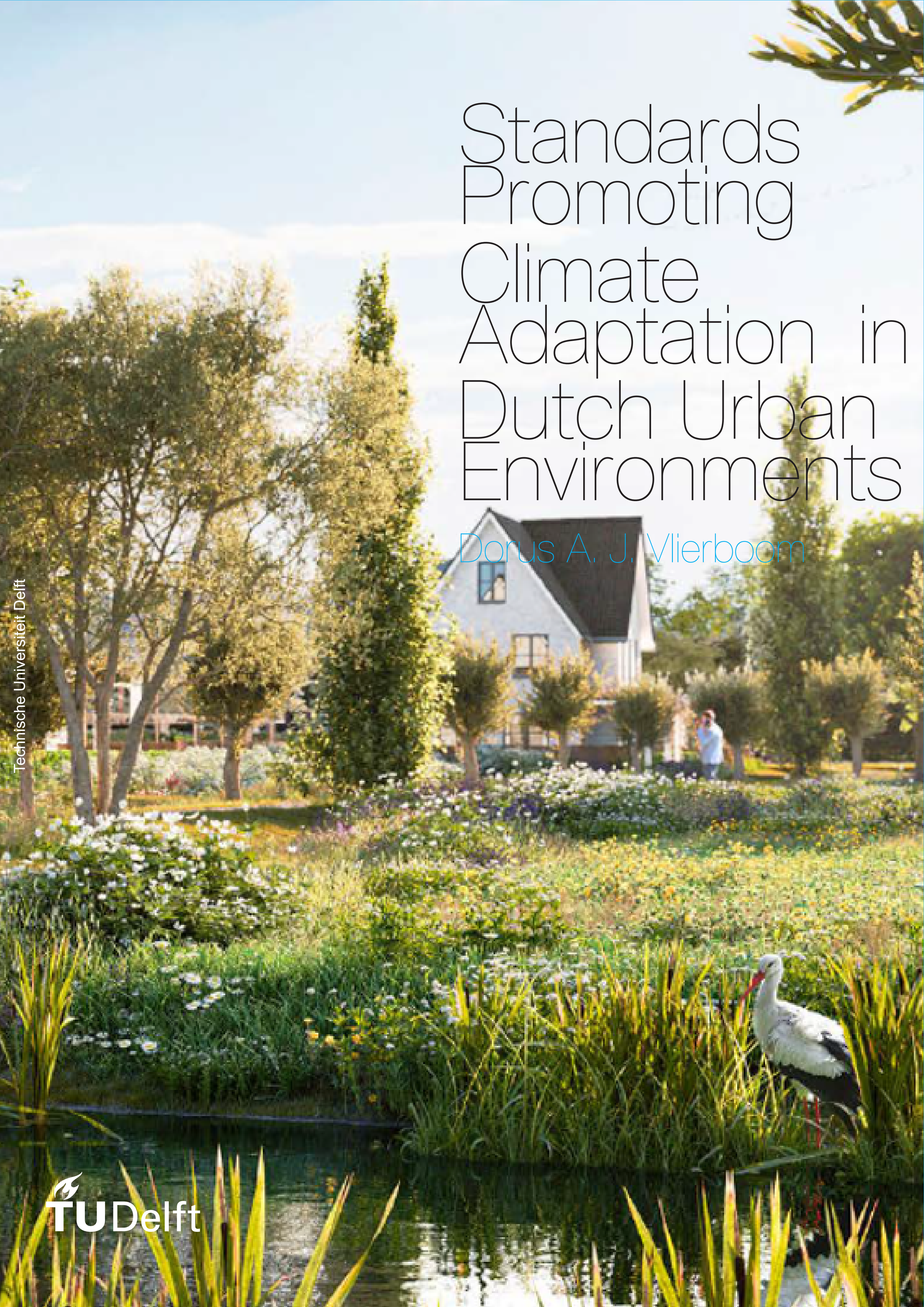

# Standards Promoting Climate Adaptation in Dutch Urban Environments

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by

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# Preface

A rule for life of mine is to always follow my interests. This is what I did when I needed to figure out where and what to study, and again when choosing a masters degree to follow. This thesis subject came to me with the title ”*Panorama New Netherlands*”. I already knew this publication by Wageningen University and was immediately intrigued by the map used as a cover page. The idea of thinking on a future where we work with climate change instead of only worrying about doomsday predictions excited me. This was what I wanted to do. However, the project was far from defined. As many fellow graduate students know, demarcating your thesis is the difficult part, especially for me.

From adaptation pathways to different climate aspects to consider in the research, everything was possible, and my supervisor, Martine, gave me complete freedom to create my own thesis subject. After a whole while we decided to hang on to an ongoing pilot in Dordrecht, where the Covenant Climate-Adaptive Building was applied for one of the first times. Here I could combine all my interests into one project. Of course, I immediately decided to research not one, but three different processes and add two extra analyses, because I felt it was needed. This proved to be a bit more work than I expected, as if no one warned me, and soon the neat planning did not check out anymore. With a few less productive weeks, months I got going again in January. I figured out my model, was taking interviews and preliminary results looked promising. Time to write everything down. With a lot of writing, iterations, focus groups and more iterations, I now managed to finish this thesis report, albeit one month later than expected.

I really enjoyed working on this subject. Many thanks to everyone that made time in their busy schedules to advise me, let me collect my interviews (I really enjoyed learning from everyone!) or listen to me giving a presentation of two hours. Thanks to Joannes, who was really helpful as member of my graduation committee with his sharp comments, but also improved the quality of my thesis considerably as a coach of the Delta Futures Lab, where we had great sessions together sharing problems and discussing various subjects that let me shed a new light on my work. Also many thanks to Jack and the others. Thank you Erik and Marjolein as part of my thesis committee. Erik helped me set up the interview analysis and provided me with a lot of help apart from the fixed moment we met with the committee. Marjolein provided much appreciated knowledge on heat stress and helped improving my thesis further. Lastly, I want to thank Martine, my main supervisor, for all the time she put in helping me. The weekly meetings in the office or on the Green Village put and kept me on track and without your advice I would have probably kept reading papers or looked into every little detail of my model.

Of course, I also want to thank all of my friends for supporting me and offering me the much needed fun and breaks during this thesis process. First of all my study friends, that offered regular coffee and lunch breaks as an escape from Studoc. With every graduation the room became emptier and my motivation suffered. Then my housemates, old house mates, friends from the Phoenix and many others that I made me enjoy a lot of great coffees (*teas), drinks and parties the last year. I will see you all soon to celebrate. It has been an experienced, but I am glad that I can finish with, in my eyes, a nice result.

*Dorus A. J. Vlierboom*
*Delft, June 2022*

# Summary

To encourage climate-adaptive building in the Netherlands the Covenant Climate-Adaptive Building (CKAB) was developed by a consortium of stakeholders (*Convenant klimaatadaptief bouwen in Zuid-Holland*, 2018). This non-binding agreement proposed standards for six (climate) aspects in order to adapt the Netherlands to a changing climate. These standards were first applied in pilots in Haarlemmermeer, Utrecht, Rotterdam (Vlot et al., 2021) and in *Dordrecht*, where the new residential area of Amstelwijck was planned. Implementing climate-adaptive measures ánd standards is yet an innovative process and iterative learning is required to improve this process. We want to know what role standards played in selecting climate-adaptive measures in Dordrecht and what result they achieved.

This study focused on three climate aspects specifically: *heat stress*, *pluvial flooding* and *droughts*. The case study in Dordrecht was evaluated by means of a *state-of-the-art* hydrological model, ***UrbanWB***. Urban plans of Amstelwijck provided the basis to research applicability of this model as a *design* and *assessment* tool (i). The goal of this method was to improve the *integral* understanding of the complexity and interrelations of a (hydrological) system for designers and policy-makers, which would allow them to make better choices. Additionally, this same model was used to assess uncertainty in *design*, *engineering* and *climate* (ii). A quantification was made for the relative relevance of design choices, such as decreasing paved surfaces, local conditions, such as soil type or drainage velocities, and climate change, with increased evaporation, precipitation and extremes. Additionally, CKAB standards and the process of applying them in Amstelwijck was researched (iii). Two groups of stakeholders, **goal oriented** (Municipality of Dordrecht, WSHD & hired staff) and **user oriented** (project developers & hired staff), were identified and these groups were interviewed with the goal of learning what kind of standards encourage climate adaptation and finding where *barriers* or *enablers* exist. This was done with the help of the concept of *user centred design* (Long et al., 2016), inspiring the stakeholder groups and a division into standards focused on *goals* or *means*, and the concepts of *principle*/*rule*-based approach (Nakpodia et al., 2016) and *creative freedom*/*specification* (Frei and Di Marzo Serugendo, 2011).

With this research it could be concluded that ***UrbanWB*** can help designers by providing arguments for *design* choices, which was mentioned as an *enabler* in interviews. The model touched on interconnectivity between different climate aspects and *five* model indicators were identified to compare the performance of different plans. For *assessment* purposes no major improvements were made yet compared to models commonly employed, except that this method offers potential for a tool, which is easy-to-adopt. By verification with other models this should become more clear. The model architecture was found to be less suitable for assessing urban plans on *heat stress* and to a lesser extent *drought*, but proved valuable for *pluvial flooding*. On uncertainty three important notions were made: climate change is a significant uncertainty; local conditions are decisive for the 'robustness', ability to perform under different conditions, of an urban system; design choices can have large effects on the hydrology of the system, some are effective enough to deal with climate change. The *type of soil* was found to be a decisive factor for every climate aspect. It is reaffirmed in interviews and focus groups that local conditions could be listed as a possible *theme* in the process of climate adaptation. In working with CKAB standards for the first two parts of this research ideas about the way of *description*, *direction* and *commitment* of standards were already formed, but the interview analysis affirmed and strengthened this view. Ideal standards should be *specific*, focused on *goals* and *rule*-based, but *principles* are leading and exceptions should be allowed to ensure *creative freedom*, which is important in an innovative process.

Designers, policy makers and engineers could apply the methodology used in this study to promote climate adaptation and deal with the uncertainty brought by climate change. The results of this research emphasized the importance of *integral* thinking in design and law-making, since this provides more insight and argumentation for selecting climate-adaptive measures A perception that standards should be focused on *goals* instead of *means* is crucial to directing urban developments.

# Contents

# List of Abbreviations

**AST** Adaptation Support Tool

**CKAB** Covenant Climate-Adaptive Building (*Dutch* = *Convenant KlimaatAdaptief Bouwen*)

**flux** magnitude and direction of the flow of a substance or property

**IBD** Engineering Services Drechtsteden (*Dutch* = *Ingenieursbureau Drechtsteden*)

**KNMI** Royal Dutch Meteorological Institute (*Dutch* = *Koninklijk Nederlands Meteorologisch Instituut*)

**NAP** Normal Amsterdam Water Level (*Dutch* = *Normaal Amsterdams Peil*)

**NBS** Nature Based Solutions

**PET** Physiological Equivalent Temperature

**SUDS** Sustainable Drainage Solutions

**UHI** Urban Heat Island

**WH** a *Warm* scenario with *High* influence of changing weather patterns

**WSHD** Water Autority Hollandse Delta (*Dutch* = *Waterschap Hollandse Delta*)

# 1

# Introduction

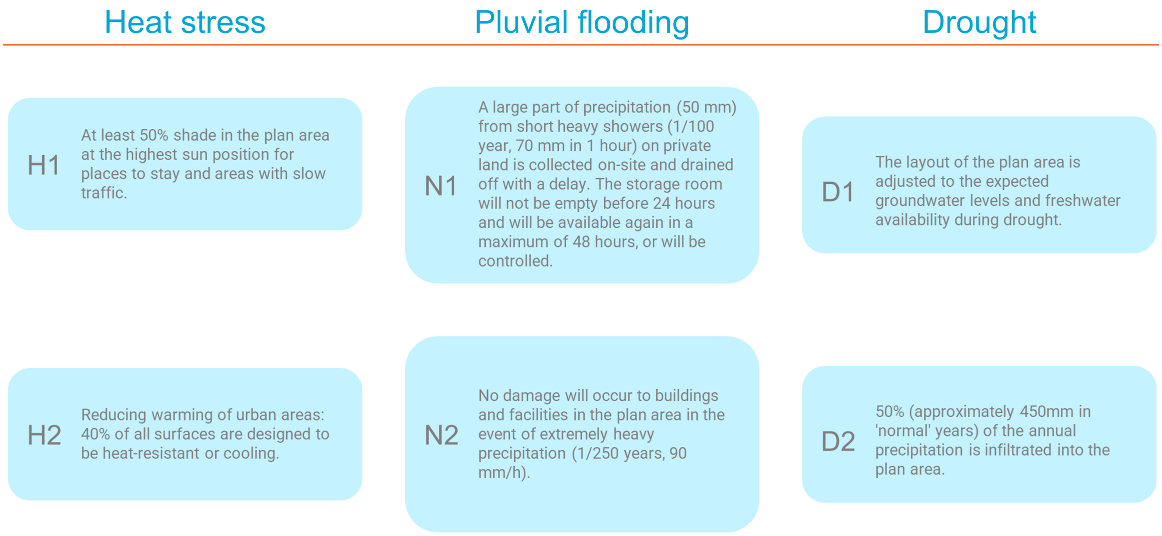
Climate adaptation is considered as one of the key challenges faced in the coming decades. Spatial adaptation is listed as one of the three parts of the Dutch National Delta Program (*Nationaal Deltaprogramma 2022*, 2021), which aims to accelerate current efforts by implementing a Deltaplan, the Dutch approach for a *systemic* national change, and develop national strategies for climate adaptation. Changing a system with long-term proven strategies and best practices takes time, resources, but also iterative learning; developing strategies for climate adaptation is yet an innovative process where no best practices are available. This research contributes to acquiring knowledge about adaptation strategies in the development of new urban areas, about standards promoting climate adaptation in urban areas.

## 1.1. Societal Relevance

This century the worldwide climate is expected to change due to the increase of greenhouse gasses in the atmosphere (IPCC, 2021). This will increase the intensity and frequency of extreme weather events (Lehner et al., 2006 & IPCC, 2021). Heat waves, droughts and heavy precipitation events are of increasing danger to communities around the world. The Netherlands will especially feel extremes because of climate change. Intensive urbanization and high concentration of economic activity in sensitive areas can amplify *heat stress*, *pluvial flooding* and *droughts* (Kluck et al., 2020 & Ritzema and Loon-Steensma, 2017). For centuries the Dutch have controlled these extreme events by managing the water system intensively (Nijhuis and Pouderoijen, 2013), but their strategies and policies on water management are being reevaluated (Ritzema and Loon-Steensma, 2017).

There is a call for action. Cities implement ever more measures to adapt to a changing climate (Voskamp et al., 2021). Grass-root initiatives like the Dutch National tile-flipping competition or green roofs on private property are getting hold. However, for adaptation to take place *structurally*, top down and bottom up regulation to encourage implementation of measures is key (Voskamp et al., 2021 & Long et al., 2016). The Dutch government and lower legislative bodies are now experimenting with standards that include climate adaptation in all building and infrastructure projects (*Convenant klimaatadaptief bouwen in Zuid-Holland*, 2018). With plans to build a million houses in the Netherlands by 2030, there are opportunities for climate adaptation in new-built property. Adapting cities to a changing climate provides a future for inhabitants without experiencing the detrimental effects of extreme climate events, but can also contribute to livability, local ecology, health and circularity in an urban environment (B. de Vries et al., 2017).

The Province of South-Holland recognizes the issue of climate change and aims to combine adaptation with building new houses. In discussion with stakeholders they developed the Covenant Climate-Adaptive Building, the CKAB (*Convenant klimaatadaptief bouwen in Zuid-Holland*, 2018). In this non-binding agreement states standards for six climate aspects; *pluvial flooding*, *drought*, *heat stress*, subsidence, biodiversity and fluvial/coastal flooding (Figure 1.1 shows the first three aspects). This Covenant should encourage developers and builders to design for a more climate-adaptive urban environment.



| Heat stress | Pluvial flooding | Drought |
|---|---|---|
| H1 At least 50% shade in the plan area at the highest sun position for places to stay and areas with slow traffic. | N1 A large part of precipitation (50 mm) from short heavy showers (1/100 year, 70 mm in 1 hour) on private land is collected on-site and drained off with a delay. The storage room will not be empty before 24 hours and will be available again in a maximum of 48 hours, or will be controlled. | D1 The layout of the plan area is adjusted to the expected groundwater levels and freshwater availability during drought. |
| H2 Reducing warming of urban areas: 40% of all surfaces are designed to be heat-resistant or cooling. | N2 No damage will occur to buildings and facilities in the plan area in the event of extremely heavy precipitation (1/250 years, 90 mm/h). | D2 50% (approximately 450mm in 'normal' years) of the annual precipitation is infiltrated into the plan area. |

Figure 1.1: Standards *heat stress*, *pluvial flooding* & *drought* as described in the Covenant Climate-Adaptive Building (*Convenant klimaatadaptief bouwen in Zuid-Holland*, 2018).

The city of Dordrecht has started by implementing these standards in the development of new urban environments. With these two challenges, building new houses and figuring out climate adaptation, a need for effective policy is apparent. Experiences from previous projects should be harnessed to improve this policy and create an urban environment resilient to climate change, an environment for the future.

## 1.2. Scientific relevance

This research considers three of the themes from the Covenant; *heat stress*, *pluvial flooding* and *drought* (Fig. 1.1). These subjects and urban climate adaptation have been widely researched. Multiple tools have been developed to assess them *individually* (Voskamp et al., 2021). However, the interconnectivity and subsequent complexity of physical processes requires an *integral* approach. Additionally, climate change introduces uncertainty, similar to the hydrological system, which is simplified in models, and design choices. Standards for climate adaptation are formulated to deal with uncertainty, but take iterative learning and improvement to be adopted.

### 1.2.1. Urban climate adaptation

*Heat stress* is a climate aspect that is difficult to tackle, because it acts on multiple scale levels, includes conflicting physical processes and is not a clear, apparent issue for people (Kluck et al., 2020). Heat stress can be defined as discomfort experienced because of high temperatures (Stagrum et al., 2020). Usually heat stress is a measure of thermal comfort for humans, but also animals, plants and even buildings and infrastructure can suffer from heat stress. Literature describes two processes as important (Kluck et al., 2020 and Koopmans, 2021): the urban energy balance (Fig. 1.2) and the human body energy balance (Fig. 1.3). Differences between urban and rural areas cause higher temperatures, mainly during the night. This is often referred to as the Urban Heat Island (UHI) effect. The second proces causes discomfort during warm days. Physiological Equivalent Temperature (PET) is widely used as a measure for thermal comfort.
One of the main drivers behind the Urban Heat Island effect are evaporation and corresponding flow of energy or energy flux, the latent heat flux, which normally consumes a large amount of energy i.e. heat in rural areas; in (Dutch) cities there can be 200-250 mm less evaporation compared to rural environments (Kluck et al., 2020). Another difference lies is urban building materials, which can have a high heat capacity and low albedo compared to natural surfaces such as soils, causing them to store a large portion of the incoming energy and release this as heat when the temperature drops, for example dur-

ing the night. More fluxes are present (see Figure 1.2) , but evaporation deficit causing a smaller latent heat flux ($QE$) and heat storage increasing the soil heat flux ($QS$) are the two most significant (Krayenhoff et al., 2021). Additional to being warmer cities are also densely populated, so extreme events such as heat waves will impact more people. PET is the most used index on physiological temperature in Europe and combines multiple meteorological variables at body height to calculate an energy balance of the human body (Fig. 1.3). Above all incoming (shortwave) radiation ($kortgolvige\ straling$) determines the intensity (Koopmans, 2021). Radiative load in cities is large, since there is less shade and less reflection back into the atmosphere. More radiation is absorbed by buildings and given back to the environment as longwave radiation ($langgolvige\ straling$), warming surfaces and consequently the surrounding air. High air temperatures ($luchttemperatuur$), which are linked to the UHI, exacerbate PET in locations with high radiative loads. Ventilation ($wind$) can be an efficient cooling mechanism, but this process is usually lacking in an urban environment (Stagrum et al., 2020).

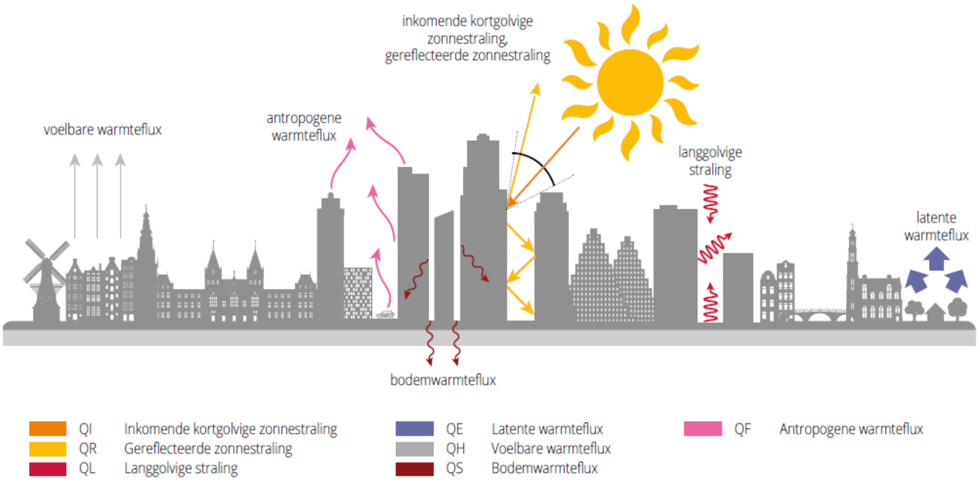


Figure 1.2: Energy balance in an urban area by Kluck et al. (2020): Incoming shortwave radiation ($QI$ Inkomende kortgolvige zonnestraling), Reflected shortwave radiation ($QR$ Gereflecteerde zonnestraling), Longwave radiation ($QL$ Langgolvige straling), Latent heat flux ($QE$ Latente warmteflux), Sensible heat flux ($QH$ Voelbare warmteflux), Soil heat flux ($QS$ Bodemwarmteflux) & Antropogenic heat flux ($QF$ Antropogene warmteflux).

