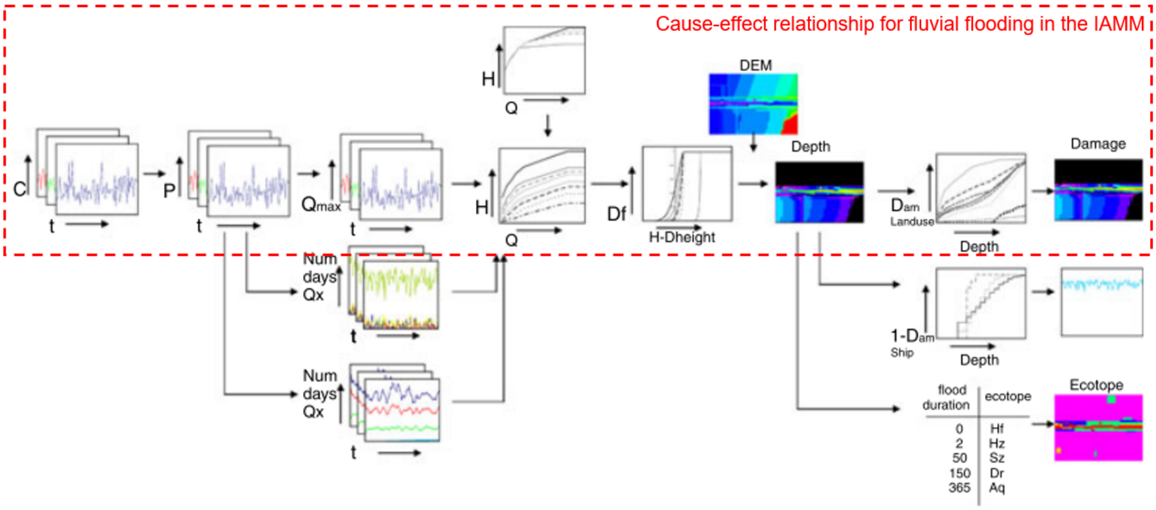


Figure G.2: Schematisation of cause-effect relations in the IAMM for Waas case, modified from Haasnoot et al. (2012). Discharges (Q) arising from precipitation (P) of transient climate scenarios (C) were translated into water levels (H) using stage-discharge relation. Resulting water levels were translated into impacts (damage) using digital elevation map (DEM) and effect functions.

in the red box). The whole chain of these simple but realistic cause-effect relations was the building block of PSIR chain (Pressure-State-Impact-Response chain) (Hoekstra et al., 1998) and was evolutionarily modeled by a set of meta models (*i.e.* the IAMM) at yearly time step over the entire simulated time horizon. Based on existing plans and potential strategies, nine individual policy options were identified by Haasnoot et al. (2012), including five flood mitigation options ("DH500", "DH1000", "DH1.5", "RfRl", and "RfRs") and four damage mitigation options ("CopU", "FloatH", "FaC", and "Mound"). These policy options were implemented in the IAMM by means of input maps and effect functions in order to evaluate their effectiveness. Besides transient climate scenarios, socio-economic factors were represented as changes in the land use map of the IAMM model. Kwadijk et al. (2010) define ATPs as points where the magnitude of change due to climate change or sea level rise is such that the current management strategy will no longer be able to meet the objectives. Therefore, it gives information on whether and when a water management strategy may fail and other strategies are needed.

Haasnoot et al. (2012) used the term "Sell-by date" (*i.e.* sell-by year) to describe the durability of an individual policy strategy. It referred to the date (year) on which the predefined objective was no longer met (*i.e.* an adaptation tipping point (ATP) was reached). Therefore, the sell-by date referred to the timing of the ATP. They assumed that a policy was considered no longer durable from a *Hierarchist*'s view if the modeled cumulative damage exceeded 2500M Euros. With the performance indicator — cumulative damage (averaged damage per year) and perspective-based objective, they determined the sell-by date of each adaptation policy option for ensembles of all transient climate scenarios. Figure G.3 below shows the results of the sell-by date of nine adaptation options for three climate scenarios from a *Hierarchist*'s perspective in the form of box plots. As shown in the figure, the computed sell-by dates varied from option to option and were dependent on the climate scenarios as well as the perspective-based objectives. Policies reaching an ATP did not imply disastrous consequences were inescapable or water management was not possible any-more. It simply meant that alternative strategies, whatever it was leveling up existing policy action, switching to or combining with other actions, were required to further manage the system (Haasnoot et al., 2012).