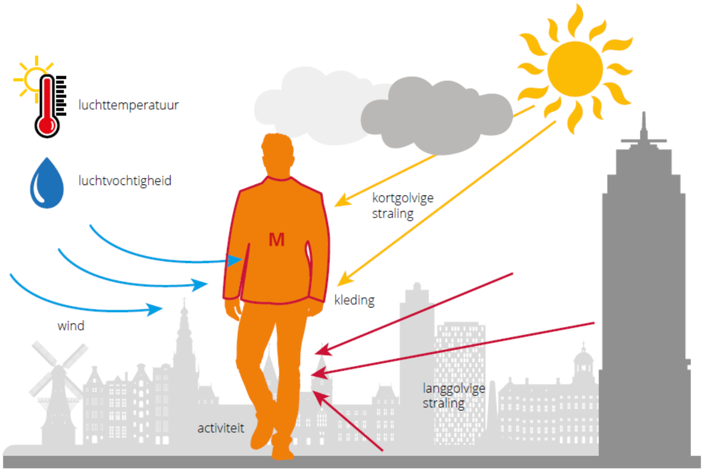


Figure 1.3: Schematic visualization of an energy balance over a human body by Kluck et al. (2020): Air temperature ($luchttemperatuur$), Humidity ($luchtvochtigheid$), Ventilation ($wind$), Shortwave radiation ($kortgolvige\ straling$), Clothing ($kleding$), Longwave radiation ($langgolvige\ straling$) & Exertion ($activiteit$).

PET is very variable on a local scale (1-100 m). Models that resolve buildings, building or street scale, are used. Other models working on larger scales i.e. cities (0.5-100 km), can capture larger atmospheric flows in the boundary layer and are often used to calculate general air temperatures, and the UHI. This distinction between microscale and mesoscale models is made in literature (Krayenhoff et al., 2021). Also, the timescale of the physical processes is different. UHI effects develop over the cycle of a day, while physiological temperatures can change every hour. Kluck et al. (2020) proposes a couple of guidelines for heat resilient design: short distance to cool spots, large percentages of shade & large percentages of green areas. Stagrum et al. (2020) also suggest large percentages of green areas, but puts an additional focus on building materials and strategic design of urban areas. In these two cases, literature does not make a clear distinction proposing solutions for UHI and PET related heat stress, in practice, this distinction is even less common.

Sustainable Drainage Solutions (SUDS), have been developed and applied to mitigate peak flows that cause *pluvial flooding* and return to a more natural hydrological response, but models that incorporate the effect of SUDS are not widely used (Voskamp et al., 2021). Pluvial flooding is caused by extreme precipitation events, rainwater that is not able to leave the water system through evaporation, infiltration or conventional drainage systems, but overflows the street or buildings, causing issues. Similarly to the heat stress problem, pluvial flooding is exacerbated due to the urban environment (Qin, 2020). Flooding affects human morbidity and mortality, causes economic damage and results in a less liveable and comfortable environment (Albers et al., 2015). Both short heavy showers and less-intense long, multiple day precipitation events can cause significant problems.

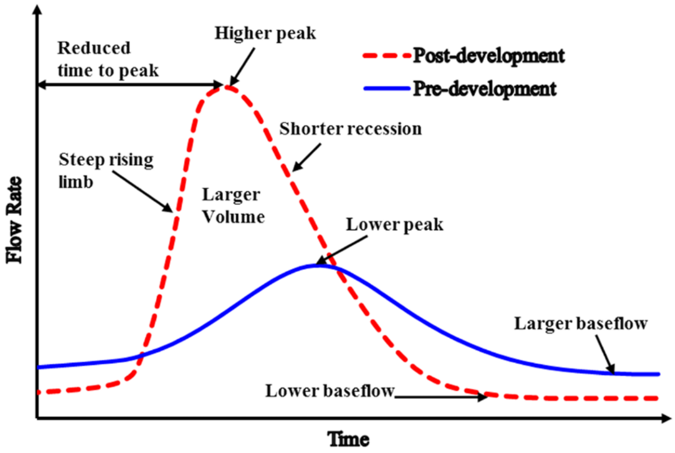


Figure 1.4: Schematic graph of the relative effects of urbanization on catchment hydrology (Rezaei et al., 2019)

Literature is available on sources of flooding (Qin, 2020, Rezaei et al., 2019 & Fletcher et al., 2013), modelling practices (Fletcher et al., 2013 & Vergroesen, 2020) and mitigation strategies (Qin, 2020). Rainfall estimation and urban hydrology are active areas of research. Climate change is expected to change the nature of extreme precipitation events, most likely increasing their frequency and intensity. Consequently, current urban water systems will not suffice. The performance of these systems in extreme events is controlled by a couple of system characteristics: storage capacity, (fast) discharge capacity, (slow) discharge capacity and runoff fraction. Urban systems have less *retention*, less storage capacity and discharge capacity through slow processes like groundwater, so *peaks* increase, by runoff and discharge through faster sewer systems (Fig. 1.4). According to Fletcher et al. (2013) *urban* hydrologic models are classified by two general criteria: spatial resolution (*lumped or spatially distributed*) and temporal resolution (*continuous or event-based*). For some events, such as short heavy showers, modelling should be done on a local, neighbourhood scale (100-1000 m) with high temporal resolution (0.1-1 h), *spatially distributed* & *event based* might work well, while multiple day events might require a larger, city-wide spatial scale (0.5-100 km) and could use coarser temporal resolution (1-24 h), then *lumped* & *continuous* might be a better option. Depending on the goal, different types of models are more suitable. Modelling is applied for a better understanding of the hydrological situation, in order to find solutions against pluvial flooding. Yang et al. (2020) and many others argue that runoff reduction and peak flow attenuation are the best ways to reduce pluvial flooding, by applying SUDS. Some tools or models such as ***UrbanWB*** have already incorporated SUDS (Vergroesen, 2020), but most do not include this function.

Local (hydrological) conditions and water management practices are decisive factors for *drought* sensitivity. When implementing measures against drought, these conditions should be taken into account. Drought is a major issue around the globe causing crop failures, famine, subsidence and salt stress (Pokhrel et al., 2021). There are four types of drought, including meteorological drought, hydrological drought, agricultural drought, and socio-economic drought, each representing a water shortage in a specific category (X. Zhang et al., 2019). In the Netherlands, in large parts of the country, water is managed intensively (with a polder system for example). Specific conditions per location can create a drought problem. There is a yearly surplus of precipitation and three major river systems have their delta here (Nijhuis and Pouderoijen, 2013). Despite this surplus there have been many recorded droughts. The effects of droughts are regional in scale (> 50 km) and they mostly occur in summer, when the difference between precipitation and evaporation is most excessive (van de Sandt et al., 2011). These periods can last weeks up to months. In the occurrence of dry periods, areas rely on groundwater reserves or external water sources. The second raises two issues: (i) the availability of water is limited during droughts; (ii) water from external sources (*”gebiedsvreemd”*) can be detrimental to water quality and ecology (Worm et al., 1997). Some regions in the Netherlands do not have an accessible freshwater resource nearby, which makes those extra sensitive to droughts (van de Sandt et al., 2011).

Droughts are caused by extreme events (Ritzema and Loon-Steensma, 2017); prolonged periods without precipitation trigger a meteorological drought. However, this would not necessarily cause problems unless this water shortage results in hydrological, agricultural or socio-economic droughts. This is controlled by other, location dependent, parameters, such as soil characteristics and corresponding water management systems (van de Sandt et al., 2011). Ritzema and Loon-Steensma (2017) distinguish three different hydro-ecological zones in The Netherlands: the man-made polder areas with *marine clay soils* along the North Sea coast and the former Zuider Sea with elevation below sea level; the *low-lying peatland areas* in the west (also below sea level) and north; and the *sandy and loamy soils* in the centre, south and east with elevations well above sea level. The sandy areas are characterized by excessive drainage upstream and flooding downstream, which makes them especially vulnerable to droughts. Peat soils have open drains and suffer from seepage and oxidation resulting in subsidence. To combat this surface water levels are kept shallow (30 to 60 cm), which often leads to waterlogging in winter, so farmers want to lower summer water level, but then the recharge of water can be insufficient with low groundwater levels as a result. Lastly, clay soils, which have problems with salt water seepage and subsidence, further contributing to seepage. Consequently, these areas require fresh water for flushing against salinization, which is inefficient and increases dependency on external water resources. Soil characteristics create different water management practices (Hoes and van de Giesen, 2015), resulting in a different sensitivity to drought.

In literature, severity of drought is most commonly measured by indices (standardized precipitation index (SPI), Palmer drought severity index, soil moisture drought index (SMI), standardized runoff index (SRI), and the TWS drought severity index (TWS-DSI5)) (Pokhrel et al., 2021). These can be used to compare different droughts. However, to assess local conditions more direct indicators, such as inspecting groundwater levels in soils or soil moisture, are used (Bachmair et al., 2016) Crop failure and unhealthy public greenery could be (visible) indicators as well. Groundwater indicators used in design are often simplified, but to set a target value for groundwater recharge requires a system analysis using a detailed groundwater model (Vergroesen, 2020). There has been some research written on controlling droughts in Dutch polder systems. Drought prediction and flood control and controlled drainage systems are proposed as viable solutions (Ritzema and Loon-Steensma, 2017). Controlling and monitoring groundwater levels and infiltration are proven measures for ensuring water availability and retaining water, but before planning with these measures, *local conditions* should be considered.

Of all three climate aspects pluvial flooding is most extensively researched. All the papers that have been written about this subject provide a large toolbox to solve problems (Qin, 2020 & Fletcher et al., 2013). However, on heat related issues there is still a debate going on how to mitigate heat stress and the awareness on heat stress is low in most of the population (Kluck et al., 2020). Drought has been a topic which circulated in the news in the Netherlands, but relatively little literature was available on innovative solutions, since the water management in the Dutch polder landscape is already highly standardized. Additionally, the locality of drought issues, results in limited literature on specific conditions. Voskamp and van de Ven (2015) argue that climate adaptation should be viewed *integrally*, because most problems ánd solutions are linked to more than one climate aspect. This can be difficult, since systems of water and energy work on many different spatial and temporal scales. For example, PET is calculated at street level, while droughts have a regional effect. Many models and tools used focus on solving one climate aspect, which means that apart from disregarding the integral effects, multiple tools are needed to assess climate standards. Complexity of systems and the ability of models to capture this complexity pose as limitations to applicability. Systems should be ”modeled (abstracted) at the highest level possible and then be progressively reduced in level of abstraction, *simplified*” (Rechtin and Maier, 2000). This notion is important to make tools and models accessible and usable for the wider public. With this goal Voskamp et al. (2021) researched which tools are available and looked at how these tools facilitate the uptake of Nature Based Solutions (NBS). They found areas where knowledge and tools were lacking. Clearly, the need exists for a climate adaptation tool that is *integral* and *easy-to-adopt*, for designers, lawmakers or other users. ***UrbanWB*** is a state-of-the-art hydrological model for implementing climate adaptive solutions (van de Ven et al., 2016 & Vergroesen, 2020). This model proves promising for analysing *heat stress*, *pluvial flooding* & *droughts* to aid the *design* and *assessment* of urban plans. However it is still uncertain how useful this model is in relation to assessing plans on the CKAB standards.

### 1.2.2. Uncertainty

Climate change introduces significant uncertainty. This is combined with multiple disciplines, the (hydrological) system and design (spatial planning), increasing uncertainty. To start, this uncertainty is caused by complexity. The term complexity can be defined in many different ways depending on the type of system interpreted (Sussman, 2002). Rechtin and Maier (2000) defines something complex when a system possesses interconnected parts, the more connections, the more complex this system is. For example, Figure 1.3 displays variables, whose interconnection cause physical heat stress. Additionally, this process is connected to the process of UHI by air temperature, which in turn is connected to the water system through evaporation. In the definition of Rechtin and Maier (2000) complexity increases in systems with multiple scale levels that are interconnected, so with multiple scales in *heat stress*, *pluvial flooding* and *drought*. The notion of complexity is important. As mentioned in the previous section, complex systems are simplified where possible, with parameterizations for example, but complexity behind these parameters remains. With high complexity and simplification, uncertainty emerges (Walker et al., 2013). Uncertainty implies limited knowledge about future, past or current situation of a system (Walker et al., 2013). Future predictions of climates are uncertain, because predictions depend on an enormous amount of parameters, for one, and because this is a very complex system, actually multiple systems interacting (Stagrum et al., 2020). A soil parameter can be uncertain, for the reason that it contains information of a large volume, possibly an average not showing temporal or spatial variability or because measurements can be uncertain (Bachmair et al., 2016). This parameter is simplified. Uncertainty in spatial planning lies in the amount possibilities for design; there is little certainty about the best solution or no ’best’ solution at all.

The only thing certain is uncertainty. Therefore dealing with uncertainty is very important. The level of uncertainty is key in determining the way of coping. Walker et al. (2013) defines five levels of uncertainty between complete certainty and total ignorance. Each of these levels has a different context, way of modelling a system and system outcomes with corresponding weights. Four ways for handling uncertainty in policy were proposed: (i) *resistance*, plan for the worst conceivable case; (ii) *resilience*, prepare for quick system recovery; (iii) *static robustness*, implement a (static) solution that performs in all situations; and (iv) *adaptive robustness*, implement solutions that can be changed if conditions change. The first two methods require a decrease of uncertainty; a ’true’ situation has to be found to prepare for. The robust policies (iii & iv) are different, since they do not require one ’truth’, but instead prepare for multiple situations. Recently, an ’*adaptive*’ approach to dealing with climate change has gained more track (IPCC, 2021). ’*Adaptive*’ as frequented term does not necessarily imply *adaptive robustness*, but can also point to a *resistance* approach ’adapting’ the current system considering a future climate. Sometimes this approach is extended with a *static robustness* approach, for example when more scenarios are considered. Several governmental organisations are attempting to implement this in their regulations and policy (*Convenant klimaatadaptief bouwen in Zuid-Holland*, 2018 & Berg and Gemeente Amsterdam., 2020). However, there are also researchers proposing to use even more flexible methods in policy and design (Haasnoot et al., 2012) resembling *adaptive robustness*. This includes modelling with different climate scenarios to identify possible future pathways (Manocha and Babovic, 2017, Haasnoot et al., 2013 & L. de Vries, 2021) or researching different mitigation strategies to create pathways (W. Zhang, 2019 & Lieftink, 2021). Several studies such as the ones mentioned above have researched uncertainty and how to deal with uncertainty. However there are no good examples of research into uncertainty considering the *integral* effect of urban designs and NBS's on multiple climate aspects.

### 1.2.3. Standards for climate adaptation

Governmental organisations implement more diverse strategies to accommodate changes and in managing extreme events. Ritzema and Loon-Steensma (2017) point out that the old method of preventive measures to provide basic security for the population (*resistance*), like building higher dikes, is now extended with sustainable spatial planning (*static and adaptive robustness*) and disaster management (*resilience*). So even in case of disaster, damage to important infrastructure and buildings is minimized and social disruption is prevented. This accepting of a changing climate, of uncertainty, and attempting to deal with it translates well into climate adaptation, "*the reducing negative or using positive effects of climate change by societies*". This different mindset allows communities to come up with new ways of dealing with climate issues. New legislation for spatial planning, Sustainable Development Goals (SDG's) (Voskamp et al., 2021), participatory Planning Support Systems (PSS) (Voskamp and van de Ven, 2015) and initiatives such as the Deltaplan (*Nationaal Deltaprogramma 2022*, 2021) and Covenant Climate Adaptive Building (*Convenant klimaatadaptief bouwen in Zuid-Holland*, 2018) aim to accelerate climate adaptation with standards, rules, methods and/or subsidies.

Implementation of these new ways is proving to be a process of trail and error. Different frameworks have been developed to aid the adoption of novel technologies or processes in the field of sustainability and climate adaptation (de Boon et al., 2021). It is recognised that *"adoption of an innovation alone may not achieve optimal outcomes, due to mismatches between the technological innovation design and the context within which it is ultimately used; as such, adoption of technology can be seen as a process of adaptation and appropriation."* (Long et al., 2016); innovation is an iterative process. An example of this are SUDS, where the technology is advanced enough for them to be effectively implemented, but they are not widely used, because maintenance, price and other barriers still hamper adoption. Similarly, new standards are not immediately perfect, but will adjusted in an iterative process for better usability and effectiveness, to become *easy-to-adopt*. Long et al. (2016) applied the concept of *user centred design* on innovations in climate-smart agriculture. This concept identifies two groups that have a barrier or duality between them preventing adoption of novel technologies (or standards). It then takes user input (co-creation) to accommodate both sides (fig. 1.5). This method has been developed to encourage user participation and ensure more bottom-up instead of only top-down design. This would encourage the adoption of innovations.

The concept of barriers allows researchers to map the factors that hamper adaptation. Long et al. (2016) identifies barriers that can be experienced by either groups. In addition enablers, the common ground, can be identified as well. Six themes were distinguished to group barriers for the adoption of pro-environmental technological innovations (Long et al., 2016): economic, institutional/regulatory, behavioural/technological, organisational, consumers/market and social. Voskamp et al. (2021) did a similar analysis while mapping different tools for planning nature based solutions. They found similar themes: the institutional setting; availability of (financial) resources; level of expertise, know-how or competence; and collaborative governance and planning. The framework developed by Long et al. (2016) could be used to improve standards for climate adaptation, by identifying the barriers or enablers and improve the standards where necessary. In this framework stakeholders were divided into two groups, with different priorities and motivations, *users* and *providers*. This resulted in different requirements for tools, rules, technology, etc. they deal with. For example, a *providers* might want to develop a product with some level of performance and also need to make a profit, while a *user* requires a product that is easy in use and cheap to acquire. They could have a conflict about the price of this product. When applied to innovation in climate adaptation, the terms of *users* and *providers* do not fit, so instead **goal oriented** and the **usage oriented** could be utilized as terms to distinguish between different stakeholder groups. Similar to Long et al. (2016) these stakeholder groups have different pri-

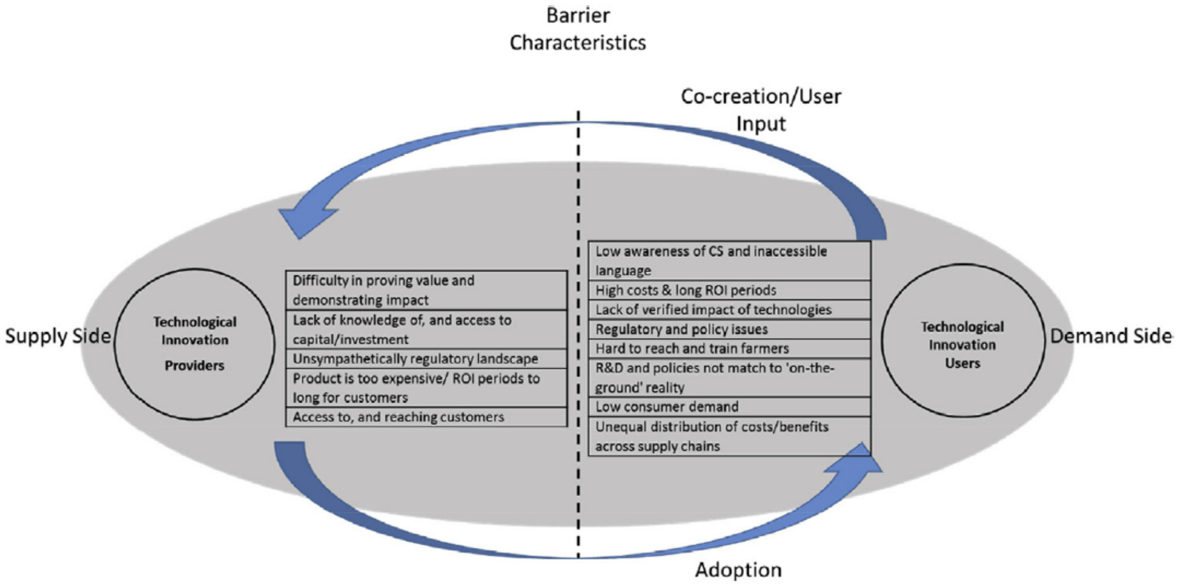


Figure 1.5: Visualisation of the concept of *user centred design* as used by *Long2015*

orities and motivations.

In order to analyse the CKAB standards, additional concepts are required. To go back on how the stakeholder distinction was made between *users* and *providers*: the first requires products focused on *goals*, the second focused on *means*. The same can be applied on standards in a process of climate adaptation. A *means* focused standard aims to achieve a goal for climate adaptation by prescribing one or more measures, while the other, with a focus on *goals*, prescribes the goal itself with less restrictions on the type of measures. Naturally, the goal for climate adaptation is inherently subjective and open for discussion. Furthermore, there are two concepts that are similar to this concept and overlapping, but should be defined separately: *principle*/*rule*-based approach (Nakpodia et al., 2016) and *creative freedom*/*specification* (Frei and Di Marzo Serugendo, 2011). Nakpodia et al. (2016) introduces *principles*, a "*voluntary/non-binding set of recommendations, standards, and best practices, issued by a collective body*" and *rules*, "*stricter laws which must be adhered to*", as two ways of prescribing practices. One allows more and trusts the users interpretation, while the other restricts, but ensures that standards are always met. Frei and Di Marzo Serugendo (2011) talk about ways of formulating boundaries and flexibility: "*to control a system, it will need to be specified, but a system too specified will limit creative freedom to localize solutions in a adaptive way*". On first appearance *specification* matches well with *means* and *creative freedom* with *goals*, but the first concept revolves on *what* is described, the direction, and the concept by Frei and Di Marzo Serugendo (2011) on the *how*, the definition description. Since climate adaptation and especially applying the CKAB standards is relatively novel in standard building practices, little research has been executed to date. The process of implementing standards for climate adaptation could be considered innovative, so the concepts above are be applied in an analysis on these standards and can help the iterative process of improving them.

## 1.3. Research objectives

Climate adaptation is an issue of uncertainty and innovation, including issues of complexity and governance. Designing urban plans that take into account the *integral* effect of *heat stress*, *pluvial flooding* and *drought* proves to be difficult; different physical processes, temporal and spatial scales all play a role. With an understanding of the system, a designer is able to make better choices. Similarly, no tool for assessing urban plans *integrally* is widely adopted. A accessible tool is important for assessing if goals for climate adaptation are met. To translate physical goals to a manageable format, standards are formulated. The way standards are described, asserted and bounded determines how these standards are implemented. This with the knowledge gaps determined in this Chapter lead to the **main**

**question** of this thesis:

*How is **climate adaptation** for **heat stress**, **pluvial flooding** & **drought** promoted in the development of urban plans by **design** & **assessment** with the **Covenant Climate-Adaptive Building** and **UrbanWB**?*

In dealing with climate change and the accompanying complexity it brings, uncertainty in a the system is meaningful. This research aims to map uncertainties in spatial planning (*design*), local conditions (*hydrological system*) and, naturally, climate change (*climate*), and their relative relevance. To reach this goal the following research question is formulated:

**RQ 1:** *Which **uncertainties** in **climate**, **design** and the **hydrological system** are relevant for designing a climate-adaptive urban plan?*

Research question 1 is answered by utilizing ***UrbanWB***, a model developed by Deltares. This model is evaluated for applicability in *design* and *assessment* of urban plans as well, which leads to the second research question:

**RQ 2:** *Can **UrbanWB** be used as a tool for **design** and **assessment** of climate-adaptive urban plans?*

lastly, standards are provided as a viable solution to encourage the adoption of solutions that deal with the uncertainty climate change brings. In order to improve these standards this research reflects on experiences of implementing standards for climate adaptation, leading to the third research question.