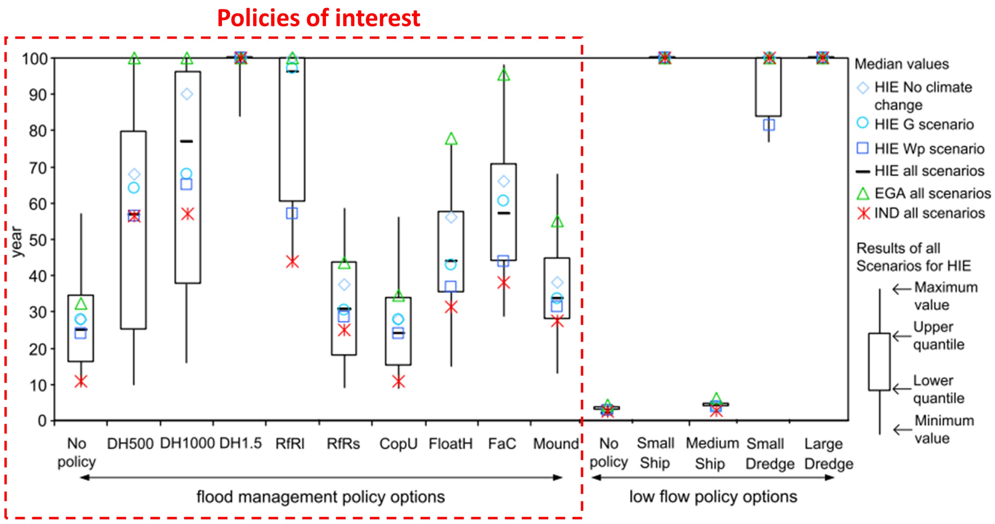


Figure G.3: Box-whisker plots of the sell-by dates of policy options based on the results for all realizations of the three climate scenarios in a *Hierarhist* future (HIE) for Waas case, modified from Haasnoot et al. (2012)

G.1.3 Adaptation pathways map

After selecting relevant options and excluding illogical ones, Haasnoot et al. (2012) made the adaptation pathways generally based on the median values of the calculated sell-by dates of all individual policy options for all transient climate realizations from a *Hierarchist*'s point of view. Below Figure G.4 shows the map of adaptation pathways for Waas Case's flood management planning over the 100-year time frame. As can be seen from the figure, 9 individual policy options are differentiated as 5 flood mitigation strategies on the upper part and 4 damage mitigation strategies on the lower part. A policy option can be shifted to or combined with another policy option to largely extend the sell-by date compared to the sell-by date of an individual policy. For example, raising the dike to cope with 1:100 discharge (DH100) is no longer durable after 77 years therefore it can be leveled up to DH1.5 (Dike improvement to cope with 1.5 times second highest discharge) or be combined with another flood mitigation strategy *e.g.* more room for the river (RfRlarge) or a damage mitigation strategy *e.g.* floating house (FaC), in order to maintain the system until the 100th year.

This adaptation pathways map presents different possible routes to reach the desired point into the future. With this adaptation pathways maps, "it is possible to identify opportunities, threats, timing and sequence of policy options, which can be used by policymakers to develop water management roadmaps into the future" (Haasnoot et al., 2012).