**RQ 3:** *What kind of standards **encourage** stakeholders to implement climate-adaptive solutions?*

For the application of these three research questions a *case study* of new-built neighbourhoods in Dordrecht is adopted (Ch. 2). In this Chapter the background, local conditions, extraction of data from the case study and a stakeholder analysis are explained. Later the *methodology* that is used to answer the research questions will be elaborated on (Ch. 3). This includes: a description of the model use (sec. 3.1.1), case study implementation (sec. 3.1.2) & indicator identification (sec. 3.1.3); methodology of assessing sensitivity of hydrological uncertainty (sec. 3.2.1), climate change (sec. 3.2.2) & spatial planning (sec. 3.2.3); and analysis of standards by theme identification, data acquisition, data analysis & data verification. The *results* are displayed in Chapter 4: results of the model analysis (sec. 4.1) and sensitivity analysis (sec. 4.2) for *heat stress*, *pluvial flooding* and *drought*; and an analysis of standards (sec. 4.3) assessing configuration, identifying barriers and enablers, grouping those into themes and verification by focus groups. Then the *discussion* (Ch. 5, which elaborates on the significance of the results, relation to scientific relevance and the practical implications. Lastly, *conclusions* are presented (Ch. 6). A review of this study reflecting on the research questions above is provided and the main question of this thesis is answered.

# 2

# Case study

This research utilizes a case study in order to test the application of the methods on a real project. This case study is named Amstelwijck, which was on of the first projects to use the standards in the Covenant Climate-Adaptive Building (CKAB). Two projects were evaluated for this research, named Amstelwijck I and Amstelwijck II. The case study is located in the city of Dordrecht, a town with a rich (geomorphological) history. The case study provides urban plans used for the model and sensitivity analysis (sec. 3.1 & 3.2), but the process of developing these urban plans is utilized as well in the standard analysis (sec. 3.3)

## 2.1. History

Dordrecht started as a small settlement in the $11^{th}$ century at the small river *Thuredrith* Boone, 1999. The town soon grew because of the important waterways nearby. In that time it was part of the large *Groote Waard* polder area, until 1421, when the *St. Elizabeth* flood inundated this whole area. Dordrecht became an island *(see Fig 2.1)*. Rivers and a landscape of tidal flats surrounded the city after the flood. This resulted in marine clay and tidal creek deposits south of the city. Over the centuries some areas had become more elevated until land rose above the water. Around the year 1600 the people of Dordrecht decided to construct dikes and create the first polder, the *Oud-Dubbeldamse polder* (Fig. 2.2). After this several other polder-works were constructed and, in 1659, the *Oostmijlpolder* and *Wieldrechtse polder*, where the case area, Amstelwijck, is situated. These polders are now centuries old, so the ground has subsided. Nowadays the surface level lies 30 to 40 centimeters below sea level and this trend is continuing. When they were first constructed the polders predominantly served an agricultural function. Over the course of the $19^{th}$ and the $20^{th}$ century the older polders became urbanized.

## 2.2. Soil characteristics

The environment that formed the soil and later land use determine hydraulic conductivity, water holding capacity and other characteristics that describe how the soil behaves. The previous section explained the evolution of the current area, where a tidal environment in the $15^{th}$ and $16^{th}$ centuries deposited a plain of marine clay crossed with creek beds that are more sandy (CAS, 2021). As a result the hydraulic conductivity of the soil is low in most places ($0.001 - 0.5m/day$), but locally higher ($1 - 10m/day$). Below this top layer lies peat and another clay layer (Fig. 2.3), with low hydraulic conductivity as well. Because of these characteristics quick infiltration of precipitation is impaired. However, there is some upwell ( $0.5mm/day$, CAS, 2021 & Brouwer, 2016) caused by higher water levels in adjacent waterways. Additionally, the peat layer causes continuous subsidence, which, in some locations, is worsened by the water management. The clay and peat layers below impair infiltration into deeper groundwater, so most of the water infiltrated ends up in the surface water.

Figure 2.1: Dordrecht and the drowned area of *Groote Waard* by *Pieter Sluyter* around 1560 (Boone, 1999).

Figure 2.2: Military topographic map of Dordrecht and the Biesbosch around 1840 (Boone, 1999).

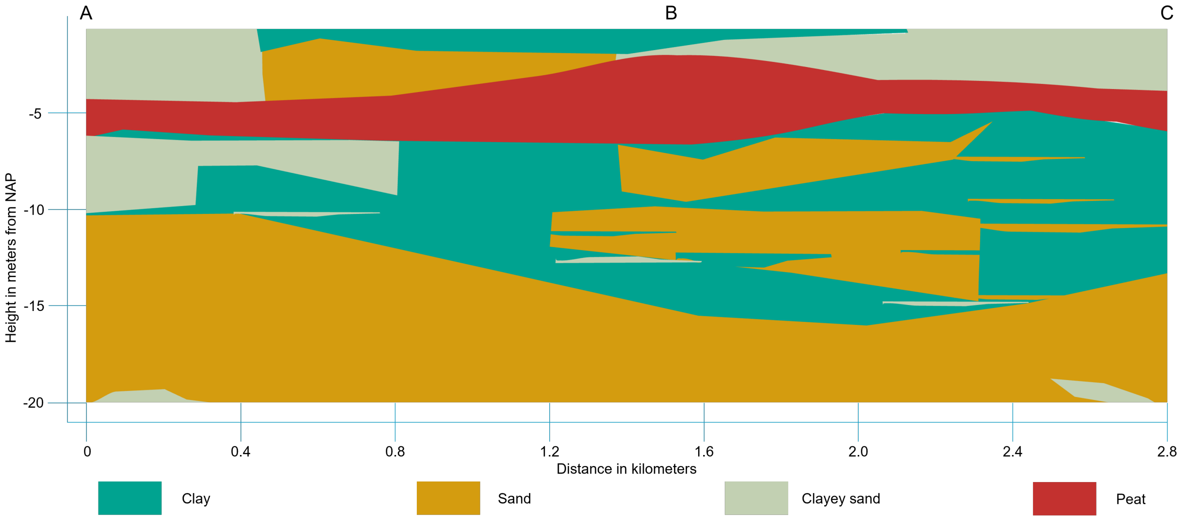


Figure 2.3: Schematic cross section (South-North) through Amstelwijck representing soil composition adapted from Dinoloket ("Ondergrondmodel Amstelwijck", 2022). Section line indicated in Figure 2.4.

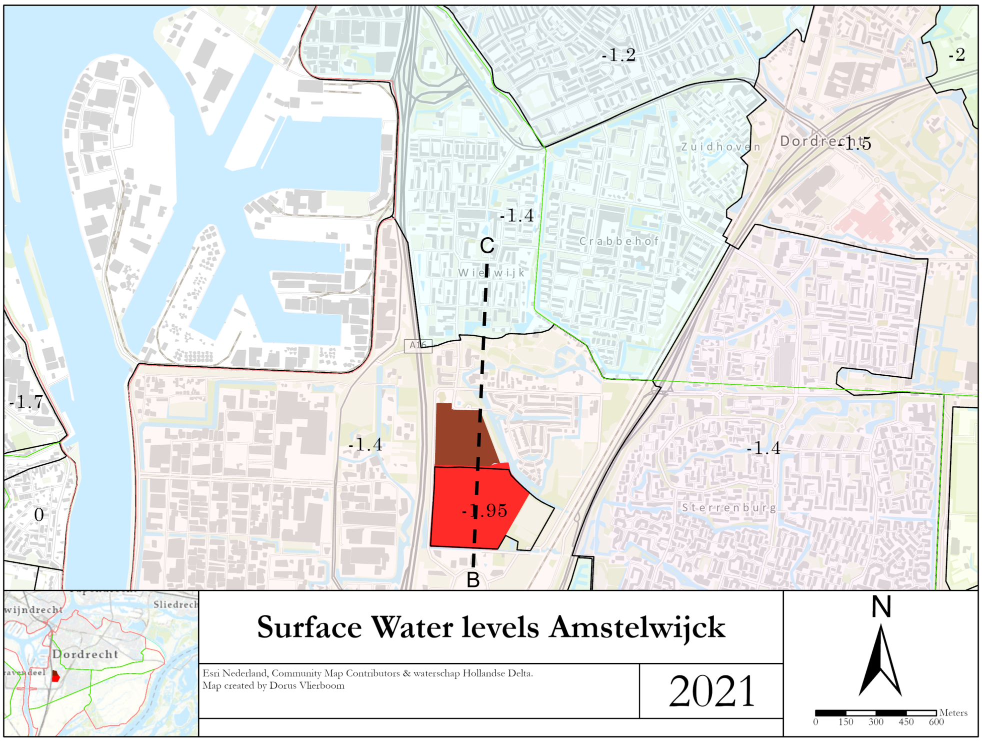


Figure 2.4: Hydrological (polder) units and surface water levels around Amstelwijck. Crossection from Figure 2.3 indicated on map.

## 2.3. Water

The water in Amstelwijck is managed with a polder system. This is a typical landform and watermanagement system in the Netherlands, especially in the western part of the country. Water levels in the area are separated from the surrounding hydrological regime and controlled by an outlet structure or pump (Hoes and van de Giesen, 2015). The polders in the case study have the same water level in winter and summer. The two case areas actually maintain two different water levels (Fig. 2.4). Amstelwijck I is situated in a hydrological unit with a level of $1.4m$ below NAP (Normal Amsterdam Level), similar to the surrounding area, while Amstelwijck II is a small hydrological unit on its own with a water level of $1.95m$ below NAP. Both systems have an urban nature, which suggests that a large portion (25% to more than 50%) of the surface is paved (B. de Vries et al., 2017). This leads to more overland and sewerage runoff towards the surface water. As mentioned in section 2.2, there are a lot of confining soil layers present. There is some outside water (upwell: $0.5mm/day$) entering the system through the confining layers.

The polder system is managed intensively. A margin of centimeters above and below the set water level is allowed, but surplus will be pumped out almost immediately and a shortage of water is solved by transporting water from another source, in the case of Dordrecht from the Biesbosch. It is undesirable to take water from foreign sources (*”gebiedsvreemd”*), since it can cause detrimental effects on water quality and ecology (Worm et al., 1997). Preferably, the surplus of water for *pluvial events* would be stored and used for periods of *drought*. Especially with an eye on the future, where higher evaporation rates and, with the implementation of climate adaptive measures that encourage evaporation (against *heat stress*, for example), a higher demand for water is expected. For the new quarters of Amstelwijck one of the main tasks will be how to manage the water year-round, taken the different climate aspects into account.

Figure 2.5: Amstelwijck I with land use classes indicated.

Figure 2.6: Amstelwijck II with land use classes indicated.

## 2.4. Urban development

Urban development changed the land use and consequently the hydrological system. Starting in the second half of the $19^{th}$ century Dordrecht started to expand outside the old city centre, but in the 1950's urban expansion in the polders accelerated with the planning and building of large residential areas (*Wielwijk, Crabbehof, Sterrenburg, Stadspolder*s) and industrial areas (*Dordtse Kil, Amstelwijck*) (Fig. 2.7). The formerly agricultural polders became built and paved. This generally moves discharge from retained drainage through the soil to more runoff and controlled drainage via pipes, etc. (B. de Vries et al., 2017)

Amstelwijck was part of this urbanization trend. Between residential area, industrial zones, highways and a railway the area was planned with multiple purposes: the *Refaja* hospital built in 1971 (location of Amstelwijck I); the neighbourhood Dordtse Hout finished in 1998; sport accommodations (location of Amstelwijck II); a municipal hatchery and orchard; and a mostly unused wooded area with a camping site.

Now these areas are being developed as residential areas, which will change the land use once more. The municipality of Dordrecht has indicated that the standards in the Covenant Climate Adaptive Building should be followed, setting more requirements for the project compared to usual developments. Project developer *ABB* is building *Amstelwijck Park* (Amstelwijck I), a small neighbourhood with 190 houses (Fig. 2.5). They implement a large fraction of green spaces for infiltration and against urban heating and add trees against heat stress. They also increase the fraction of open water in order to store more water in cases of heavy rain and to combat urban heating as well. Additionally there is a *wadi* system implemented able to store $1025m^3$ of water in case of heavy rain and *rain barrels* are connected to every house. Lastly on roofs of garden sheds *green roofs* are applied.

In the adjacent plot *Dordts Buiten* (Amstelwijck II) is planned by developers *Plegt-Vos* and *Roosdom-Tijhuis* (Fig. 2.6). There, similarly, a lot of space is reserved for green and more surface water is added as well. There are also a lot of existing, large trees that provide shade. Additionally, every house will be equipped with a rain barrel that captures water from the roof.

Figure 2.7: Urban development of Dordrecht in the 20th century (Sleebe, 2000).

## 2.5. Stakeholders

The case study of Amstelwijck has multiple parties involved in the process. Public institutions, such as the Municipality of Dordrecht and the Water Authority, Waterschap Hollandse Delta (WSHD), directly, and the Province of South Holland and Government of the Netherlands indirectly, are involved in deciding on policy and developing boundary conditions that have to be followed when building. These public institutions hire semi-governmental engineering consultants, in Dordrecht the Engineering Services of Drechtsteden (IBD), that provide advise and help with assaying engineering projects. On the other hand there are private parties. The first would be inhabitants, both future and current in surrounding neighbourhoods. They care about their direct environment and how this changes in the future. Current inhabitants can directly stress their concerns, for future inhabitants this would be indirect. Secondly, the project developers and hired staff introduced in section 2.4 are a private party that develops the urban plan and builds the neighbourhood. They need to meet the boundary conditions set by the governmental institutions and try to include concerns of inhabitants in their plans.

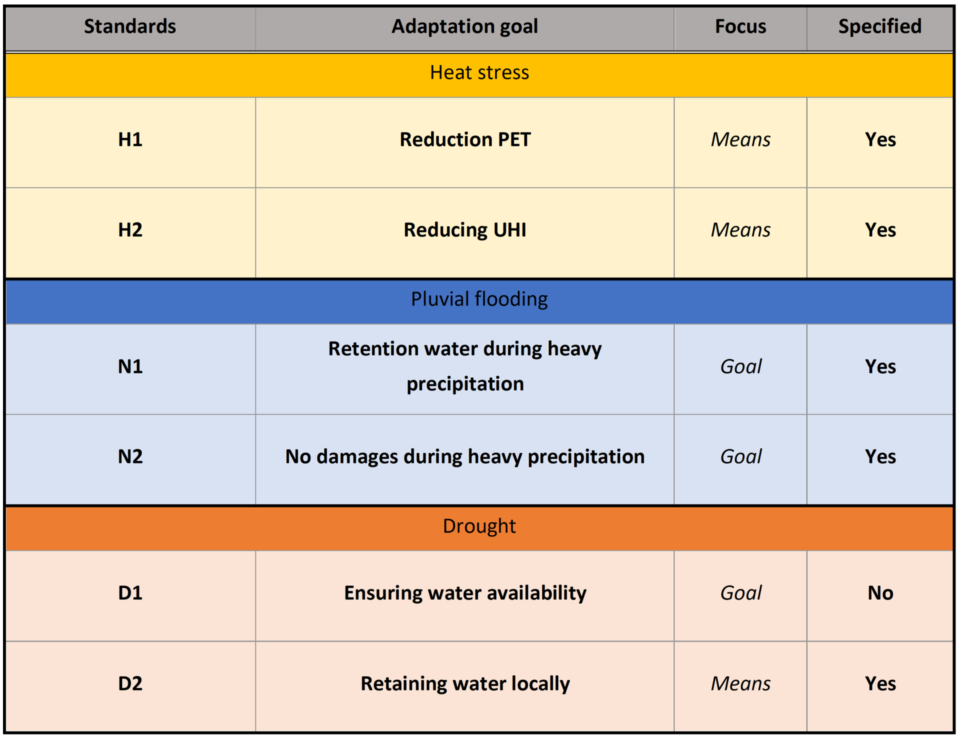
The most important stakeholders, i.e. the stakeholders most directly involved in the project, are the municipality and the project developers. The Municipality of Dordrecht has multiple employees (a projectmanager, urbanist, landscape architect & legal expert) working on policy and converting this policy to a *bestemmingsplan*, a development plan, that defines the boundary conditions for building. Additionally there is a maintenance department in the municipality that manages the public space after construction and advises for standards used in policy. They provide different services, such as road management, landscaping, etc. The project developer has a project manager and hires their own urbanists and landscape architects that take the development plan design an urban plan. These individuals should be included in the research, since they have closest ties to the project. However, there are other stakeholders involved that might also have relevant information or visions about the project. IBD has been involved advising the municipality and they employ people that have extensive knowledge about the area and physical processes happening. WSHD manages the open water areas an consequently has standards of their own if land use changes occur. This is required by the *watertoets*, an instrument used by water authorities as an argument for handing out permits for changing the hydrological system. As a result, this organisation is involved as well.

In Chapter 1 the concept of *user centred design* and **goal** and **usage oriented** groups were introduced. To distinguish these two groups assumptions are made on what motivations and incentives characterize each group: *goal oriented* stakeholders are focused on *goals*, while *user oriented* stakeholders prefer *means*. The municipality directs the policy and boundary conditions, they decide on the standards and direct the *goals*, so they are part of the **goal oriented** group. The same goes for IBD that advises and WSHD that sets their own standards. The project developers and their teams need to make sure that the plans they develop meet the standards, so they need standards that are user-friendly, with a focus on *means*. These belong to the **usage oriented** group. After conducting the interviews this division will be assessed again.

## 2.6. Standards in CKAB

The six standards reviewed in this study were introduced in Chapter 1 (Fig. 1.1). These standards have been developed under a consortium of stakeholders from (local) governments to project developers to water authorities and builders. Standards in the development plan were slightly modified to match the local conditions for Amstelwijck. In this research the CKAB standards are considered as a base for evaluation. This section contains an analysis using concepts introduced in section 1.2.3, before reassessing the standards later.

Table 2.1: Adaptation goals (assumed), focus and specification per standard in CKAB (Fig. 1.1) for *heat stress*, *pluvial flooding* & *drought*.



| Standards | Adaptation goal | Focus | Specified |
|---|---|---|---|
| Heat stress | | | |
| **H1** | **Reduction PET** | *Means* | **Yes** |
| **H2** | **Reducing UHI** | *Means* | **Yes** |
| Pluvial flooding | | | |
| **N1** | **Retention water during heavy precipitation** | *Goal* | **Yes** |
| **N2** | **No damages during heavy precipitation** | *Goal* | **Yes** |
| Drought | | | |
| **D1** | **Ensuring water availability** | *Goal* | **No** |
| **D2** | **Retaining water locally** | *Means* | **Yes** |

The CKAB standards have a particular description: some are focused on *means* instead of *goals* or more *specified*. To evaluate the standards goals for adaptation were formulated in Table 2.1. These goals are assumptions made with knowledge on climate adaptation and from the literature in section 1.2. Considering the goals in Table 2.1, this first concept can be used to subdivide standards into the two groups of focus: *goals* and *means*. **H1** is a good example of a *means* focused standard. A certain percentage of green is prescribed, which is meant to serve the goal of reducing Physical Temperature PET. Other ways of reaching this goal, such as enhancing ventilation, are not prescribed. On the other hand, a clear example of a goal focused standard would be **N2**. The goal is preventing damages, which is exactly what the standard prescribes. The second concept revolves more on the direction, on *what* is described in the standards (Frei and Di Marzo Serugendo, 2011). An example of a *specified* standard is **N1** (see Fig. 1.1). This standard prescribes an exact amount, 50 mm of a 70 mm precipitation event, and time span, 1 hour and storage between 24 and 48 hours; there are *clear* boundaries for water retention during extreme precipitation. On the other hand, **D1** is an example of a standard that allows *creative freedom*: ”expected groundwater levels and freshwater availability” is multi-interpretative, but lots of different solutions are possible.

Lastly, the concept of *principle* or *rule*-based (Nakpodia et al., 2016) was applied on the Covenant Climate-Adaptive Building. A covenant is considered a *principle* agreement. However, in this case study the standards from the Covenant were instituted in a development plan, which project developers were bound to. Because this project was considered a pilot, some possibilities for exceptions were left open, so in this case the standards are considered nearing *rule*-based, but not entirely. With the standards linked to the three concepts, assumptions can be stated. The first assumption derives directly from the stakeholder analysis: **goal oriented** stakeholders prefer *goal* focused standards and **usage oriented** stakeholders standards focused on *means*. Then, secondly, the **goal oriented** stakeholders are expected to prefer *rule*-based standards, while the other group would like more freedom with *principle*-based standards. Lastly, both groups are expected to prefer *specified* standards above *creative freedom*.

# 3

# Methods

In order to answer the research questions, multiple methodologies are applied. Three goals are of importance: application of ***UrbanWB*** for *assessment* and *design* of urban plans; analysing uncertainty in *climate*, *design* and the *hydrological system*; and evaluating the implementation of CKAB standards in climate-adaptive building. All these components are researched using the case study, Amstelwijck. For the first component, the model is reviewed, the case study implementation is discussed and indicators are identifyied. Then for the second part, again, the same model is used, but the focus shifts to the sensitivity of urban plans; how relevant is climate change compared to other uncertainties. Lastly, the stakeholders most involved in the case are analysed and interviewed to review the standards and framework introduced in Chapter 2: what are good standards; what barriers and enablers for climate adaptation; what are important themes. The combination of these methodologies provides important insights on standards promoting climate adaptation in Dutch urban environments.