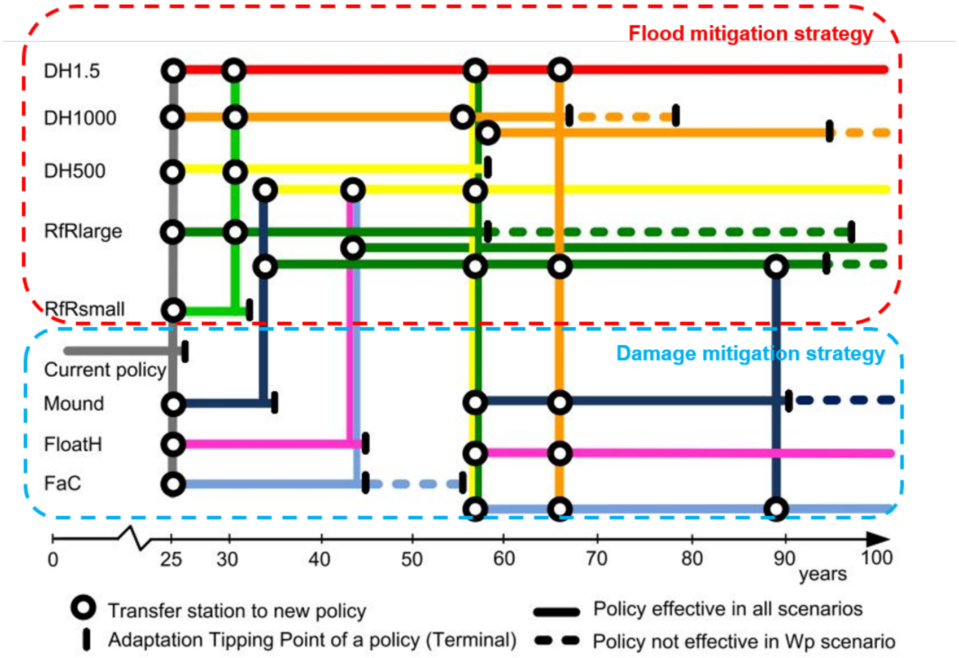


Figure G.4: Time-based Adaptation Pathways map for flood management from a *hierarchist*'s perspective for Waas Case, modified from Haasnoot et al. (2012)

G.2 Kent Ridge Catchment case

G.2.1 Study area

Kent Ridge Catchment Case study is a typical bottom-up implementation of the adaptation pathways approach on urban flood management conducted by Manocha and Babovic (2017). A detailed documentation of this case study is also available in Manocha's Ph.D. thesis (Manocha, 2018). In this case study, they took Kent Ridge Catchment as an example to study the applicability of adaptation tipping points and adaptation pathways approach on the strategical stormwater management infrastructure planning in Singapore and extended the original mode with additional economic evaluation and sub-selection of preferred pathways as a meaningful supplement to the original framework of adaptation pathway approach (Manocha and Babovic, 2017). The objective of this case study was to develop adaptation pathways to ensure the Kent Ridge Catchment free from flooding over the entire 100-year time horizon under changing climate and socio-economic conditions.

G.2.2 Scenarios, Adaptive actions, Assessment model, and Adaptation tipping point

In order to understand the individual and coupled impacts of climatic and anthropogenic factors on the timing of the adaptation tipping point, both climate and socio-economic scenarios representing an envelope of possible futures were modeled by (Manocha and Babovic, 2017). Four climate scenarios namely "Baseline", "Wet1", "Wet 2", "Dry 1", which were developed on the basis of Singapore climate change report (CCRS, 2015) and IPCC climate change report (IPCC, 2014), were employed as the possible climatic futures. Three anthropogenic scenarios included with "Current", "Green" and "Sustainable Grey", which were described as different land use configurations, were applied as the possible socio-economic futures.

In comparison with the top-down Waas case study, Kent Ridge Catchment case study is a typical bottom-up implementation of the adaptation pathways approach since its assessment model can be considered as a system vulnerability assessment that is independent on the climate scenarios. The assessment model of Kent Ridge Catchment case was a simple indicative model, which was modified from a model previously designed for evaluating engineering flexibility in Kent Ridge Catchment (Deng et al., 2013). Adaptation tipping points refer to the physical boundary conditions where acceptable technical, environmental, societal or economic standards may be compromised (Walker et al., 2001), therefore requiring the implementation of new actions to meet the specified objective (Manocha and Babovic, 2017, 2018b). The model assessed the adaptation tipping point (vulnerability) of the system with a certain configuration — the maximum annual rainfall (mm/year) that a given configuration can withstand, *i.e.* the maximum annual rainfall above which the flooding occurred thus the system failed to meet the objective (Manocha, 2018; Manocha and Babovic, 2017).

Figure G.5 below shows an example of the calculated ATPs in Kent Ridge Catchment case. Although it is the general practice to use individual rainfall events to design urban drainage, the study argued that the annual rainfall could be used as a proxy for individual rainfall events to support the first-level planning assessment and provide macro-level general directions for decision-makers (Manocha and Babovic, 2017). As such, the computed adaptation tipping points (*i.e.* maximum annual rainfall) were independent on time and climate scenarios but only determined by the magnitude of climate change. Therefore, once the adaptation tipping point for a system with a certain configuration was computed, by assuming a linear change in the climate from now and an end-point, the adaptation tipping point can be positioned on the time horizon for a given climate scenario.

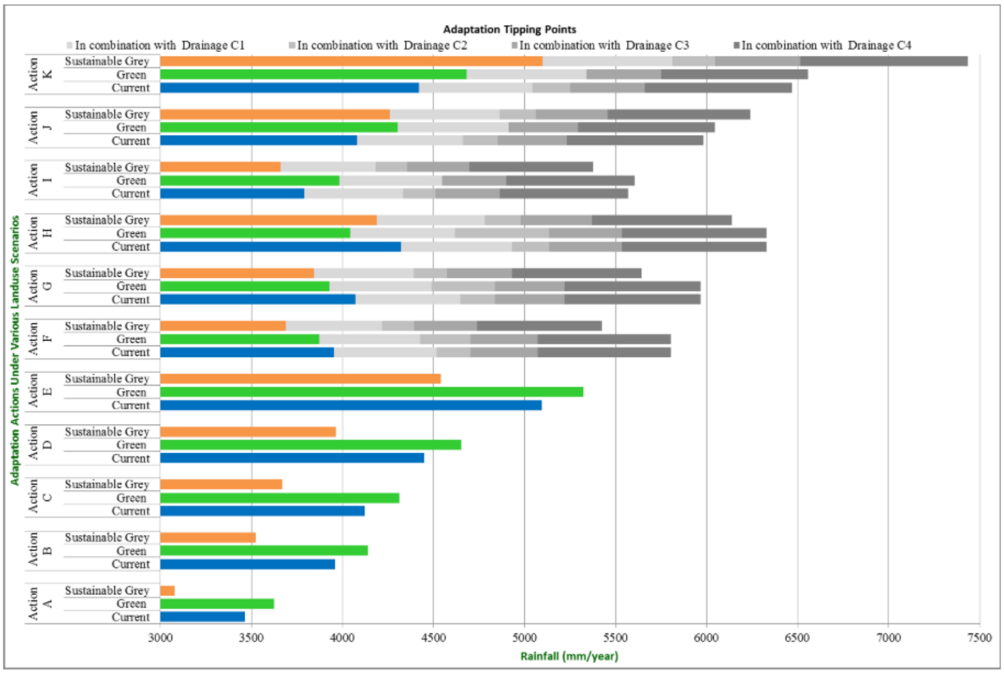


Figure G.5: Adaptation Tipping Points of actions in isolation for Kent Ridge Catchment case

Compared to the top-down Waas case which used transient climate scenarios to drive the assessment model, the bottom-up Kent Ridge Catchment case applied the vulnerability assessment which could be implemented even without climate scenarios. According to Manocha and Babovic (2017), since ATPs were defined only dependent on the magnitude of annual rainfall, they are not subject to the outlined scenarios and are therefore easily adaptable to new scenarios which are initially disregarded. In the cases where adaptation tipping points are defined in terms of other indicators (*e.g.* cost, associated damage), the ATPs developed would be dependent on the climatic scenarios but the results would only be usable for a specific ensemble of scenarios (Manocha and Babovic, 2017). Hence, through switching to or combining with other actions, the threshold value (*i.e.* adaptation tipping point) for the current system can be increased with updated configurations. In this way, the system can be upgraded continuously to ensure the objective (no flooding) being met throughout the entire time frame.

G.2.3 Adaptation pathways map

With the calculated adaptation tipping points for adaptive actions in isolation and combination, the condition-based adaptation pathways maps were assembled by Manocha and Babovic (2017) under certain rules. The difference between this condition-based map and the time-based adaptation pathway map in Figure G.4 can be clearly seen especially in the part marked with red dashed lines.

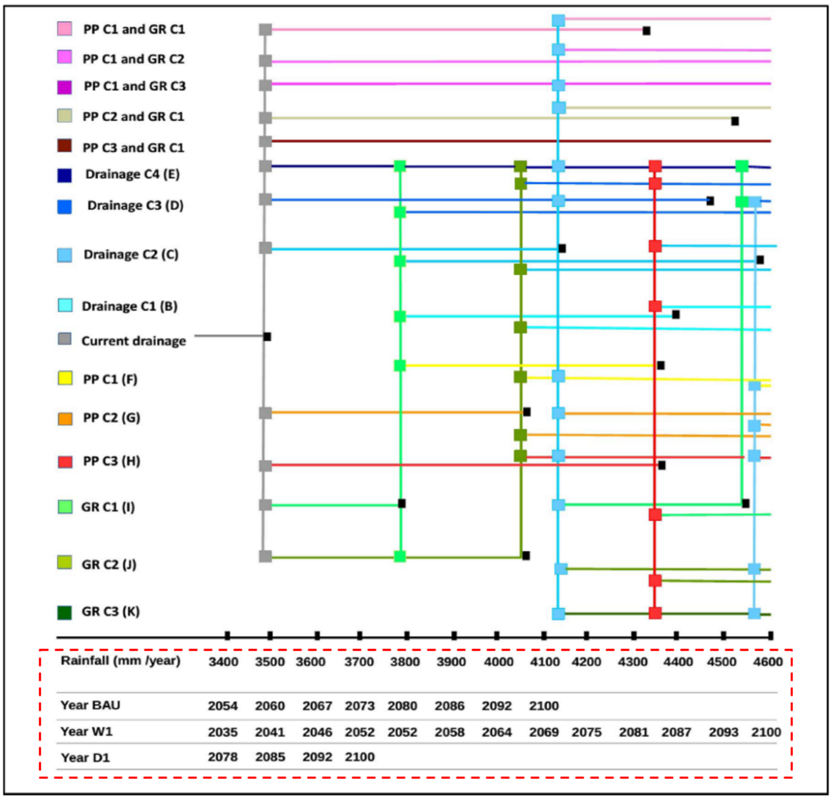


Figure G.6: Condition-based Adaptation Pathways Map, for the current land use and for climate scenarios including business and usual, for Kent Ridge Catchment case, reprinted from Manocha and Babovic (2017)