## 3.1. UrbanWB: water balance model

To answer the first research question the ***Urbanwb model*** developed by Deltares (Vergroesen, 2020) is used in order to explore the applications as a *design* and *assessment* tool for newly build urban areas. This model is a water balance model that can include the effect of Sustainable Urban Drainage Systems (SUDS) and model their effect on the system, which makes it an useful tool for analysing hydrological systems without requiring large computing power. An online tool, *kbstoolbox*, uses typologies of Dutch neighbourhoods to determine land use fractions as input parameters for this model. However, in this research land use fractions are extracted from the urban plans for Amstelwijck, which improves model representation of the hydrological system. Historical precipitation and evaporation data provided by the KNMI are used as forcing for the model. ***Urbanwb*** produces output containing indicators on *heat stress*, *pluvial flooding* and *drought*.

### 3.1.1. Model mechanics

This specific water balance model is a lumped model, which means that variables are not a function of space, and a conceptual model, i.e. a simplified mathematical conceptualization of a system. There is no spatial distribution, but the area is subdivided in fractions of land use, and all fluxes happen instantaneously. Figure 3.1 shows the different model components (boxes) and possible fluxes between these components (arrows). There are three external boundaries defined that can exchange water: the **atmosphere** with precipitation flux into the system and extracting evaporation and transpiration from the system; the **outside water** with an outgoing pumping flux or water inlet; and the **deep groundwater** with seepage as in or outgoing flux. The case area contains five components representing fractions of land use, that have different interactions with the boundaries and other model components: **paved roof** (PR), **closed paved** (CP), **open paved** (OP), **unpaved** (UP) and **open water** (OW). **Closed paved** areas generate more runoff and sewerage flow, while the **open paved** and **unpaved** components allow possible infiltration and percolation into the components below. In turn the three components below (**unsaturated zone**, **groundwater**, **stormwater sewer** and, only if applicable, **combined sewer**) serve as storage volumes and have their own interactions with the boundaries and other components.

The model components are connected by internal fluxes that indicate how a system functions. The size and direction of these fluxes are determined by model parameters. Changing parameters will alter the system behaviour. Some determinative model parameters include: the external head of **deep groundwater** and flow resistance ($head\,deepgw$, $vc$) or constant seepage flux ($down\,seepage\,flux$); horizontal drainage resistance from **groundwater** to **open water** ($w$); soil type & crop type (see available options in Table B.1 & B.2 in appendix B); infiltration capacity **open paved** and **unpaved** ($infilcap\,op$ and $infilcap\,up$); and the fractions of **paved roof**, **closed paved** and **open paved** disconnected from **sewer** ($discfrac\,pr$, $discfrac\,cp$, $discfrac\,op$). Parameters are listed as represented in the model.
By applying climate-adaptive measures the dynamics of the system are altered, by changing parameters or changing land use fractions, or by adding storage, for example.

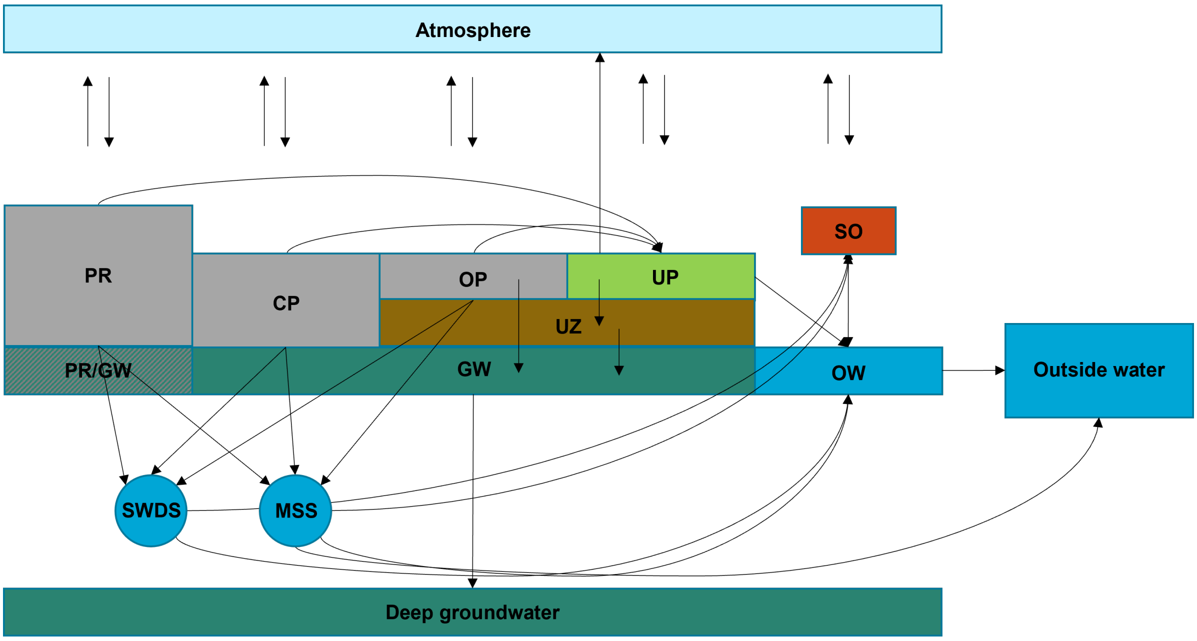


Figure 3.1: Schematic overview of ***UrbanWB*** model, adapted from W. Zhang (2019).

In addition to fluxes at the boundaries, there are multiple ways water can move through the model. How is determined by the parameters such as listed above. As combination of the system configuration and forcing results in changing fluxes over time. The values of these fluxes are recorded by the model. A couple are particularly interesting: runoff to **unpaved** and **open water** ($r\,pr\,up$, $r\,cp\,up$, $r\,op\,up$ and $r\,up\,ow$); drainage from **groundwater** to **open water** ($d\,gw\,ow$); drainage from **sewer** to **open water** ($q\,swds\,ow$ and $q\,mss\,ow$); and percolation from **open paved** and **unpaved** (through the **unsaturated zone**) to **groundwater** ($p\,op\,gw$ and $p\,uz\,gw$). These could be indicators for climate aspects.
Additionally, model components have states. States represent how much water is stored in the component at a specific time step. Most components have little storage, but in the **unsaturated zone**, **groundwater** and **open water** there is significant room for storage available, so theses states are important to take into account.

This model has the possibility to include climate-adaptive measures in simulations. When a system fails under extreme conditions, measures for climate adaptation, such as extra storage or more shade, can be applied. These are usually non-standard changes to the environment that only cover a small part of the surface. Because of this, the model allows a customized measure to be added that acts like an extra component. Measures can be defined as only a 1-layer structure, a 2-layer structure or a 3-layer structure. Examples of different types of measures can be found in the *AST documentation* (Vergroesen, 2020). A measure covers and area and has an inflow area in one or more land use components. A 1-layer structure collects water from the inflow area in an **interception layer** that has the possibility for storage and evaporation. The 2-layer structure adds a **bottom storage layer**. This layer allows storage, evapotranspiration, percolation to groundwater and controlled runoff. The **top storage**

**layer** is added for 3-layer measures with a growing medium (green roofs, bioswales). The **bottom storage layer** then acts as a drainage layer. These layers can each be specified in size and characteristics. Internal measure parameters, such as internal fluxes ($interc\ down\ meas$, $perc\ top\ meas$) and storages ($int\ meas$, $inistor\ top\ meas$, $inistor\ btm\ meas$) give insight in the measure functioning. The effect on the surroundings is visible in the fluxes from ($sum\ r\ meas$) and towards other components ($q\ meas\ ow$, $q\ meas\ uz$, $q\ meas\ gw$, $q\ meas\ swds$, $q\ meas\ mss$, $q\ meas\ out$).

### 3.1.2. Case implementation

Most parameters and boundaries in the model are determined by the case study areas. A couple of important assumptions and implementations are discussed in this section (an extensive summary is available in appendix F). First, the **atmospheric** boundary, which is governed by historical time series of hourly precipitation and potential evaporation (*Makkink* and *Penman-Monteith*) contained in a $.csv$-file. This weather data can be collected from several stations of the Royal Dutch Meteorological Institute, KNMI (KNMI, 2021). The Dutch climate is considered temperate year-round and is relatively consistent over the whole country (Beersma et al., 2021). However, there are still some regional differences. Station *Herwijnen* is selected as closest to Dordrecht, so it is assumed that these time series represent the conditions in the case areas fairly well. This station has $27.5\,years$ of usable data available from 1993 to 2020. Precipitation is readily available as hourly data, but hourly potential evaporation is calculated with daily evaporation data ($E^d_{ref}$) and hourly ($Q^h$) and daily global radiation ($Q^d$) (eq. 3.1).

$$E^h_{ref} = E^d_{ref} * Q^h/Q^d \tag{3.1}$$

Reference evaporation $[mm]$ determined from daily Makkink evaporation $[mm]$ and hourly and daily global radiation $[J/m^2]$.

Parameters and boundary conditions determine the processes, how the system functions, but these are usually predefined through the hydrological situation, they are set. The choices made in the design process mostly affect land use classes, which determine the *magnitude* of processes in the model components and in consequently the magnitude of fluxes. In Amstelwijck the two cases studies have developed different strategies to include the climate aspects. Figures 2.5 and 2.6 in chapter 2 give an example of the choices that are made, fractions of land use classes are summarized in Table 3.1. *Private property* is not included as a class in the model, but separated nevertheless. Land use here is uncertain, because inhabitants will choose the land use of their gardens themselves. For the model it is assumed that 60% of *private property* is **unpaved** and the remaining 40% is **closed paved**. This is also the division made by project developers and municipality in their calculations. For both areas buildings (**paved roof**) and **open water** take up roughly the same fraction of land. However, the two areas do differ in strategy on two aspects. The first is using permeable pavement (**open paved**) in Amstelwijck I. This is supposed to improve infiltration. The second difference is created by the amount of *private property*. Amstelwijck I chooses to work with larger gardens (increasing *design* uncertainty), while in Amstelwijck II more public green areas (**unpaved**) are realized. As a result the amount of **closed paved** surface is similar for both areas, but Amstelwijck II has larger **unpaved** surface. Strategies for measures implemented differ as well. The developer in Amstelwijck I aims to realise a large water storage in the public space and in Amstelwijck II storage is realised locally.

Table 3.1: Land use fractions for Amstelwijck I & II. *Private property* land use is added to **closed paved** and **open paved** fractions.

| Land use class | Amstelwijck I | Amstelwijck II |
|---|---|---|
| Paved roof | 17 % | 18 % |
| Closed paved | 12 % (+*13 %*) | 18 % (+*8 %*) |
| Open paved | 9 % | 0 % |
| Unpaved | 22 % (+*19 %*) | 36 % (+*13 %*) |
| Open water | 8 % | 7 % |
| *Private property* | *32 %* | *21 %* |

The case study settings, boundary conditions, soil parameters and land use, are all combined in a neighbourhood input file, $neighbourhood.ini$, with $TOML$-format. Settings for measures are implemented using a separate measure input file, $measure.ini$. Two example input files can be found in

Appendix D. These input files contain more parameters and conditions than discussed in this report, but some parameters are not changed for the purpose of simplicity in this research or because there is insufficient knowledge on specific values.

### 3.1.3. Model indicators

The ***Urbanwb*** model contains information about the hydrological system and can indicate how this system performs on different climate aspects. Indicators can show if the system meets the standards for climate adaptation. The CKAB contains two standards for every climate aspect (Fig. 1.1). Each standard addresses problems on a different timescale and spatial scale, which makes it important to understand the physical background behind the problem and the goal of the standard. This section will look into the physical background behind the CKAB and identify what variables from the model can serve as indicator for *assessment* and *design*. The indicators will be analysed during extreme events: a heat wave, extreme precipitation event or a drought event. Table 3.2 lists the standards with (perceived) adaptation goals, scale levels and corresponding indicators.

Table 3.2: Indicators coupled with standards from the Covenant Climate-Adaptive Building, (perceived) adaptation goals and scale levels: **bold** indicators are calculated by the model, *italic* derived from input data.

| Standards | Adaptation goal | Scales | Indicator |
|---|---|---|---|
| Heat stress | | | |
| **H1** | **Reduction PET** | Street<br>(1-100 m)<br>Hours | **Evaporation**<br>*Amount of green*<br>*Open water*<br>*Shade by trees* |
| **H2** | **Reducing UHI** | City<br>(0.5-100 km)<br>Day | **Evaporation**<br>**Soil moisture content**<br>*Amount of green*<br>*Open water* |
| Pluvial flooding | | | |
| **N1** | **Retention water during heavy precipitation** | Neighbourhood<br>(100-1000 m)<br>Minutes/hours | **Storage**<br>**Runoff**<br>**Discharge** |
| **N2** | **No damages during heavy precipitation** | City<br>(0.5-100 km)<br>Hours/days | **Storage**<br>**Runoff** |
| Drought | | | |
| **D1** | **Ensuring water availability** | Region<br>(>50 km)<br>Weeks/month | **Evaporation**<br>**Soil moisture content**<br>**Groundwater**<br>**Open water discharge** |
| **D2** | **Retaining water locally** | Neighbourhood<br>(100-1000 m)<br>Weeks | **Groundwater**<br>**Infiltration flux** |

### Heat stress standards

- H1: At least 50% shade in the plan area at the highest sun position for places to stray and areas with slow traffic.
- H2: Reducing warming of urban areas: 40% of all surfaces are designed heat-resistant or cooling.

The first standard for heat stress is focused on thermal comfort, which is related to the PET. The thermal comfort is influenced by the following variables: air temperature, humidity, wind speed, shortwave radiation, longwave radiation, body isolation and physical activity (exertion) (see Fig. 1.3). High air temperatures and net shortwave radiation decrease the thermal comfort the most, so problems arise mainly during the day. The effect is very local (1-100 m) and can change every hour. An extreme event for this aspect would be a hot summer day, during a heat wave. The model contains only one direct indicator that gives information about thermal comfort, **evaporation**, which decreases the air temperature. Other variables related to shortwave radiation such as reflection and shade might be extracted indirectly from the *amount of green*, *open water* or *shade by trees*. This information is contained in the input data, but are not a result from the modelling. However, these indirect are the best approximations possible with the available data. Due to the absence of timeseries in these indicators no extreme event can be selected.

The second standard has a focus on air temperature itself, specifically the city-wide (0.5-100 km) temperature that is higher as the result of the surrounding environment i.e. UHI effect. This temperature is determined by energy fluxes in and out of the city: longwave radiation, shortwave radiation, latent heat flux, sensible heat flux, storage heat flux and anthropogenic heat flux (see Fig. 1.2). The distribution of fluxes determines the sensible heat flux, which can increase the background air temperature. It is mainly alterations in the net shortwave radiation, latent heat flux and storage heat flux that change this distribution. This process repeats itself on a daily timescale, where during the day there is a lot of energy input and during the night energy is released. Especially high nighttime temperatures are problematic. For the analysis of these energy fluxes an extreme event, a heat wave in the start of August 2020, is selected. Three indicators can be extracted from model variables. **Evaporation** relates to the latent heat flux and **soil moisture content** and *open water* surface relate to the storage heat flux. Additionally, the *amount of green*, related to latent heat flux and shortwave radiation, could be extracted from input data. This adaptation goal is analysed using a recorded heat wave the start of August 2020. (KNMI, 2022)

### pluvial flooding standards

- N1: A large part of precipitation (50 mm) from short heavy showers (1/100 year, 70 mm in one hour) on private land is collected on-site and drained off with a delay. The storage room will not be empty before 24 hours and will be available again in a maximum of 48 hours, or will be controlled.
- N2: No damage will occur to buildings and facilities in the plan area in the event of extremely heavy precipitation.

N1 focuses on retention for short heavy showers. If these heavy precipitation events are discharged very quickly, pressure is put on surrounding hydrological systems. These events last from minutes up to hours and cause local, neighbourhood level (100-1000 m) problems. The goal of this standard is to reduce the peak runoff and spread this over a longer time period, which can be reached by implementing rainfall retention and additional (temporary) storage. A system has fast and slow drainage mechanisms that the model contains as well. Sewer discharge and runoff are fast and cause high peaks, while drainage through the ground or through a measure have a retention. The same goes for components where water is stored. Preferably, water is stored in the **groundwater** or in a **measure** before ending up in the **open water**. Consequently **discharges**, **runoff** and **storage** variables from the model are indicators for this standard. An extreme precipitation event on the 28th of June 2011 is selected for this analysis.

The second standard for pluvial flooding has the goal of minimizing the damaging effects of extreme precipitation. These events have a longer timescale up to multiple days and the problems are caused on a city-wide scale (0.5-100 km). A combination of rainfall duration and rainfall intensity determine the water load that has to be processed by the system, and then available storage capacity and discharge capacity determine if problems occur. The solutions to this standard could be similar to those above, be it in a more extreme situation, but now the focus lies in preventing flooding. Mainly the **open water** level i.e. **storage** is an indicator for this: if the level exceeds a surface level, flooding occurs. The occurrence of overflow mechanisms and **runoff** also indicates system boundaries for this standard. The same extreme event a for the previous adaptation goal is selected to analyse this goal.

**drought standards**

- D1: The layout of the plan are is adjusted to the expected groundwater levels and freshwater availability during drought.
- D2: 50% (approximately 450mm in 'normal' years) of the annual precipitation is infiltrated into the plan area.

The first standard of the drought aspect aims to ensure water availability in combat subsidence and loss of ecology because of droughts. This is supposed to be done without relying on an external water source, since this could harm the local ecological system and is not widely available during droughts. A drought event can last weeks up to months and the meteorological effect is always regional, so at a large spatial scale (>50 km). Depending on local conditions or management practices a drought can be more severe locally. **Groundwater** levels depend on the water availability directly, water uptake by plants and subsidence indirectly. The model contains multiple indicators related to these variables except for subsidence. Only, **groundwater** levels are not very useful as an indicator, since there is a minimum **open water** level which the **groundwater** is related to embedded in the model i.e. the level during a drought will always be at the lowest possible according to ***UrbanWB***. **Plant water uptake** is related to **soil moisture content** and can be combined to indicate drought stress in plants. Also **evaporation** from **unpaved** areas could be used as a more indirect indicator. Mainly the **external intake amount** is a clear indicator, because it directly shows the water demand of system that is not available, which is the goal of this standard. The Dutch "growing season" (1st of april to 30 of september) is used as a timeframe for the analysis.

The second standard focuses on increasing infiltration with the aim of maintaining **groundwater** levels so that these do not cause problems. The adaptation goal here is to retain water locally, at a neighbourhood level (100-1000 m), and the timescale is shorter, in the order of a week. The most important variable is the soil conditions in the **unsaturated zone**. These conditions allow the possibility for infiltration and determine the size of the **infiltration flux** and in turn the variability in **groundwater** levels. Again, **groundwater** levels cannot go below a certain equilibrium in this model, so looking at low **groundwater** conditions due to a lack of infiltration is not very useful. Instead looking at the opposite problem, high **groundwater**, to determine the amount of infiltration is useful. **Storage** and **infiltration flux** variables can be used as indicators to determine maximum infiltration amount for the particular system without causing problems. November 1st 1998 is used for an extreme event analysis considering the effect of infiltration.

## 3.2. Sensitivity analysis

Amstelwijck is designed according to the CKAB standards, so the claim is that the neighbourhood is ”*climate-adaptive*”. This raises the question: what components make a neighbourhood resilient to a specific climate and what uncertainties have the most impact on the system functioning. Section 3.1 demonstrated the usability of ***UrbanWB*** for analysing urban plans on climate aspects and adaptation. The same model is used for a sensitivity analysis. This analysis is done by changing parameters or boundary conditions in the model input, creating different scenarios. First *hydrological uncertainty* is assessed by adjusting soil parameters (sec. 3.2.1), then the **atmospheric boundary** input, the forcing, is changed (sec. 3.2.2) to simulate *climate change*, and lastly the effect of *spatial planning* is investigated by changing land use fractions (sec. 3.2.3).

The motivation for performing a sensitivity analysis, is the amount of uncertainty connected to *climate*, *design* and the *hydrological system* (sec. 1.2.2). There has to be knowledge about the degree of uncertainty to develop policy to deal with this uncertainty. In this section different scenarios are introduced that cover situations from very probable to extreme. This will result in a range of solutions indicating the range of uncertainty. This approach helps to develop the *static* and *adaptive robustness* approaches of dealing with uncertainty as described by Walker et al. (2013). In order to assess sensitivity, the indicators from section 3.1.3 are used. Their applicability was researched for testing standards for climate adaptation (sec. 3.1 & 4.1). These indicators show how the system reacts to a change in forcing or parameters. This analysis is done for three different kinds of input that are related to the aforementioned uncertainties in *climate*, *design* and the *hydrological system*. For each, a different method of assessing the sensitivity is applied.

### 3.2.1. Hydrological uncertainty

First, hydrological uncertainty is assessed. This uncertainty arises from the soil complexity and consequent simplification by the model. In an heterogeneous soil, such as the clay and peat in Amstelwijk (ch. 2), parameters only describe large scale averages of behaviour or they are ambiguous. Additionally, the model used is simplified. It applies a conceptualization of the physical processes, so much of the behaviour of fluxes and storages is represented by parameters. The result is extensive parameterization, which means that parameters contain a large amount of information inherently increasing complexity and uncertainty. For this reason the sensitivity of a couple of parameters were further analysed: $croptype$; $soiltype$; drainage resistance to **open water** through **groundwater** ($w$); and infiltration capacity for **unpaved** ($infilcap\,up$). Because the exact value for these parameters is ambiguous, a range of solutions can give an indication of magnitude and impact of uncertainty.

Hydrological uncertainty is tested by varying one parameter at the time with a range of possible values. For $croptype$ there is a list of possible arrangements that can be called by the model (tab. B.2 in appendix B) representing the behaviour of several crops. This parameter is expected to have a high degree of uncertainty since the model only simulates one type of crop for the whole system, while in reality there will be a mix of different type of crops. Further the choice of crops is unknown and might depend on the effectivity for certain climate aspects. Secondly, $soiltype$ can be highly uncertain, because of the heterogeneity in the soil or little-known properties of the soil. Similar to $croptype$ the model uses a list of common soil types to choose an arrangement of parameters (tab. B.1 in appendix B). $w$ is related to the hydraulic conductivity of the soil and the average distance to **open water**, so this is a parameterization of soil properties and spatial arrangements combined. For the sensitivity analysis a range is taken of values that are found probable. The same goes for the values for infiltration capacity. Geohydrological site investigations gave an estimation of $infilcap\,up$ for the case study areas ($300 - 1300\,mm/d$) and this range is extended to include lower and higher values. Chosen parameter ranges for $w$ and $infilcap\,up$ can be found in table 3.3.