G.3 Comparison between two case studies

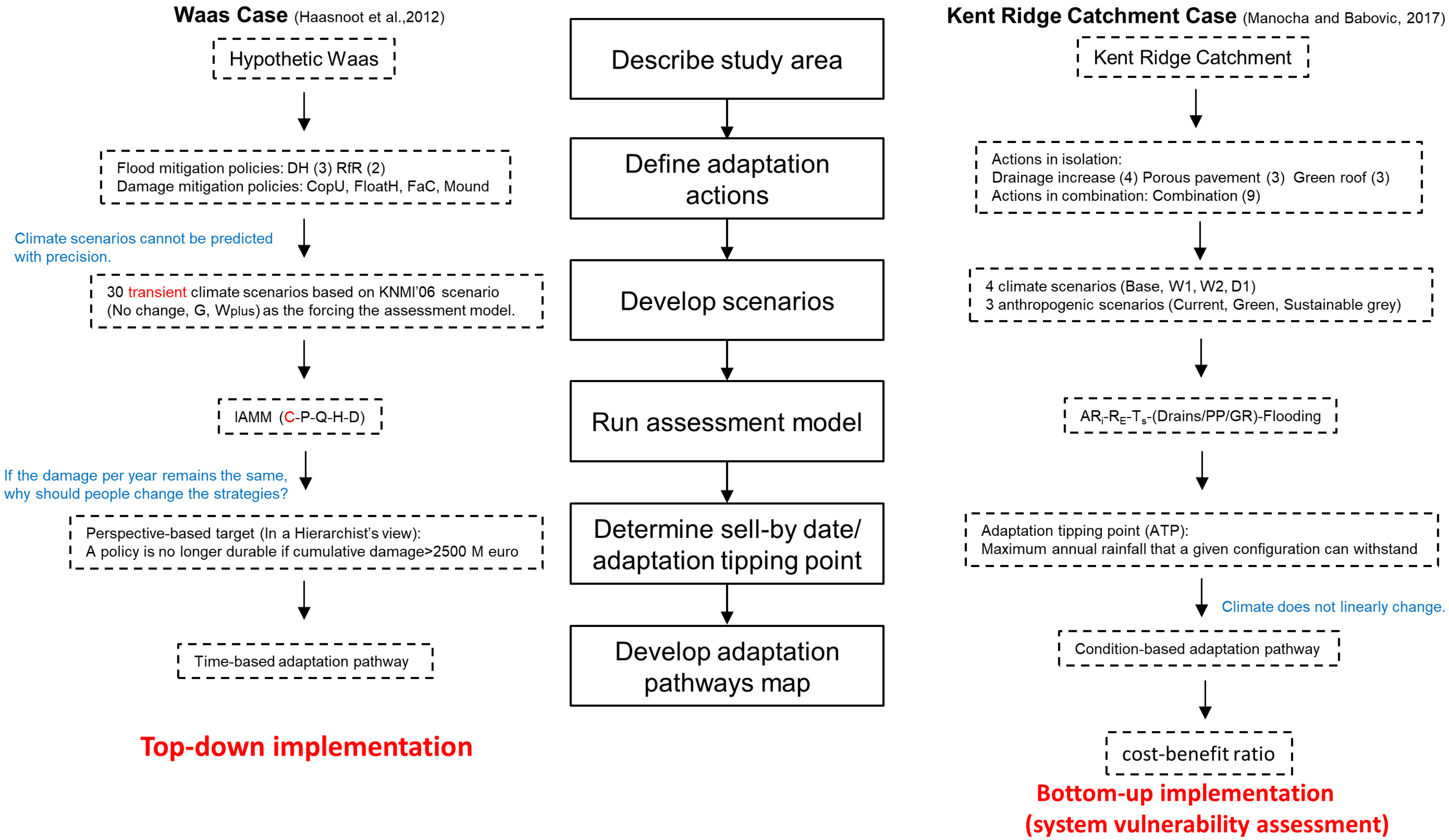


Figure G.7: Comparisons between Waas case and Kent Ridge Catchment Ridge case

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