Table 3.3: Parameter variations to assess hydrological uncertainty.

| **resistance,** $w$ **[**$days$**]** | **infiltration capacity,** $infilcap\,up$ **[**$mm/d$**]** |
|---|---|
| 10 | 100 |
| 25 | 200 |
| 50 | 300 |
| 100 | 400 |
| 200 | 500 |
| 300 | 600 |
| 400 | 700 |
| 500 | 800 |
| 750 | 900 |
| 1000 | 1000 |

### 3.2.2. Climate change

Chapter 1 demonstrates that climate and climate change can add a lot of uncertainty. In the future *predictions* indicate more extremes in temperature, precipitation and droughts. To capture and analyse this uncertainty with the model the forcing, a time series of precipitation and evaporation, is adapted with KNMI scenarios (Tank et al., 2014). This uncertainty is the main reason adaptation is necessary, so it is interesting to see what the magnitude of the effects climate change can be with respect to uncertainties in *modelling* and *design*.

The KNMI translated the IPCC report of 2013 to the situation of the Netherlands and developed multiple scenarios of future climates. The report states a scenario for 2030 and four scenarios for both 2050 and 2085 with reference period 1981-2010. With the variations per season almost 50 indicators of climate change are listed. For this sensitivity analysis seven indicators were used to adjust the forcing. Table 3.4 lists the seven indicators and the yearly change in precipitation. Precipitation was adjusted with seasonal indicator values, evaporation with a yearly value for autumn, winter and spring, but a seasonal value for summer. Additionally, there is a separate value for extreme summer precipitation used to assess the extreme precipitation event that is used in the analysis (28 june 2011). Three scenarios were chosen to compare to the current forcing (1993-2020) implemented in the model: the scenario for 2030, the WH scenario for 2050 and the WH scenario for 2085. W indicates a *warm* scenario, instead of G, *average* and H indicates a *high* influence of changing weather patterns, L, *low*. A WH scenario is a *warm* scenario with *high* influence of changing weather patterns. These extreme scenarios were chosen, because it represents the limits of adaptation expected to be necessary.

Table 3.4: Change in precipitation for different climate scenarios (Tank et al., 2014)

| | **2030** | **2050 WH** | **2085 WH** |
|---|---|---|---|
| *yearly precipitation* | *+5%* | *+5%* | +7% |
| yearly evaporation | +2.5% | +7% | +10% |
| winter precipitation | +8.5% | +17% | +30% |
| spring precipitation | +5.5% | +9% | +12% |
| summer precipitation | +0.2% | -13% | -23% |
| summer evaporation | +3.5% | +11% | +15% |
| autumn evaporation | +5.5% | +7.5% | +12% |
| extreme precipitation summer | +11% | +25% | +40% |

### 3.2.3. Spatial planning

Of all uncertainties in the case study, the spatial planning, related to *design*, is the one that can be controlled the most. The design choices made have consequences for the system functioning, so they need to be put into perspective. In this section land use fractions are the parameters that will be adjusted, since these represent design choices in the model. A couple of different setups were tested.

First, a comparison between the two case study areas. Here hydrological conditions, such as water level and soil, differ slightly, but mainly the choices made in design are different. Then uncertainty for *private property* is assessed. Lastly, a maximization analysis is done on the land use fractions.

A second sensitivity analysis is done for private property. This land use contains the most uncertainty in both urban plans, since the layout of private property, the yard, is eventually decided by choices made by inhabitants, not by designers. For examination of the urban plans a layout of 40% **Closed Paved** (**CP**) and 60% **Unpaved** (**UP**) was assumed, the same division is used in the base case model simulations of both areas. In this analysis two other fractions will be used: one with fully **CP** private property and one with fully **UP**.

The last analysis was done by reviewing a couple of design choices that are (in)directly imposed by the Covenant and are expected to have a large effect for climate adaptation. For the sensitivity analysis one land use class is maximized at the expense of another to measure the impact of these standards. The first standard (**H2**, fig. 1.1) aims to reduce heat stress by promoting heat-resistant or cooling surfaces. In Amstelwijck this is translated into a requirement for green (**UP**) surfaces. In the analysis all **UP** was replaced by **CP**. The following (drought) standard (**D2**, fig. 1.1) promotes infiltration. A way to increase infiltration would be to include permeable pavements (**OP**) instead of regular pavements (**CP**) that mainly create runoff towards the **sewer** system or **UP** areas. Here two variations were applied: (i) all **CP** is replaced by **OP**; (ii) all **OP** is replaced by **CP**. Maximization of the land use classes shows the effect extreme design choices can have on a hydrological system.

## 3.3. Analysis of standard implementation

The result of setting standards for climate adaptation was investigated using a model (sec. 3.1 and 3.2). The model tests how developed urban plans (with CKAB standards) perform on several climate aspects. However, in order to find *how* standards *encourage* climate adaptation, a different approach is required. The third research question will be answered by taking interviews with different parties involved in the case study. In section 1.2.3 a relevant framework and useful concepts have been explored for identifying themes in the process of adoption of innovative solutions. Section 2.5 connected stakeholders in the case study to the two different groups: **goal oriented** and **usage oriented** stakeholders. In section 2.6 these two groups were connected to the identified concepts. This section explains how the process of using CKAB standards in this case study is researched with the framework of *user centred design* and concepts of *principle* & *rule*-based, *creative freedom* & *specification* and *goals* & *means*. Interviews are used to indicate important themes by identifying barriers or enablers and by evaluating experiences with standards from the *Covenant Climate-Adaptive Building*. Finally, the interview analysis is verified by two focus group sessions.

### 3.3.1. Interview analysis

Interviews are a qualitative instrument to evaluate the innovative process of standard implementation the case study. Interviewees give answers that are influenced by their experiences and opinions and in part by the interviewer, so in order to find relatively objective conclusions, results from the interviews are coded. This is done by identifying barriers and enablers from the interview results and counting by how many interviewees each barrier or enabler is mentioned. Then using the conceptual framework from section 1.2 those barriers and enablers are grouped into themes similar to how Voskamp et al. (2021) & Long et al. (2016) did this. By the first, barriers that hamper the adoption of innovations were grouped in four themes: *institutional setting*; *availability of (financial) resources*; *level of expertise*; and *collaborative governance and planning*. These themes will serve as a basis for classifying barriers and enablers in this research as well. They aim to qualitatively show where in what fields standards are not performing and how they could be improved: if a lot of barriers are mentioned related to one theme this might be an area of attention. The themes from literature will be taken as a starting point, but additional themes could be identified after the interview analysis.

On the base of these barriers and enablers, the division into **goal oriented** and **user oriented** stakeholders made in section 2.5 is reassessed; if the interviewees experience different barriers and enablers. Mainly the number of mentions per theme is noted and compared. Then the interviewee's opinion on the standards is assessed. Some type of standards might be experienced as a barrier and others could be enablers. After coding the interview results an overview is available, so the importance of certain enablers can be evaluated. Further, assumptions on preferences per group are reassessed. These preferences are connected to concepts from section 2.6 to evaluate *how* standards encourage climate adaptation.

### 3.3.2. Interview procedure

The interviews will be conducted individually with a standard list of questions to make sure all interviews address a somewhat similar list of topics. However, the conversation may be unstructured, so other, possible unknown topics can be explored as well. During interviews the data is recorded using written notes that are later processed into a small report. The report is then send to the interviewee for revision. In this way the conversation is continuous, but information is also written down in a concise manner, which is efficient for later processing. Taking written notes is beneficial for later memory as well. The themes have been used as an inspiration for developing interview questions. To extract the information required, questions have to direct the interviewee to certain topic, but not to an answer. No themes are mentioned, but topics where certain barriers could occur are explored. Examples for the questions are listed below.

**Interview questions:**

1. *Could you tell me something about the project you have worked on?*
2. *What are things you find when working on building a climate-adaptive neighbourhood?*
3. *What are incentives to apply climate-adaptive measures?*
4. *Is the Covenant Climate-Adaptive Building workable?*
5. *For which of the three climate aspects (heat stress, pluvial flooding, drought) is most difficult to meet the standards?*
6. *How do you check if your plans reach the goals that are set? Are you using tools? (maps, online tools, models)*
7. *What is the biggest hurdle in the proces?*
8. *Who else is important in the project?*

In order to make sure research ethics are followed in this thesis, interviewees will be asked for consent. According to the Authority Personal Information, the privacy law (“Algemene verordening gegevensbescherming”, 2018) is followed when permission is voluntary, the goal must be transparent and the organisation handling personal information must be clear; specific, no unnecessary information should be collected; and informed, the goal must be clear and reasonable to the interviewee. Additionally, collected data must be secure and up-to-date. To reach these requirements, the following procedure is instated:

1. Information about the research project is given in the first email to the interviewee. I will explain what the goal is and what the data is used for. The interviewee can then agree to an interview with these conditions.
2. Before the start of the interview more information about the research is explained, so they understand the background. After the interviewee is made aware of the use of the written notes as research data and that they will get a chance to revise the report.
3. The written notes are processed into a report and another email will be sent to thank the interviewee. In that email I will ask them if they require to check the notes before I use the data.

With this procedure informed consent is assured. Emails will provide proof of consent for participants.

### 3.3.3. Focus groups

As a verification of the analysis interviewees are invited to 'focus group' sessions. In these sessions the results and conclusions of the whole research are presented, but the preliminary results of the interview analysis is checked as well. Groups consist of four to six interviewees and sessions are held via Microsoft Teams in May 2022. To verify the results and conclusion of this analysis a poll is issued. The questions in this poll are based on the interview conclusions and are more directive to a limited number of answers than the interview questions to force interviewees to make a choice between suggested results. The questions are listed below and an extended version of these questions with possible answers is available in Appendix A.

**Poll questions:**

1. *What is the most important barrier for climate adaptation?*
2. *What is the most important barrier for climate adaptation?*
3. *Standards focused on **goals** are more suitable than standards focused on **means***
4. *Strict standards that include legal obligations (**rule**-based) are a barrier or enabler?*
5. *An ideal standard provided much **creative freedom** or is **specified**?*
6. *At which theme did you experience most barriers?*
7. *At which theme did you experience most enablers?*

This poll is issued *before* any conclusions about the analysis of standard implementation are presented. After presentation of last conclusions and results, an open discussion about the result of the research is held in order to provide an extra opportunity for new suggestions. This discussion is mainly focused on the *how* standards should be formulated and applied, but also about *applicability* of ***UrbanWB*** for the participants of the focus group.

# 4

# Results

## 4.1. Model for climate aspects

In chapter 3 the ***UrbanWB*** model was explained (sec. 3.1), first *model mechanics* (sec. 3.1.1), then the implementation of the *case study* (sec. 3.1.2) and finally possible *model indicators* (sec. 3.1.3). This section shows how this model can be used to analyse urban plans for three aspects of climate adaptation, **heat stress**, **pluvial flooding** & **drought**, and how the standards in the Covenant Climate-Adaptive Building (CKAB) are evaluated. Indicators were chosen and applied for case study Amstelwijck I. Using figures and/or tables these indicators were analysed and evaluated.

For the analysis of each climate aspect, an extreme event with a specific time frame was selected. Since physical processes related to the urban climate originate in different spatial scales and time scales, extreme events that can cause problems occur at specific moments as well (sec. 1.2.1). Dates were selected using climatology information from the KNMI or specific events in the input data were selected.

### 4.1.1. Heat stress

Heat stress is difficult to measure, especially since the model used in this research, the ***UrbanWB*** model, doesn't contain a direct calculation of energy fluxes. Nevertheless there are methods to infer information about heat stress, both for Physiological Equivalent Temperature and the Urban Heat Island effect.

Most direct indicators for the PET could not be retrieved from the input data. **Evaporation** is calculated by the model, but is solely an indirect indicator for air temperature with minor effect on PET. Three indirect indicators were derived from the data: **amount of green surfaces**, **open water area** and **shade by trees**. Table C.1 in appendix C lists PET reduction factors for different interventions. PET reduction in $^\circ C$ is determined by taking the difference between *local PET* and the *minimum PET* value in the area and multiplying it with the PET reduction factor. Without any knowledge about 'true' values, the assumption is made that *minimum PET* is around $30^\circ C$ and for *local PET* an extreme value of $44^\circ C$ is taken, resembling heat stress conditions in Dutch urban environments (CAS, 2021 & Koopmans, 2021). A reduction of 75% in some location would then result a decrease in PET of $10^\circ C$.

Table 4.1: PET reduction Amstelwijck I.

| Land use | Fraction of total area | reduction |
|---|---|---|
| Green surfaces | 0.42 | 4.2 % |
| Open water | 0.08 | 0.8 % |
| Trees shade | 0.22 | 16.5 % |
| Green roofs | 0.007 | 0.07 % |

A general form of this procedure is followed for calculating heat stress reduction in terms of PET in the Amstelwijck case study. Figure 4.1 indicates the measures of interventions taken in Amstelwijck I. The **amount of green surfaces**, **open water area** and **shade by trees** are considered with PET reductions of 10%, 10% and 75% respectively. Additionally, the green roofs that are applied have a reduction similar to green surfaces. These surfaces contribute to a significant reduction of local Physiological Equivalent Temperature (tab. 4.1). The total PET reduction of all surfaces combined reaches **21.8%**, which would mean a difference of more than $3^\circ C$ in locations suffering from extreme heat stress.

Figure 4.1: Climate-adaptive measures applied in Amstelwijck I

Even though the Urban Heat Island effect is not calculated directly, there were a couple possible indicators (sec. 3.1.3). However, contributions of indicators related to the storage heat flux (**soil moisture content** & **open water** area) and shortwave radiation (*reflection*) on the city wide energy fluxes are difficult to determine without extra data and modelling. Data on **evaporation**, which is directly related to the *latent heat* flux, can be derived from the model. This parameter gives a lot of information on the distribution of energy fluxes (sec. 1.2.1). All the energy not converted to *latent heat*, the *excess heat*, is available to heat up the surroundings causing the city to heat up, causing heat stress conditions. One millimeter of water evaporated in one hour is equal to $627.8W/m^2$ of energy consumed. With this values for *latent heat* flux and *potential latent heat* flux are calculated from actual evaporation (data from the model) and potential evaporation (retrieved from input data). The *excess heat* flux is then defined as the difference between *potential latent heat* flux and *latent heat* flux.

The energy fluxes during the heat wave of August in 2020 are visualised in figure 4.2. *Global radiation* represents the incoming energy amount. Part of this energy is reflected back into the atmosphere, but another part is distributed to other energy fluxes. The *latent heat* is the smallest of the fluxes during this heat wave: less than a tenth of the incoming radiation is converted to *latent heat*. However, there is a larger amount of *excess heat* available that heats up the surroundings. In order to put the heat

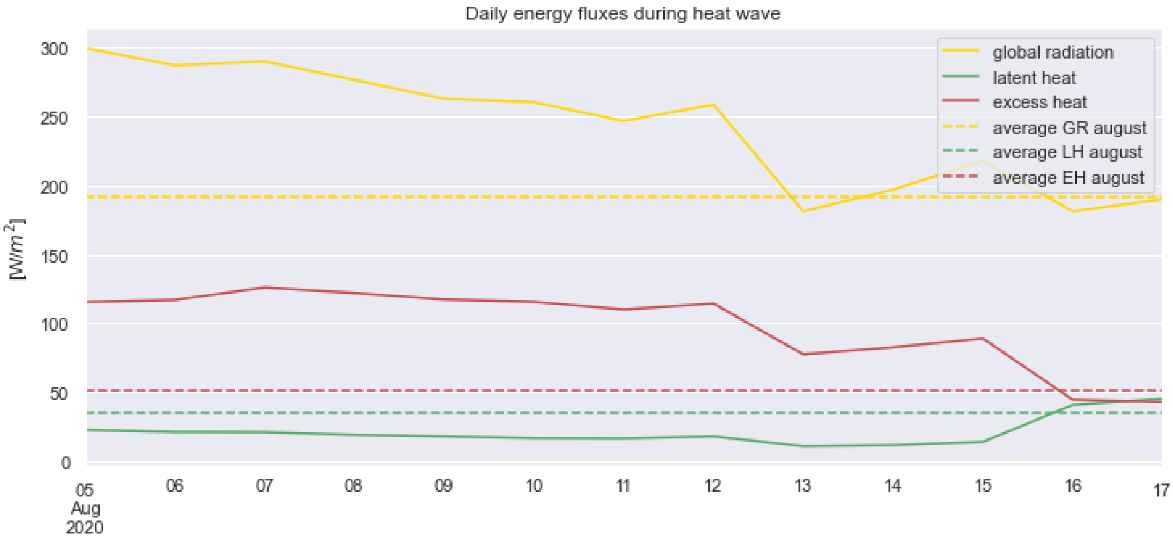


Figure 4.2: Daily averages for energy fluxes during a heat wave and averages for the same period in August 2020: *global radiation*, *latent heat* flux and *excess heat* flux (= potential LH - actual LH).

wave conditions into perspective, they were compared to averaged conditions in the start of August (tab. 4.2). This indicates that the *latent heat* flux is lower, but *excess heat* flux and *global radiation* are higher during a heat wave.

Table 4.2: Energy fluxes Amstelwijck I in start of August.

| | **Average conditions** | **Heat wave conditions** |
|---|---|---|
| Latent heat flux | 34.4 $W/m^2$ | 21.1 $W/m^2$ |
| Excess heat flux | 51.6 $W/m^2$ | 97.7 $W/m^2$ |
| Global radiation | 191.8 $W/m^2$ | 242.2 $W/m^2$ |

### 4.1.2. Pluvial flooding

To reduce pluvial flooding, many mitigation strategies have been proposed and modelling their effect is said to be well understood (sec. 1.2.1). The ***UrbanWB*** model was used to assess the effect of strategies with respect to the CKAB standards, in this case particular the *wadi* applied in Amstelwijck I. Two standards for mitigating the effects of pluvial flooding were formulated (sec. 3.1.3): one focuses on increasing retention for *short heave showers*, the other on mitigating damaging effects of extreme precipitation, i.e. *preventing flooding*. The model contains information on water in the system, where it is stored and where it flows, which facilitates assessing pluvial flooding.

Data from ***UrbanWB*** is utilized to look at retention in case of *short heavy showers*. **Storage** can be used as an indicator by looking at the amount of water stored in **groundwater** or a **measure** instead of **open water**. However **storages** only provide a limited view on the path the water takes through a system. **Discharge** and **runoff** fluxes show the complete path. The distribution of these fluxes determine the retention of the system, so considering these fluxes over time indicates how fast water is moving through the system to open water i.e. how much retention is provided by the system. Standard N1 from the Covenant requires around 70% of water to be held for at least 24 hours (3.1.3). This was tested with the model by reviewing **discharge** and **runoff** for 24 hours after an extreme precipitation event.

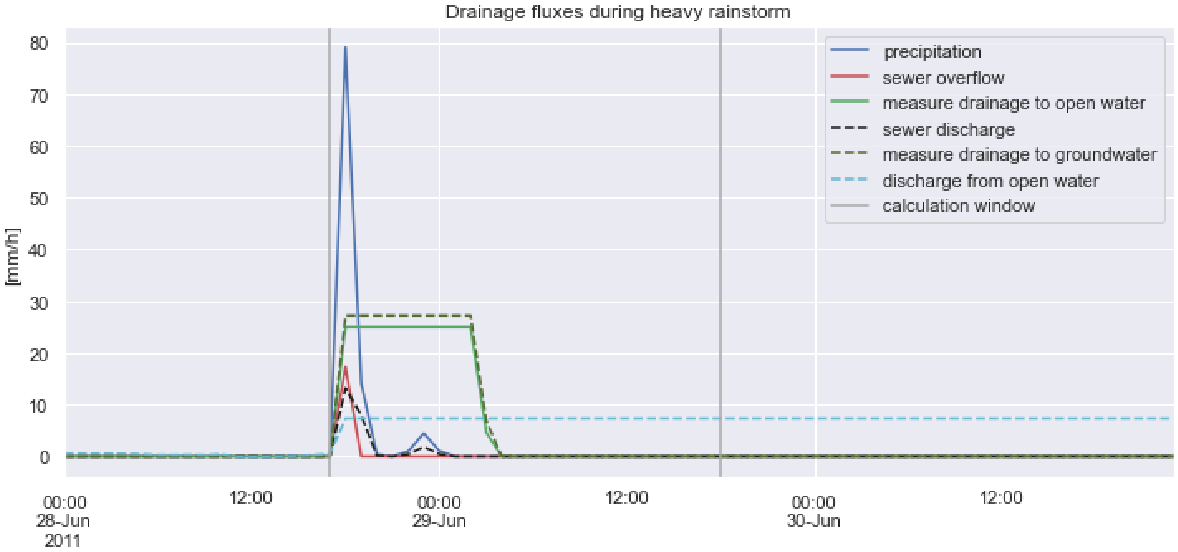


Figure 4.3: Drainage fluxes during an extreme precipitation event (June 28, 2011): **sewer** discharge & overflow, **measure** drainage and **open water** discharge to **outside water**.

An extreme precipitation event on the 28th of June 2011 is selected for this analysis. Figure 4.3 shows the precipitation flux in this event together with five modelled fluxes for Amstelwijck I. The lines represent in situ fluxes, while in Table 4.3 fluxes were converted to volumes, both in situ as with respect to the total area. These are volumes calculated for the first 24 hours after the event. Fluxes towards **open water** are considered fast drainage mechanisms, other fluxes are slow, as a consequence the amount of fast drainage was calculated by dividing the total inflow to **open water** by the amount of precipitation resulting 40% fast drainage. This means that retention the first 24 hours in this *short heavy shower* is **60%**.

Table 4.3: Discharge and runoff amounts Amstelwijck I the first 24 hours after a short heavy shower.

| | **Total in situ volume** | **Total volume with respect to entire area** |
|---|---|---|
| Precipitation | 100.4 $mm$ | 100.4 $mm$ |
| Sewer overflow | 17.3 $mm$ | 8.7 $mm$ |
| Measure drainage to OW | 229.6 $mm$ | 7.4 $mm$ |
| Sewer discharge | 24.1 $mm$ | 12.1 $mm$ |
| Measure drainage to GW | 252.0 $mm$ | 8.1 $mm$ |
| Discharge from OW | 184.2 $mm$ | 15.0 $mm$ |
| Total inflow to OW | 521.8 $mm$ | 40.5 $mm$ |

The second standard for pluvial flooding is more focused on *preventing flooding*. **Storage** and **runoff** are indicators for flooding. **Runoff** occurs when components in a system overflow, which is not necessarily problematic and even allowed to a certain degree (*Convenant klimaatadaptief bouwen in Zuid-Holland*, 2018 ). Overflowing **storage** indicates total system failure. Consequently, this is a good indicator to assess where real damages occur, when water levels in **storages** reach above levels of important infrastructure or reach the building levels, for example.

**Storage** and flooding were assessed with the same extreme precipitation event of 100 $mm$ (June 28, 2011). This is a higher than 90 $mm$ required by the CKAB standard (**N2**, sec. 3.1.3). Figure 4.4 visualizes **storage** in three components: **open water**, **groundwater** and in a **measure**. Additionally, three surfaces relative to the model surface level were included. The maximum water level before overflow occurs is indicated as well. In the case of this event the model predicts no major flooding to occur.

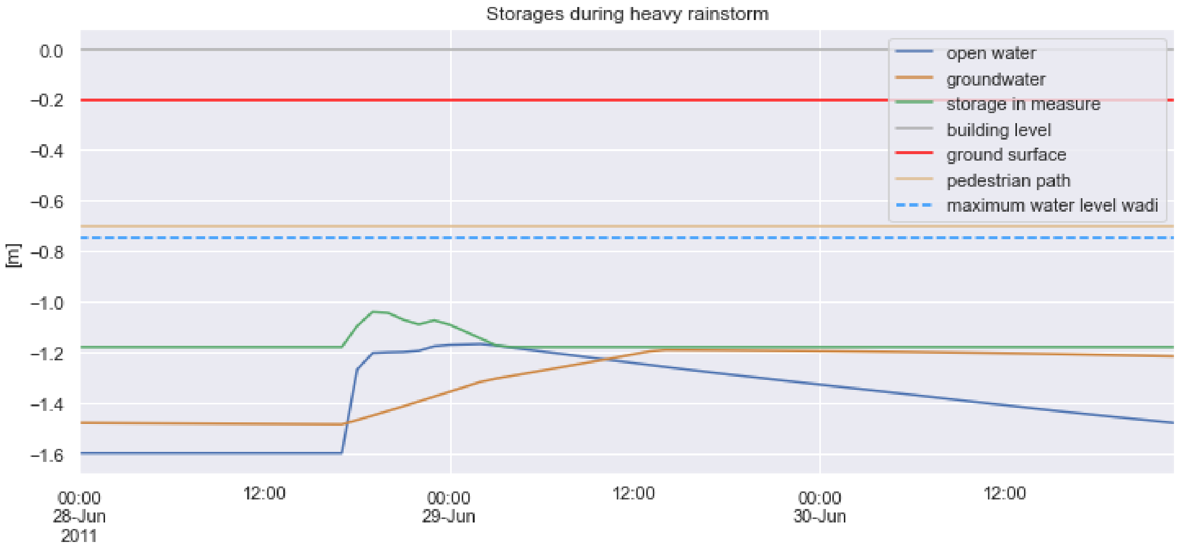


Figure 4.4: Storage during an extreme precipitation event (June 28, 2011): **open water** level, **groundwater** level and water level in **measure**.

### 4.1.3. Drought

Similarly to pluvial flooding, the model contains many variables related to drought as well. Droughts can be assessed with multi-year time series of precipitation and evaporation. Two standards for drought were reviewed (sec. 3.1.3): one focused on *water availability* (**D1**), a second one on *infiltration* and the effect on the groundwater table (**D2**).

The Dutch drought problem is seasonal (sec. 1.2.1): systems are designed to handle a surplus of water, but have a water deficit in summer. Standard **D1** in the CKAB aims to increase *water availability* in dry periods. Of possible indicators in section (sec. 3.1.3), discharge to **outside** water gave the most direct and clear indication of water shortage. This discharge is usually positive, but can be negative in times of water shortage (the model adds water into the system to sustain the target water level in **open water**). Negative drainage or inlet indicates the amount of water required by the system i.e. the *water availability*.

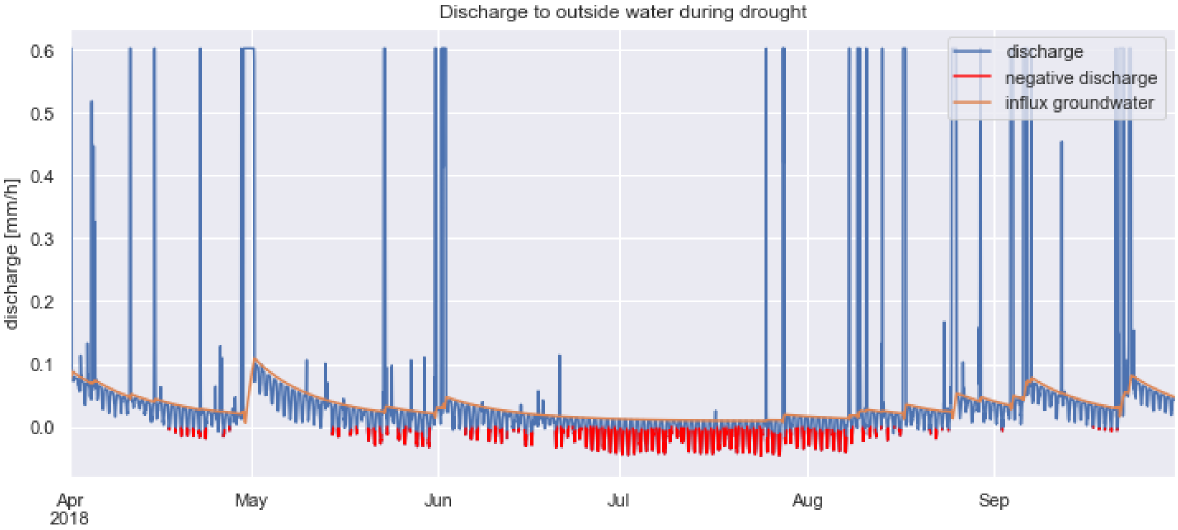


Figure 4.5: Discharge from **open water** to **outside water** during drought year (2018): positive discharge, negative discharge (inlet) and **groundwater** influx.

For the analysis on *water availability*, discharges in the Dutch "growing season" (1st of april to 30 of september) were compared. In Figure 4.5 these discharges are visualized for 2018, a year with severe drought conditions (*bron: KNMI droogtes*). The discharge of periods without precipitation is sustained by an influx of **groundwater** in the model, but in in dry periods, especially in Juli and August, much negative discharge occurred, indicating water stress. Table 4.4 compared this event to normal discharges during the growing season. The positive discharge to **outside water** was smaller during the dry year, but the inlet almost doubled. This drought event had a significantly lower *water availability*.

Table 4.4: Discharge from **open water** to **outside water** during growing season

| | Average conditions | Drought conditions |
|---|---|---|
| Discharge to outside water | 286.7 $mm$ | 208.9 $mm$ |
| Inlet (negative discharge) | 8.5 $mm$ | 15.8 $mm$ |

*Infiltration* is proposed as a method to decrease *water availability* and increase **groundwater** levels (sec. 1.2.1). However, excessive *infiltration* without drainage can result in high groundwater levels, causing problems. Standard **D2** states that half of the precipitation is supposed to be infiltrated, but this standard can be adapted when high **groundwater** is expected to cause problems. For this reason, **infiltration flux** was assessed in combination with **storage** indicators. The infiltration flux was derived from model data ($sum\,i\,uz$, $p\,op\,gw$ & $q\,meas\,ow$) and then **groundwater** levels were checked for the occurrence of flooding.

Table 4.5: *Infiltration* volumes in Amstelwijck I for period with extremely high **groundwater** conditions (23-10-1998 to 13-11-1998).

| | Total in situ volume | Total volume with respect to entire area |
|---|---|---|
| Precipitation | 195.3 $mm$ | 195.3 $mm$ |
| Unpaved infiltration | 195.2 $mm$ | 81.1 $mm$ |
| Open paved infiltration | 61.4 $mm$ | 5.3 $mm$ |
| Measure drainage to GW | 1701.7 $mm$ | 54.8 $mm$ |
| Total infiltration | 141.2 $mm$ | 141.2 $mm$ |

November 1st 1998, the model produced the highest **groundwater** level in this time series, an extreme event. These sustained high levels were caused by 195 $mm$ precipitation from 23 October to 13 November. During this event 72% of precipitation infiltrated in case area Amstelwijck **I**, saturating the **groundwater**, 42% (81.1 $mm$) in unpaved surfaces and 28% (54.8 $mm$) infiltrated in the *wadi* (Tab. 4.5). **67%** of yearly precipitation is infiltrated into the ground under normal conditions, which is higher than 50%, which is required by the Covenant standard (**D2**). The **groundwater** level rises to 53 $cm$ below surface level. Taking Figure 4.4 into account, this would probably result in the wadi filling up, possibly even overflowing and flooding the pedestrian path. This analysis shows the effects excessive *infiltration* can have in an extreme event.

## 4.2. Sensitivity analysis

Section 3.2 described uncertainties in *modelling*, *climate* and *design* that were investigated with a sensitivity analysis. Four different indicators for **heat stress**, **pluvial flooding** and **drought** were reviewed by varying parameters and the forcing. The results of this analysis was visualized in figures and summarized in tables in appendix E. This section shows a selection of these results, for every climate aspect: a figure, a table comparing two analyses and a summary of the general sensitivity of the indicator.

### 4.2.1. Heat stress

During sensitivity analysis the energy fluxes of *latent heat* and *excess heat* were analysed. These fluxes are a indicator to the Urban Heat Island effect (sec. 4.1.1), so this analysis can demonstrate what uncertainties have the biggest influence on the UHI.

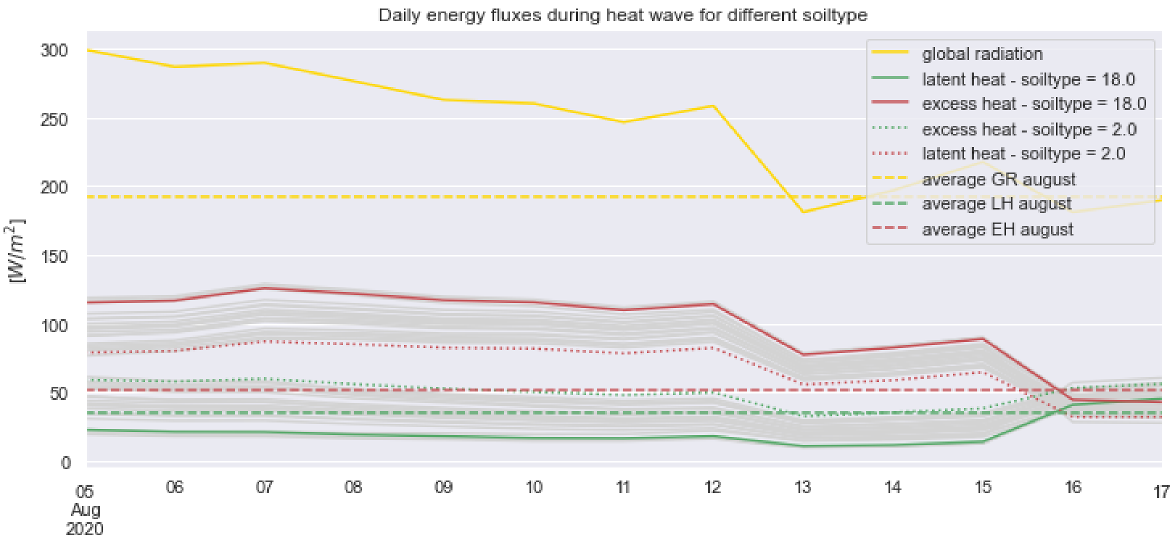


Figure 4.6: Daily averages for energy fluxes during a heat wave and averages for the same period in August 2020 for different $soiltype$: *global radiation*, *latent heat* flux and *excess heat* flux (= potential LH - actual LH).

Figure 4.6 presents energy fluxes during a heat wave for different types of soil (sec. 3.2.1), simulated for case study, Amstelwijck I. The *solid* lines represent the current situation, a soil of *clay on peat*, while the *dotted* lines are limits of *latent heat* flux and *excess heat* flux. Averages of energy fluxes under normal conditions are indicated as well (*dashed* lines). Soil type 2.0, representing a *peat and sand mixture* soil, produces both lowest values of *latent heat* as highest of *excess heat* (Tab. E.3). In Table 4.6, the indicators for a couple of soil types were compared to energy fluxes in different climate scenarios (sec. 3.2.2). The soil types have more variability in energy fluxes than the scenarios. The current soil type produces one of the highest values for *excess heat* and one of the lowest for *latent heat*. In future scenarios *excess heat* would even increase, increasing UHI, while *latent heat* flux remains similar.

Table 4.6: **Heat stress** indicators for different $soiltype$ & climates.

| # | **Soil type** | *Latent heat* | *Excess heat* | **Scenario** | *Latent heat* | *Excess heat* |
|---|---|---|---|---|---|---|
| 2 | peat/sand mixture | 49.8 $W/m^2$ | 69.0 $W/m^2$ | 2007 | *21.1* $W/m^2$ | *97.7* $W/m^2$ |
| 14 | course sand | 19.3 $W/m^2$ | 99.5 $W/m^2$ | 2030 | 21.3 $W/m^2$ | 101.6 $W/m^2$ |
| 18 | clay on peat | *21.1* $W/m^2$ | *97.7* $W/m^2$ | 2050 WH | 21.3 $W/m^2$ | 110.5 $W/m^2$ |
| 19 | clay on sand | 46.9 $W/m^2$ | 71.9 $W/m^2$ | 2085 WH | 21.2 $W/m^2$ | 115.4 $W/m^2$ |

### 4.2.2. Pluvial flooding

Two indicators with respect to flooding were reviewed with the sensitivity analysis. The first, indicator for retention in *short heavy showers*, consist of two **discharge** and **runoff** fluxes used in section 4.1.2 and the precipitation flux. The other indicator is for *preventing flooding*. *Storage* in **open water**, **groundwater** and the *wadi* were calculated for the different forcing and uncertain parameters.

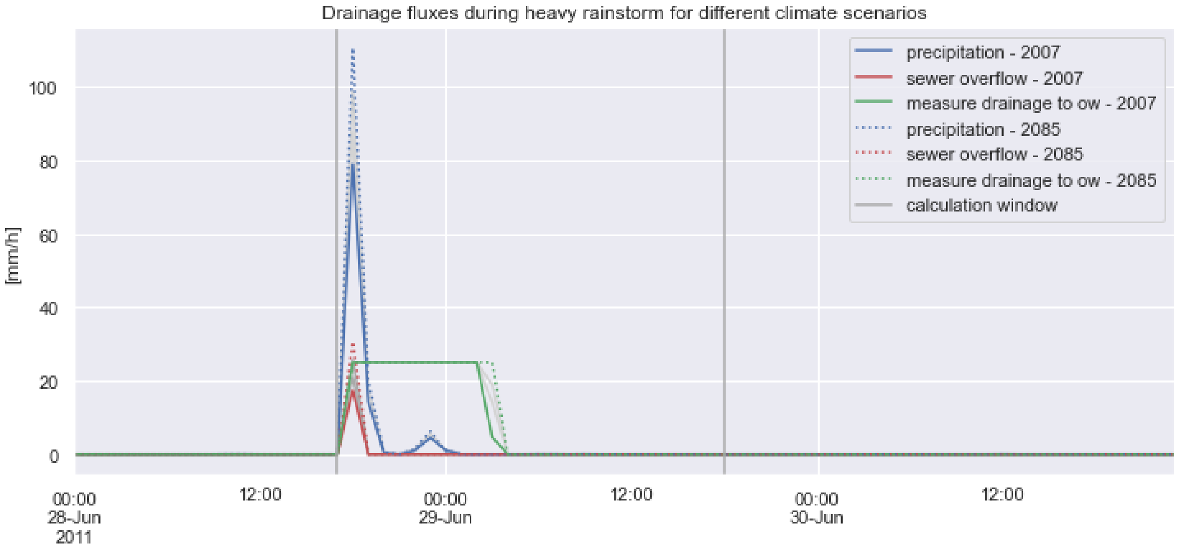


Figure 4.7: Drainage fluxes during an extreme precipitation event (June 28, 2011) for different climates: precipitation, **sewer** overflow and **measure** drainage.

Figure 4.7 displays drainage fluxes in an extreme precipitation event for future climate scenarios (sec. 3.2.2). Extreme summer precipitation increased with 40% in 2085 (Tab. 3.4) and as a result **sewer** overflow almost doubled, while the drainage from the *wadi* to open water increased only slightly (Tab. 4.7. Comparing this to drainage fluxes for different designs of *private property* in Table 4.8 (sec. 3.2.3), designing all yards completely unpaved, would result in overflow conditions similar to the 2050 scenario. When *private property* were completely paved, the **sewer** overflow would increase dramatically, to 20.7 $mm$ over the whole case area. The increase in *wadi* drainage was, again, minor.

Table 4.7: **Pluvial flooding** indicators for different climates.

| **Scenario** | *Precipitation* | *Total sewer overflow* | *Total measure drainage to ow* |
|---|---|---|---|
| 2007 | *100.4* $mm$ | 8.7 $mm$ | 7.4 $mm$ |
| 2030 | 111.3 $mm$ | 10.6 $mm$ | 7.7 $mm$ |
| 2050 | 125.0 $mm$ | 12.9 $mm$ | 7.9 $mm$ |
| 2085 | 139.7 $mm$ | 15.4 $mm$ | 8.1 $mm$ |

Table 4.8: **Pluvial flooding** indicators for different *private property* designs.

| **Design** | *Precipitation* | *Total sewer overflow* | *Total measure drainage to ow* |
|---|---|---|---|
| No change | *100.4* $mm$ | *8.7* $mm$ | *7.4* $mm$ |
| Private property = CP | 100.4 $mm$ | 20.7 $mm$ | 7.6 $mm$ |
| Private property = UP | 100.4 $mm$ | 12.7 $mm$ | 7.5 $mm$ |

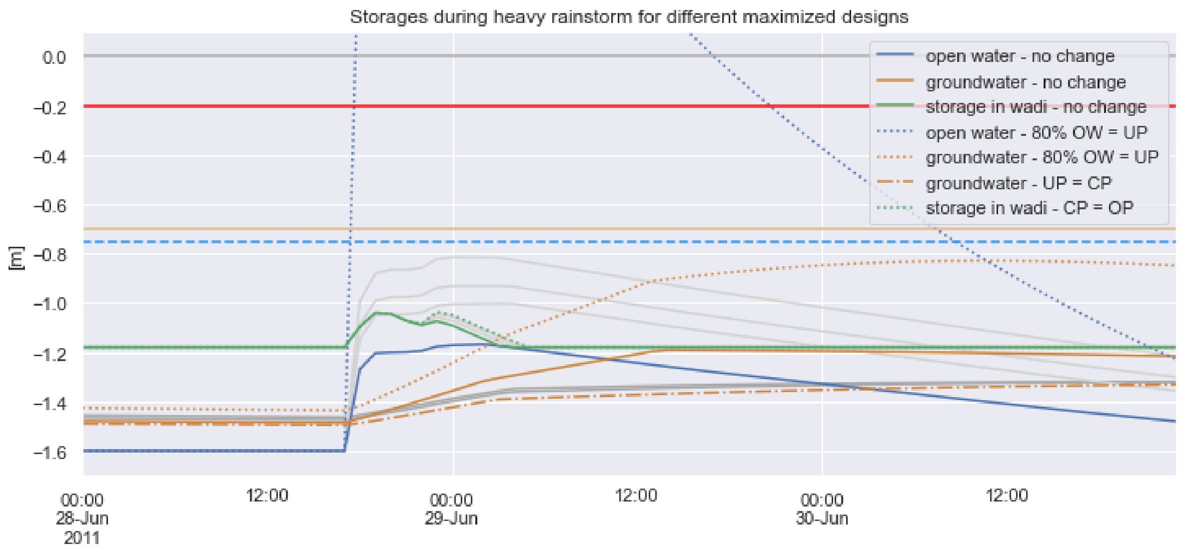


Figure 4.8: Storage during an extreme precipitation event (June 28, 2011) for different maximized designs: **open water** level, **groundwater** level and water level in **measure**.

In Figure 4.8, **storages** for a extreme precipitation event were visualized, now for different maximized design choices. Three of the maximized designs increase the **open water** level significantly, but the fourth, converting 80% of **open water** to **unpaved** surface, increases this level to over a meter (Tab. 4.9), most certainly causing damages. The increase in **groundwater** for this scenario is significant as well. For the other scenarios, **groundwater** levels are lower, possibly because of decreased infiltration. Table 4.9 containing information on the design scenarios of Figure 4.8 was compared to different scenarios for values of drainage resistance of **groundwater** or $w$ (Tab. 4.10). The second produced less extreme levels of **open water**, but significant rise of **groundwater** levels. The extreme **groundwater** level of the **open water** removal case is similar to a $w$ scenario of 500 $days$. The highest **groundwater** scenario was produced by the highest drainage resistance. Only for very small values of $w$ does the level appear to be slightly higher than higher resistances, possible because the **open water** level is around the same level, hampering flow to **open water**.

Table 4.9: **Pluvial flooding** indicators for different maximized designs.

| **Design** | *Maximum open water level* | *Maximum groundwater level* | *Maximum measure water level* |
|---|---|---|---|
| No change | *-1.18* $m$ | *-1.19* $m$ | *- 1.04* $m$ |
| UP = CP | -0.81 $m$ | -1.33 $m$ | -1.04 $m$ |
| CP = OP | -1.00 $m$ | -1.32 $m$ | -1.04 $m$ |
| OP = CP | -0.93 $m$ | -1.32 $m$ | -1.04 $m$ |
| 80% OW = UP | 1.11 $m$ | -0.83 $m$ | -1.04 $m$ |

Table 4.10: **Pluvial flooding** indicators for different $w$.

| **w** | *Maximum open water level* | *Maximum groundwater level* | *Maximum measure water level* |
|---|---|---|---|
| 10 | -1.22 $m$ | -1.26 $m$ | - 1.04 $m$ |
| 25 | -1.20 $m$ | -1.27 $m$ | -1.04 $m$ |
| 50 | -1.18 $m$ | -1.25 $m$ | -1.04 $m$ |
| 100 | *-1.17* $m$ | *-1.19* $m$ | *-1.04* $m$ |
| 200 | -1.16 $m$ | -1.10 $m$ | - 1.04 $m$ |
| 300 | -1.16 $m$ | -1.01 $m$ | - 1.04 $m$ |
| 400 | -1.16 $m$ | -0.93 $m$ | - 1.04 $m$ |
| 500 | -1.16 $m$ | -0.86 $m$ | - 1.04 $m$ |
| 750 | -1.16 $m$ | -0.64 $m$ | - 1.04 $m$ |
| 1000 | -1.15 $m$ | -0.44 $m$ | - 1.04 $m$ |

### 4.2.3. Drought

A sensitivity analysis on drought was performed for one indicator, inlet from **outside water** representing *water availability* (sec. 4.1.3).

Table 4.11 summarizes inlet amounts during the growing season in a drought year: for different types of soil, values for drainage resistance, maximized designs and climate scenarios. $Soiltype$ contains the largest variability ranging from 10 to 60 $mm$ inlet in the growing season. Then there is $w$ which also contains a range of inlet amounts. Remarkably, low resistance values produce the highest water requirements, but there seems to be an optimum around 400 days before inlet values rise again. All maximized surfaces have higher water availability (or smaller water requirement), especially when removing **open water surface**. Lastly water availability decreases in future climate scenarios according to the climate sensitivity analysis.

Table 4.11: **Pluvial flooding** indicators for different $soiltype$, $w$, climate scenarios & maximized designs.

| **#** | **Soil type** | *Inlet* | **w** | *Inlet* | **Design** | *Inlet* | **Climate** | *Inlet* |
|---|---|---|---|---|---|---|---|---|
| 1 | Peat mixed | 24.0 $mm$ | 10 | 25.1 $mm$ | No change | 15.7 $mm$ | 2007 | 15.7 $mm$ |
| 2 | P/S mixed | 33.9 $mm$ | 25 | 20.7 $mm$ | UP = CP | 14.9 $mm$ | 2030 | 16.4 $mm$ |
| 4 | P with C on S | 32.9 $mm$ | 50 | 17.9 $mm$ | CP = OP | 12.9 $mm$ | 2050 WH | 19.1 $mm$ |
| 6 | Peat on clay | 18.9 $mm$ | 100 | 15.8 $mm$ | OP = CP | 13.4 $mm$ | 2085 WH | 20.8 $mm$ |
| 7 | Loose sand | 19.5 $mm$ | 200 | 13.8 $mm$ | 80% OW = UP | 0.02 $mm$ | | |
| 9 | Fine sand | 35.7 $mm$ | 300 | 12.8 $mm$ | | | | |
| 14 | Course sand | 11.1 $mm$ | 400 | 12.4 $mm$ | | | | |
| 18 | Clay on peat | 15.8 $mm$ | 500 | 12.5 $mm$ | | | | |
| 19 | Clay on sand | 42.6 $mm$ | 750 | 13.7 $mm$ | | | | |
| 21 | Loam | 60.6 $mm$ | 1000 | 15.8 $mm$ | | | | |

## 4.3. Analysis of standard implementation

Section 3.3 described the method of standards analysis and the procedure of interviews and focus groups. In this section, the standards in the *Covenant Climate-Adaptive Building* were analysed with help of the interview results. First, a summary of interview statistics: barriers and enablers were analysed, counted and grouped into themes. Secondly, some recurring barriers and enablers were further evaluated. Then, the stakeholder groups and standard preferences were reassessed. Lastly, the focus groups are discussed if these session confirm the analysis of the interviews. This procedure allows a qualitative judgement to be given.

### 4.3.1. Interview statistics

A total of 12 interviews was taken of which *seven* interviewees were related to the municipality or any other governmental organisation (IBD, WSHD), the supposed **goal oriented** group, and *five* belonged to either of the two project developers, the **usage oriented** group. After processing of the written notes a report was written per interview. An analysis of the reports reveils that the interviewees mentioned 33 unique barriers and 38 unique enablers (App. A), where some were mentioned by multiple individuals. The *seven* **goal oriented** interviewees mentioned barriers 55 times and enablers 71 times, while the *five* **usage oriented** mentioned 27 barriers and 56 enablers. Most notable barriers were: *habits/customs* (8), *lack of funds/financial costs* (7), *low permeability soil* (6), *underground infrastructure* (6). *maintenance* (5), *execution construction NBS/CAS* (5) & *conflicting interests climate aspects* (5). As enablers were mentioned: *clear standards* (7), *ambition* (7), *strict standards* (6), *goal focused standards* (6), *measure addressing multiple climate aspects* (5), *model/tool representing system functioning* (5), *ecological value* (5), *climate robustness* (5), *communication* (5), *tailored policy* (5) & *network for knowledge* (5). The most recurring keywords were analysed further in section 4.3.2.

Subsequently, the barriers and enablers found were grouped into themes. Apart from *four* barriers (*low permeability soil*, *high groundwater*, *low groundwater* & *subsidence*), every barrier and enabler could be grouped into one of four themes introduced in section 1.2.3. These four barriers were taken aside as a point of discussion in the focus groups. Appendix A section A.1 shows this grouping into themes. The number of mentions of every barrier and enabler was noted by group. Table 4.12 summarized the results per theme.

Table 4.12: Barriers and enablers mentioned by **goal oriented** and **usage oriented** interviewees grouped per theme: *institutional setting*; *availability of (financial) resources*; *level of expertise*; and *collaborative governance and planning*.

| Number mentioned | Institutional | Resources | Competence | Collaboration |
|---|---|---|---|---|
| Barriers **goal oriented** | 16/7 | 14/7 | 17/7 | 8/7 |
| Barriers **usage oriented** | 9/5 | 6/5 | 5/5 | 7/5 |
| Enablers **goal oriented** | 30/7 | 7/7 | 15/7 | 19/7 |
| Enablers **usage oriented** | 26/5 | 12/5 | 4/5 | 14/5 |
| Total barriers | 25/12 | 20/12 | 22/12 | 15/12 |
| Total enablers | 56/12 | 19/12 | 19/12 | 33/12 |

### 4.3.2. Recurring barriers and enablers

Topics that were mentioned more often, probably had more meaning to the interviewees. A couple of these barriers and enablers are discussed further. *Habits* were mentioned the most as a barrier. 6/7 **goal oriented** interviewees said that the old way of working is often impeding the implementation of innovations. Little less than half (2/5) of the **usage oriented** group mentioned this as well. A second barrier is *financial cost* or *lack of funds*. Mostly **usage oriented** (4/5) interviewees indicated this as an obstacle . **Goal oriented** people mentioned it less (3/7), but did indicate it as an issue that should be payed attention to, particularly since the incentive of the other group is to minimize financial spending. There were also individuals that expressed no concern about finances and two even felt funding to be an enabler.

The local conditions have been mentioned quite often as a barrier. These barriers were difficult to group into one of the four themes and might require a separate theme. The *low soil permeability* was mentioned the most. Especially **goal oriented** interviewees (5/7) mentioned this as a barrier. Of the other group only *one* person mentioned the permeability as a barrier. *Underground infrastructure* or more generally, *lack of space*, was mentioned quite often. 4/7 in the **goal oriented** group and 2/5 in the **usage oriented** group saw this as an issue difficult to deal with. Space is limited an with the extensive underground infrastructure in the Netherlands that is steadily shrinking, climate adaptive solutions are competing for this space. Interviewees indicated that this obstacle is solvable, but does take more work than usually.

Standards were clearly seen as enablers, but sometimes as barriers as well. *Clear standards* have been mentioned the most as an enabler. Of all different descriptions of good standards for climate adaptation 'clear' was agreed upon by most interviewees, also equally by both groups. 4/7 **goal oriented** and 3/5 **usage oriented** interviewees mentioned *clear standards* specifically. The definition of 'clear' could be disputed, but in this sense most meant by clear that the meaning and task should be easily understandable and particularly no unexpected demands would be encountered later on. The second enabler that was mentioned often was *ambition*. When asked for incentives *all* **usage oriented** (5/5) interviewees mentioned *ambition* as an important driver. Some **goal oriented** (2/7) interviewees mentioned this as well, but significantly less. This was quite remarkable.
*Strict standards* were mentioned both as an enabler and a barrier, a couple of times even by the same person. Mostly **goal oriented** people (4/7) appear to prefer stricter rules, to make sure a lower limit of goals is always met. 'Strict' and 'clear' seemed interchangeable at times, but there is a distinction in that *strict standards* set the amount of commitment, while *clear standards* point to a way of describing standards, what are the boundaries. Lastly, standards focused on *goals* were mentioned as an enabler by many. Interviewees preferred to work towards a goal instead of a very specified standard that might be reached without reaching the goal itself. Remarkably, **usage oriented** interviewees mentioned this more (3/5) than **goal oriented** interviewees (3/7).

### 4.3.3. Stakeholder groups

The distinction between **goal oriented** and **usage oriented** stakeholders was made on the assumption there are groups of stakeholders that have different motivations and incentives for climate adaptation. The current distinction was mainly based on the assumed preference on the standard focus: *goals* or *means*. However, as mentioned in the previous section, more **usage oriented** interviewees prefer standards focused on *goals*, while **goal oriented** interviewees are not far behind; this is not what distinguished these two groups. Standards focused on *means* are never mentioned specifically, except possibly when interviewees talk about *clear* standards, they sometimes refer to something in the direction of *means*. The validity of this statement was checked in the focus group sessions (sec. 4.3.5).

Other barriers and enablers did show where the two groups could be distinguished. In this section the five most noticeable examples are discussed further. First, *ambition*, which was overwhelmingly mentioned as an enabler by all **usage oriented**, but not by **goal oriented** interviewees. Apparently, ambition is a important motivator for project developers and designers. These interviewees have ambitious plans themselves, because they want to built the best project, but they also appreciated ambition in other stakeholders to help and boost the project goals. Ambitious plans were, however, not always enough to ensure climate adaptation. The weight of barriers such as lack of funds was often stronger than ambition. The second subject, mentioned as a barrier mainly by **goal oriented** interviewees, was *habits* or customs. This was a big issue for this group, mostly as self-reflection. Processes such as the case study are new and not stream-lined yet. Old customs was mentioned as a barrier at the maintenance department (also by people from the maintenance department), where more similar barriers were found, but as barriers at, for example, inhabitants and contractors as well.

Three less significant motivations distinguishing **user** and **goal oriented** interviewees, were *corporate values*, *lack of funds* and *low permeability soil*. The first was mentioned as an important enabler for climate adaptation by **user oriented** interviewees, but not by **goal oriented** ones. Surely, the second group has corporate values as well, but apparently only **user oriented** interviewees felt to mention them. They were mentioned as a reason to think about climate adaptation in every project. However, similar to ambition, corporate values only helped guide the process and in the end they did not always possess enough weight to weigh up to certain barriers, such as resources or habits for example. Then there were *lack of funds*, which was experienced as a barrier, mainly by **user oriented** interviewees. In the end they wanted to be competitive and that was not always easy when implementing (expensive) measure for climate adaptation. Some **goal oriented** interviewees experienced this as a barrier as well, but others theorized that this could also be an enabler for project developers, because it increases the value of property. However, the benefits do not always reach the developing party. Lastly, low permeability of the soil was indicated as a barrier by many **goal oriented** interviewees, but only by one **user oriented** stakeholder. A similar pattern was found for other barriers related to the local conditions (*high groundwater*, *low groundwater* & *subsidence*). This is interesting since both groups deal should deal with the same problems if considering they are talking about the same location.

### 4.3.4. Assessment standards

One of the main goals of the interviews was to identify what standards work best. By analysing answers provided by interviewees, preferences for certain kinds of standards could be derived. As mentioned above *clear* standards were a requirement for more than half of the interviewees. Clear is not really a specified term, but does connect to a couple of concepts. For example strict, *rule*-based standards, which were perceived both as a barrier and an enabler, sometimes even by the same interviewee, a duality. *Rules* do give a lot of clarity compared to *principles*. One of the main reasons mentioned for this kind of standard to be perceived as an enabler was that *rules* would provide a strong argument to counteract barriers. On the other hand strict standards were found to be barriers, because of rigid institutions i.e. when no exceptions were possible, if the situation would benefit from it. In this case study many stakeholders where happy with the way standards were applied.

Another duality was found in the second concept: *specification* and *creative freedom*. This was not mentioned overly excessive and no preference for one of the two types of formulating standards was preferred by any group. On the one hand according to interviewees *specified* standards gave, again, clarity. However, in this innovative process of improving these standards and encouraging climate-adaptive building, the case study pilot, *creative freedom* was greatly appreciated as well. Lastly, both groups preferred standards that were focused on *goals* instead of *means*. A reason mentioned by multiple interviewees was that *goals* provided more *creative freedom* to find adaptive solutions. And in one interview it was mentioned that *goal* focused standards would encourage *integral* thinking, "combining measures for *heat stress* and *pluvial flooding*" for example.

### 4.3.5. Focus groups

The focus group sessions gave more insight in the interview results. Nine interviewees participated in the poll. Some interpretations were confirmed and some did not match the interpretations. In these groups the setting, presented information and way of asking questions differed from the interview to check consistency with those interviews. This section provides a short overview.
From the poll, the scores for barriers were: *habits/customs* (4), *lack of funds/financial costs* (3), *low permeability soil* (2), *underground infrastructure* (3). *maintenance* (1), *execution construction NBS/CAS* (3) & *conflicting interests climate aspects* (3). As enablers were mentioned: *clear standards* (4), *ambition* (4), *strict standards* (0), *goal focused standards* (2), *measure addressing multiple climate aspects* (4), *model/tool representing system functioning* (0), *ecological value* (2), *climate robustness* (3), *communication* (2), *tailored policy* (2) & *network for knowledge* (0). These results correspond with the interviews for the most part. Only the *low permeability of the soil* was found to be less of a barrier in the focus group, while *execution of NBS* was highlighted. As enablers *strict standards* and *goal focused standards* gained less support, while some previously smaller enablers (*ecological value*, *climate robustness*, *communication*, *tailored policy*) were highlighted. When asking interviewees in the focus groups a direct question on which themes they deemed important instead of inferring this from barriers and enablers, a remarkable change appeared compared to the interviews. *Institutions*, rules were not found to be a major barrier anymore, while *collaboration*, which did not come forward as a barrier during the interviews was overwhelmingly suggested as a barrier. Enablers did align with the interview results. Apparently, the proper management by *institutions* (by standards for example) and *collaboration* are important enablers for climate adaptation. Either the classification of barriers and enablers or the interpretation of the themes by focus group attendees did not match the situation.

Table 4.13: Themes with most barriers and enablers indicated in poll by *nine* interviewees.

| Number mentioned | Institutional | Resources | Competence | Collaboration |
|---|---|---|---|---|
| Barriers | 2 | 2 | 3 | 7 |
| Enablers | 7 | 1 | 1 | 5 |

Last in the poll, the preference for certain standards was checked. The poll participants mostly agreed with the interpretation found through the interview analysis. However the focus group participants were somewhat more nuanced. As expected everyone experienced *strict* standards both as barriers and enablers, but more interviewees chose the option for *creative freedom* above *specification*, although still most chose the option 'both'. The main nuance pointed to the fact that interviewees were ambiguous about *goal* focused standards. *Five* out of nine chose the option that a focus *goals* is not always better. In the focus group discussion this was clarified; the difficulty lied in *assessing* standards. Standards focused on *means* were often perceived as easier to assess, but other attendees countered this argument by stating that this would restrict the range of solutions. As a solution it was proposed to create a selection of measures allowed, but with the possibility to allow other solutions with an extra check required. There was also discussion on creating a separate theme for *local conditions*. One attendee argued the importance of this theme, but another categorized all local barriers as *competence* related, no clear majority was reached on this point. Lastly, there was a small discussion on the applicability of ***UrbanWB*** as a *design* or *assessment* tool. Similar to interpretations from the interviews, there was enthusiasm on having a tool to provide more argumentation for implementing climate adaptive measures, since this was still an uncertain issue, the *why*. An integral view on processes was an added feature much appreciated, plus knowing which climate aspect might require additional attention in this specific location. The focus group attendees considered ***UrbanWB*** mainly as a *design* tool, but did not know if the performance was good enough for this model to be used as an *assessment* tool.

# 5

# Discussion

The results described in Chapter 4 have been produced with information and methodologies from Chapters 2 and 3. This was done by using assumptions and applying a model and a framework that are simplifications of reality. This Chapter aims to explain what notable assumptions could alter the results; what is the significance of these results. Further, the results are put into context; what is the scientific relevance. And lastly, the meaning of this research is reviewed; what is the implication in practice.

First on account of the significance of the results, an important notion about *heat stress*. ***UrbanWB*** is a water balance model, essentially it simulates storages and fluxes of water, so not all energy fluxes are included. The indicators used for assessment of this climate aspect were *indirect* (PET reduction) or *incomplete* (latent heat flux). Physiological Equivalent Temperature (PET) is normally determined with seven (meteorological) variables (see Fig. 1.3) and simulations of PET are usually done using fine-meshed models such as **UMEP** (Kluck et al., 2020), **ENVI-MET** (Koopmans, 2021 and Krayenhoff et al., 2021) or with an empirical approach with fine-meshed spatial data as proposed for the standard Dutch national ’stresstest’ (De Nijs et al., 2019 and Koopmans, 2021). In this research a method proposed in Vergroesen (2020) based on PET reduction for a variety of measures from Kluck et al. (2020) was chosen, because in this way model *input* data could be utilized. This method, while based on scientific literature, is not exact and *indirect*. Mainly, it is a summary of general effectiveness of certain measures, so contrary to the other indicators there is no option for timeseries analysis, and it generalizes spatial variability over the whole case area, while PET is a very local effect. This means that for the case study analysis no extreme events could be analysed and local ’hot spots’ are not clearly represented when looking at the indicator value representing the whole neighbourhood (100-1000 m) Although this method is not perfect it does offer the advantage that it is simple to execute and doesn’t require a lot of advanced knowledge or computing power, which makes it an *easy-to-adopt* method for analysing how a design performs for (physiological) *heat stress*.

Yet, for an indication of this case study’s contribution to the Urban Heat Island (UHI) effect, ***UrbanWB*** wás able to calculate one direct indicator, latent heat flux derived from evaporation. However, latent heat flux represents, albeit an essential indicator, only a part of the energy fluxes that lead to a UHI. Similar to PET, UHI is determined by multiple variables, an energy balance over the whole city (see Fig. 1.2). The second most important of these fluxes for UHI is the storage heat flux, the fraction of energy stored by the city’s materials, water and ground, which is not considered with the current model. Consequently, the diurnal cycle of an urban environment, where energy, which would normally be used for evaporation in a natural situation, is converted to mainly storage heat flux during the day and released as sensible heat during the night, was not well represented by ***UrbanWB***. For the case study results this means two things: (i) there is no actual number for the night temperature, only a indication of how much energy is available for heating the surrounding environment during extreme events; (ii) the latent heat flux, or excess heat flux (assuming that it represents the amount of extra energy available for heating well), can however be used to compare different designs, local conditions or climatological situations. *Heat stress* is considered as a climate aspect that is difficult to grasp or calculate, which was also reflected in the simplicity of *means* oriented descriptions of the CKAB standards and reaffirmed by interviewees, and again in the focus groups, although most attendees indicated in the poll that *goal* focused standards are not *always* better. The methodologies applied for PET in this thesis reflected and combined often used *indirect* indicators for *heat stress*, such as distance to cool spots, amount of shadow, amount of green (Kluck et al., 2020). Knowing that these features are related to one or more physical parameters that determine either PET, UHI or both, assumptions can be made on the magnitude of *heat stress*, without resorting to difficult calculations that require a lot of data. The the UHI indicator was similar in the sense that 'only' latent heat indicated the behaviour of a more complex process, but the timeseries and extreme event analysis provided more possibilities than the latter.

A second model weakness was reflected by unrealistic behaviour for **open water** levels. Firstly, the target open water level was set as an *absolute minimum*, while in practice **open water** and **groundwater** can recede to lower levels. The model added water into the system (inlet) when this would happen. Low groundwater causes the most damaging effects of urban droughts: subsidence; damage to foundations, underground infrastructure or plants and trees (Veraart and Voskamp, 2022). The indicator provided by ***UrbanWB***, inlet, represented the amount of water required to maintain target **open water** level. This is an indirect indicator of water availability and **groundwater** levels. For example 1 $mm$ of inlet would mean that in reality **open water** level would recede more than 1 $cm$ and subsequently less water would be available to maintain **groundwater** levels and evaporation for plants. However, because receding below target level was not allowed by ***UrbanWB***, the rest of the system could not respond and as a consequence aforementioned **groundwater** levels and evaporation during droughts were *overestimated*. Secondly, discharge to **outside water**, the pumping, was *static* in the model, only one pumping speed was possible. In a regular polder system, pumps operate a full capacity in case of very high water, but not in when **open water** levels are just above target level, so the pumping is more variable. In a more dynamic system pumping may even start before the onset of rain by means of weather forecasts (Ritzema and Loon-Steensma, 2017). ***UrbanWB*** did not allow any form of dynamic water management, which *overestimated* the amount of discharge, especially during dry periods, *overestimating* the impact of specific drought events. This was no problem for the sensitivity analysis however, since all possible configurations were equally affected by this.

The analysis on ***UrbanWB*** was designed as a feasibility study exploring the possibilities with this model. This research demonstrated the use as a *design* and *assessment* tool. However, simultaneous implementation of multiple measures was not achieved. The integral effect of a measure on multiple climate aspects was found, but ***UrbanWB*** is currently only equipped to implement a single measure, in the case study only the *wadi* or *bioswale*. One could use the sum of single measures implemented for an indication of the effect, which is common practice, but this does not represent the integral effect on the system when multiple measures are implemented. Further development of ***UrbanWB*** could make implementation of multiple measures possible. Then the *rain barrels* and *green roofs* that were also featured in the urban plans of Amstelwijck could be included as well. Additionally, the scope of this study was limited. Extreme events, such as heat waves, were selected to analyse the climate aspects, but only one event per climate aspect, one heat wave was analysed. For more conclusive results on the system functioning a multiple of events should be analysed in order to simulate behaviour under different conditions. For example, during the selected heat wave, conditions were *water limited*; the year 2020 was the third of three consecutive years of drought. The behaviour of latent heat flux could be very different when considering another heat wave event. This statement could not be proven in the scope of this research. However, considering uncertainty in design choices, no significant differences were found in *latent* and *excess heat flux* during the selected heat wave. An analysis during conditions where water wás available did show a significant decrease in *latent heat flux* with decreased **unpaved** surface, indicating that specific, *water limited* conditions during this heat wave were indeed the cause of these curious results. In practice, some standards from CKAB are recommended to be tested with a so-called "stresstest", which is a representation of only one extreme event as well. For a part, this methodology represents the 'old', *resistance* approach to dealing with uncertainty (Walker et al., 2013), where only the worst conceivable case is considered, while suitable *additional* strategies for coping with a changing climate such as *static* or *adaptive robustness* could be adopted when considering more events or by updating standards regularly.

An important notion on the relevance of this thesis can be made as well by putting the method of *designing* and *assessing* urban plans into perspective. As discussed above, but also mentioned by Ritzema and Loon-Steensma (2017) *resistance* is still a much used strategy to provide basic security, certainty. However, adopting this strategy with climate change is difficult, since you would design for an uncertain situation (climate change) by assuming that you know the future situation. Many of the standards in the Covenant Climate-Adaptive Building are applied *resistance*-based. Requirements for some future climate projection are set and the design is made according to that projection, while reality could result in a different situation. One could pose the question on how adaptive these standards are other than adapting from the current situation. Some do pose more resemblance to *static robustness*, where all possible situations are considered, for example by testing multiple events or multiple scenarios. They do not ask for solution related to a specific scenario, but instead focus on general system adaptation, which is a different way to account for uncertainty. This research included an evaluation of *four* climate scenarios, current, 2030 and WH scenarios for 2050 and 2085, which is a good step in the direction of *static robustness*. However, a the research could be extended by considering more scenarios and other types of scenarios. Another approach, *adaptive robustness*, preparing for a *changing* situation, is not considered. It would difficult to implement this in something as static as standards, except by including regular updates of standards to account for changing situations; making standards inherently 'adaptive'.

Also, the scale of physical processes introduces difficulties in modelling integrally. As mentioned previously in this report (Ch. 1), processes related to the climate aspects happen on different scales of time and space and usually specific models are used to simulate such a process realistically. An example are the above-mentioned models to calculate PET. ***UrbanWB*** is built for an area roughly around the scale of a neighbourhood (0.01-1 $km^2$) and simulates on hourly basis with time series of 30 years. As a result processes at a lower spatial scale, local flooding (1-100 m) or PET (1-100 m) for example, go unnoticed and higher scales, such as UHI (0.5-100 km) or water availability (>50 km), are only simulated partly. On the other hand, the model covers the temporal scales of relevant processes quite well; only processes such as short heavy precipitation might require a higher resolution of 5 to 15 minutes. Often results of calculations with non matching temporal or spatial scale levels are still valuable, but scales should always be taken in mind carefully when interpreting results; the short heavy precipitation can be analysed with an hourly scale, but one should be aware of some of the variability being lost. An analysis by AM and Merosh, a project developer and an engineering consultant that researched several projects where the CKAB was implemented, encountered the importance of scales as well when dealing with climate adaptation (Vlot et al., 2021); climate aspects such as *pluvial flooding*, biodiversity and subsidence should be handled on the scale of the project area (100-1000 m) according to their analysis. Since not all scales were captured by this model, the modelling is not a perfect representation of the (hydrological) system, verification of the results is required. By analysing a climate aspect for the same case study, but then using a more appropriate model that captures the required scale level, the *value* of this model for practical use can be evaluated. The value or usability for *assessment* was also a question posed by interviewees and in the focus groups. Literature suggests a couple of frequently used options: microscale models such as **ENVI-MET** or the PET map from the Dutch national 'stresstest' for PET (De Nijs et al., 2019, Koopmans, 2021 and Krayenhoff et al., 2021); mesoscale models such as **WRF** or another energy balance model for UHI (Krayenhoff et al., 2021) (*heat stress* aspects); hydrological models such as statistical or distributed hydrology-soil-vegetation models (Fletcher et al., 2013) (*pluvial flooding* aspects); or geohydrological models (Vergroesen, 2020) (*drought* aspects). Mainly the aspects of heat stress and drought, processes that were determined by ***UrbanWB*** indicatively, not exact, would benefit from verification.

As well as verification with other models, model input parameters should be verified. A number of parameters were uncertain, so these parameters were examined with a sensitivity analysis (sec. 4.2). Some parameters, namely the type of soil and drainage resistance ($w$) in groundwater, were revealed to be very sensitive, i.e. uncertainty matters, while others, the type of crop and infiltration capacity, did not show a significant effect during the selected extreme events. The interviews conducted for this research established the importance of '*locality*', especially the type of soil. This is confirmed by AM and Merosh through several analyses executed on projects developed with CKAB (Vlot et al., 2021). *Locality* surfaces in scientific literature as well: Ritzema and Loon-Steensma (2017) distinguish three hydro-ecological zones in the Netherlands and van de Sandt et al. (2011) considers particular local conditions when assessing droughts. Drainage resistance as defined in ***UrbanWB*** is a combination of soil characteristics, water management and drainage practices (sec. 3.1.1), so a *local* parameter. Local heterogeneity can either be captured or not visible depending on the scale of modelling used. In this case, drainage resistance does not show the heterogeneity, but serves as a parameterization for the whole system. The type of crop and infiltration capacity are *local* as well and many interviewees emphasized the importance of the type of plant and infiltration in a climate adaptive design, which is also reflected in CKAB standards. One explanation for this not being reflected by the model is the analysis with extreme events that create very specific conditions, the selected heat wave event mentioned above for example. Conditions during a drought were found to be mainly determined by the soil type and water management practices. This largely explains why type of crop was found to be an insignificant uncertainty, but another explanation can be found the *locality* of crops, which was not considered by ***UrbanWB***, not in the type of crops. Plants or crops adapt to their surroundings, to low or high groundwater conditions, and to regular drought intervals. This was mentioned by several interviewees and by literature (Monshausen and Gilroy, 2009). Changing infiltration capacity did not produce any effects, not even for droughts, probably because of influence of soil type and drainage resistance in ***UrbanWB***, but mainly because in a polder system **open water** and thus **groundwater** levels are maintained and water infiltrated is discharged before the drought occurs.

The stakeholder analysis in the start of this research (sec. 2.5) established two distinct groups based on priorities and motivations. The **goal oriented** group was hypothesized to prefer standards focused on *goals*, while the **usage oriented** group would require standards based on *means*. This was the main argument to distinguish these groups. Though the two groups could still clearly be distinguished based on other priorities and motivations, results from interviews indicated that both groups preferred standards focused on *goals*. In the case of Long et al. (2016) *users* and *providers* represented stakeholders in an innovation process in climate-smart agriculture, but this research was executed under different conditions with other types of stakeholders. In this case study the '**goal oriented**' can act both as *providers* and *users*; the municipality creates the boundary condition, but is also the end user. Perhaps groups should be renamed by considering where the two groups differ the most in priorities and motivations. Many '**goal oriented**' interviewees indicated *habits* as a barrier, where this was not prevalent under '**usage oriented**' interviewees. Similarly, *ambition* was considered as an enabler by all '**usage oriented**' interviewees. This could be more suitable grounds for distinction instead of the *goals*/*means* division. A note on the sample group in the interview analysis: *twelve* interviews were conducted and, in total, 20 individuals were consulted. The sample size of the first group was *seven* and the second *five*. This is considered as a small amount and consequence the results can only be interpreted *qualitatively*. For quantitative results more interviews should be conducted, possibly for other case studies as well. The consideration of only one case study is another limitation. However, it was found during the interviews that saturation was reached, meaning that at some point no new information was found. This strengthens validity of the results. Also, the focus groups affirmed the conclusions from the interviews. This analysis provides a first evaluation on how CKAB standards were implemented on which future research can expand.

One of the implications of this thesis is recognizing the value of an (integral) view on different processes and climate aspects in urban design. Standards are merely a translation of physical goals that make an urban plan climate adaptive, 'robust'; affecting physical processes related to the climate aspects holds as the primary target of adaptation. In the case of Amstelwijck standards were focused on both *goals* and *means* (Fig. 1.1), **N1**, **N2** and **D1** on the first, **H1**, **H2** and **D2** on the second. *Goal* focused standards aim to reach climate goals by prescribing the goal itself, they ensure a direction, but this can be unclear. On the other hand *means* focused standards are often clear an prescriptive in implementation of measures. However, in the model analysis and by consulting stakeholders connected to Amstelwijck it became apparent that *means* do not always lead to an effective solution and possibly to (innovative) solutions being excluded. As an example, one standard aims to reduce PET and describes to increase shade (**H1**). While shade is a very effective measure or *means* to reduce PET and very manageable to implement, other variables such as wind, evaporation or radiating buildings are disregarded. This is apparent in the urban plans in the case study, through the large sections of shade implemented. Interviewees pointed out that this greatly restricted design possibilities (the threshold was even lowered during the process), while not necessarily functional. It touches on a similar dilemma as flexibility of standards, with *creative freedom*, and *specified* standards, only these concepts are applied on *definition* of standards instead of *direction*. When *specifying* standards, setting boundary conditions, there should be enough room left for innovation; only specifying that you should have a certain amount of infiltration closes the door on other, *creative* solutions that could retain water locally. Key is to put *goals* and corresponding physical processes forward. Another aspect of this implication is the integral view. In a complex system climate aspects are interrelated and implementing a measure to solve one aspect, influences others. If ***UrbanWB*** was used earlier in the design process, less focus could be on the *means* of infiltration. This standard (**N2**) was met generously, because this was encouraged with large unpaved surfaces and a wadi. However, the model showed that because of the local hydrological conditions, too much infiltration during multiple day precipitation, causes high groundwater. This effect was found by assessing the designs integrally. Another example would be implementing a ’green’ solution, like a wadi, instead of a ’grey’ underground water buffer. With ***UrbanWB*** the increased infiltration (*drought)* and evaporation (*heat stress)* are taken into account instead of only considering the effect on the *pluvial flooding* climate aspect. Positive and negative feedbacks of measure implementation can be detected with this *integral* model.

Lastly, an important notion for implementation already mentioned in an earlier paragraph, but reaffirmed by interviews is *locality*. This was experienced as a significant as multiple barriers could be connected to this as a theme. However, *locality* was not considered as a theme before. During the discussion with the focus groups, interviewees were divided: it was proposed to add a theme, but another interviewee mentioned that *local conditions* could be considered as part of the ’lack of knowledge’ theme. This could be researched further, but this research has at least indicated the importance of *locality*. Also tailored policy was mentioned as an enabler in several ways throughout interviews. Again, this explains why standards focused on *means* are less suitable; certain measures achieve different impacts based on the *local* conditions. Standards with *means* (**H1**, **H2** & **D2**) should be redefined towards *goals*: reducing physiological temperature (PET) (**H1**), reducing urban heating (UHI) (**H2**) and retaining water locally (**D2**). The second version of the Covenant Climate-Adaptive Building developed by the Building Adaptive platform in March 2022 made a couple of these improvements. *All* climate aspects have *goals* featured more prominently than before and some previously prominent *means* (**H1**, **H2** & **D2**) are now presented as grading subjects. In this way, more *goal* focused climate adaptation should take place, but experiences from this research showed that *goals* should be emphasized continuously, because the grading subjects, which are still largely *means*, still encourage stakeholders to resort to only looking at *specific* measures instead of innovating, which is needed in the field of climate adaptation.

# 6

# Conclusion

Standards for climate adaptation are required in order to deal with climate change. The worldwide climate is expected to change, but the severity of the effects of climate change is still uncertain. Adaptation, the reducing negative or using positive effects of climate change by societies, is equipped as a way of dealing with this uncertainty. The Province of South Holland came to a Covenant for Climate-Adaptive Building (CKAB), which sets standards for climate adaptation in new-built areas in six categories of climate aspects; *heat stress*, *pluvial flooding*, *drought*, subsidence, biodiversity and fluvial/coastal flooding. This thesis researched "*How **climate adaptation** for **heat stress, pluvial flooding** & **drought** was promoted in the development of urban plans by **design** & **assessment** with the **CKAB** and **UrbanWB***" Standards related to these climate aspects were analyzed with a case study, the development of two urban plans in the city of Dordrecht. In this case study, named Amstelwijck, stakeholders from the municipality and project developers were involved in the design process of a 'climate-adaptive' urban plan designed according to standards in the CKAB. Both groups were interviewed about the process. In this way, the standards were assessed. Stakeholders connected to the municipality were part of a **goal oriented** group, while the project developers and partners would be **usage oriented**. The prediction was that the first groups would want standards focused on *goals* and the second a focus on *means*. Additionally, a model was used to *assess* the case study, the effect of implementing standards, and the usability of this model as a *design* tool. ***UrbanWB*** was chosen, because this model has the possibility to simulate at the scale of an urban plan, neighbourhood scale (100-1000 m), and its ability to use hourly weather data time series. Lastly, uncertainties in *modelling*, *climate* and *design* were assessed in order to determine relative magnitudes of these uncertainties.

To answer the third research question, stakeholders in the Amstelwijck case study applied standards of the Covenant Climate-Adaptive Building were interviewed. The interviewees generally agreed that standards should be focused on *goals* in the first place, a *clear* direction of what is meant to be reached, then *specific* minimal required standards should be set as a *clear* guideline, a description. These should be *strict* (*rule*-based) in order to ensure they weigh up to the barriers. Only, if a solution is found that reaches the goal, but does not meet standards, exceptions should be possible to allow for *creative freedom*. Clear, in description of a standard as well as the direction of the standard, because clarity decreases uncertainty for stakeholders, mainly designers. When standards are ambiguous, multi-interpretative, designers could create plans that not necessarily meet the *goals*. *Goal* focused standards were preferred by *both* groups. A focus on *goals* instead of *means*, standards with specific measures, provided creative freedom for designers, but ensured that *goals* for climate adaptation were not lost out of sight, this was nuanced, but reaffirmed in the focus groups. *Strict* standards, rules that are ambitious and legally binding, help stakeholders with an argument for implementing climate adaptive solutions, against financial barriers for example. Half of interviewees mentioned that they appreciated having strict standards. However, strict standards were also experienced as a barrier, when a solution was found that achieved the goal, but did not meet the standard. As an example, one requirement in the case study was an amount of green of 40% to combat *heat stress*, but such a standard disregards variation in effect of different types of greenery let alone other measures against the UHI, such as decreasing heat capacity. At the same time, solutions for *drought* or *pluvial flooding*, or housing for

that matter, compete for the same limited space, while this standard states a requirement for 40% of surfaces. The standards for heat stress might be too strict, while adaptation goals could be reached in other ways.
Overall, interviewees appreciated the CKAB, although *heat stress* standards were perceived as not focused enough towards *goals*, but on *means*, and the *drought* standard for water availability was not *clear*, since the description was not *specified*. *Pluvial flooding* standards were received positively by all interviewees.

For the second research question, ***UrbanWB*** managed to calculate indicators for water related climate aspects well, but failed in calculating *every* energy flux and in simulating groundwater and discharge dynamics. The urban plan did not meet all standards. However these standards were sometimes focused on *means* or not *clear*. An integrated approach allows the designer to create benefits for multiple climate aspects and make choices that take the complexity, the interrelation between system components, into account. Again, standards focused on *goals* were preferred by interviewees, but these kind of standards are advantageous for assessment as well. Since a standard based on *means* does not contain a threshold for a goal, assessing climate aspects with these standards is difficult and the goal of adaptation is not necessarily achieved. For example, a standard describes increasing green, blue or other "heat resistant" surfaces, but not what goal should be reached. This one standard can lead to designs with a variety of *heat stresses*. For Amstelwijck, the model indicator, latent heat flux, demonstrated that this design choice had no significant effect during a heat wave, due to a lack of water availability. On a note: the model calculates *heat stress* indicators only partly, which makes it less suitable for looking at this climate aspect. *Pluvial flooding* standards were, on the other hand, focused on *goals*, which made these easier for assessing urban plans. The *flooding* standard in the case study was met, but retention was not sufficient according to the standard. Here the model was able to provide a more reliable estimation of indicators. The first standard for drought was focused on *goals*, only not *specific*; no threshold was set to limit water use or discharge. The other standard was focused on *means* to reach the goal of retaining water locally. The model was able to produce indicators and found that for the case study the *means* of *infiltration* to be met, but groundwater and discharge dynamics were not sufficiently incorporated in the model for exact measures of drought. The performance of a model is dependent on how well it can represent of physical processes, especially the scale they occur. With spatial scales far below or above neighbourhood level (100-1000 m) modelling is less reliable. For example, local, street level (1-100 m) flooding goes unnoticed in this model. Temporal scales are largely captured by ***UrbanWB***. An hourly simulation provided advantages to many other models that use larger timescales. As a *design* tool ***UrbanWB*** was able to judge *integrated* effects of extreme events on an urban plan, but was less effective in *assessing* if the standards applied resulted in a *robust* urban plan, a plan that performs in all situations. Indicators were reliable for *pluvial flooding*, but less for *heat stress* and *drought*.

In the end, ***UrbanWB*** in this research was also applied to evaluate uncertainty in the system, in *climate*, *design* and the *hydrological system*. Uncertainty brought by *climate* change is the decisive argument to implement *Climate*-Adaptive Solutions. However, while different *climate* scenarios were found to be of effect for *every* climate aspect in the sensitivity analysis, effects of local, *hydrological* conditions and *design* choices were of larger magnitude. Mainly *soil type* was crucial for the severity *heat stress* and *drought*, and of significant effect for *pluvial flooding*. *Drainage resistance* in **groundwater** had a significant effect on flooding as well, since high values resulted in soaring **groundwater** levels. Some *design* choices such as increasing **closed paved** surface or decreasing the **open water** area were very significant for *pluvial flooding* and *drought*, while others were more in the same order as the uncertainty in *climate change*. The proposed *design* choices did not show a significant effect for the *heat stress* aspect and *private property* design was only efficient for *pluvial flooding*. This culminates in three important notions: (i) climate change is a significant uncertainty; (ii) local conditions are decisive for the 'robustness', ability to perform under different conditions, of an urban system; (iii) design choices can have large effects on the hydrology of the system, some are effective enough to deal with climate change. Most standards were found to still resemble the *resistance* approach of dealing with uncertainty, but with *UrbanWB* more possibilities to add *static robustness* or even *adaptive robustness* approaches become available. Adding these approaches to the portfolio increases the resilience of urban environments to a changing climate.

This research has combined evaluating ***UrbanWB*** both as a *design* tool and a model for system *assessment* with evaluating the standards for climate adaptation in the Covenant Climate-Adaptive Building. However, this tool is mostly useful to provide *argumentation* for *design* choices, and does not perform as well as an *assessment* tool. Clear, *specific* and strict, *rule*-based standards in the CKAB help to promote climate-adaptive urban plans. However, according to both ’**goal oriented**’ as ’**usage oriented**’ interviewees *all* standards should become focused on *goals* instead of *means* and exceptions on standards should be possible when found to be too strict or *specific*. Then the *principle* should be leading, allowing innovative solutions that achieve the goal of climate adaptation, allowing *creative freedom*. To answer the main question: the development of *climate-adaptive* urban plans are best promoted by implementing standards focused on *goals* and using *integral* tools such as ***UrbanWB*** helps by providing more insight into the system and by providing *argumentation* that can counterbalance barriers for selecting climate-adaptive measures. ***UrbanWB***, as well as the CKAB standards, promote climate adaptation and deal with the uncertainty brought by climate change.

# A

# Interview setup

Interviews with different stakeholders from municipality and project developers have been conducted. Appendix A serves as an extensive summary of methodology and interview and focus group results. In section A.1 all *barriers* and *enablers* identified during the interviews are listed. Section A.2 provides a more extensive explanation on the *four* themes identified in literature. Then, the Dutch version of the interview questions and (extensive) poll questions are listed (sec. A.3). All participants have been told that they take part in the research in the introduction email and the opportunity for later revisions was mentioned during the interviews.

## A.1. Barriers and enablers

The interviewees were expected to provide insights in possible aspects that affect the implementation of climate-adaptive measures. This section includes a list with predefined (from literature and early conversations) and added (during the research) barriers and enablers. These aspects are grouped in different themes by using the theme definitions (see section A.2).

### A.1.1. Barriers

**Institutional setting**

- Current regulation/standards
- Strict standards
- No exception on standards/non-flexible
- General standards
- Responsibility NBS/CAS
- Maintenance division
- Uncertainty
- Political choices
- Unfavourable local conditions
- Housing demand
- Short-term vision

**Availability of (financial) resources**

- Lack of funds
- Focus on efficiency & effectiveness
- Maintenance
- Cheap & reliable drinking water
- Underground infrastructure
- Private property

**Level of expertise, competence**

- Lack of expertise in models
- Lack of expertise ecology
- Lack of expertise soil
- Execution construction NBS/CAS
- No updated maintenance manual
- Habits/customs
- Too many unproven plans

**Collaborative governance and planning**

- Communication
- No cooperation
- No early involvement maintenance
- Lack of trust between stakeholders
- Conflicting interests climate aspects

### A.1.2. Enablers

- Strict standards
- Clear standards
- Bandwidth in standards
- Specified standards
- Goal oriented standards
- Flexible standards
- Watertoets
- Development plan
- Water authority
- Involved municipality members
- Ambition
- Awareness inhabitants
- Political choices
- Flexible urban planning
- Corporate values

**Availability of (financial) resources**

- Funds
- Commercial value
- Aesthetic value
- Improvement livability
- Ecological value
- Climate robustness
- Bad (river) water quality

**Other barriers**

- Low permeability soil
- High groundwater
- Low groundwater
- Subsidence

**Level of expertise, competence**

- Expertise in ecology
- Performance labels
- Model/tool representing system functioning
- Stresstest
- Proven innovations/implementations
- Experience
- Monitoring
- Educative maps

**Collaborative governance and planning**

- Measures addressing multiple climate aspects
- Early involvement maintenance department
- Communication
- Tailored policy
- Tailored urban planning
- Network for knowledge
- Trust between stakeholders
- Cooperation

## A.2. Themes

There were four themes identified by Voskamp et al. (2021). These themes served as a basis for categorizing *barriers* and *enablers*. In this section a more extensive description is provided that is used for the categorization.

**Institutional setting**

- Awareness (politicians and municipal members)
- Responsibility
- Regulatory conditions
- Politics

**Availability of (financial) resources**

- Funding
- Lack of space
- Resources

**Level of expertise, competence**

- Knowledgeable personnel
- Way of working
- Cost/benefit consideration
- Available models/tools

**Collaborative governance and planning**

- Collaboration
- Engagement stakeholders
- Siloed governance structures

## A.3. List of questions

### A.3.1. Interview questions

This section presents the questions (in Dutch) that are used to structure the interview. They are not a literal guide, but instead make sure to roughly collect the same information in every interview. In practice every interview is specified to the interviewee.

1. *Kunt u me wat meer vertellen over het project en waar u zich mee bezig houdt?*
2. *Wat voor een dingen kom je tegen bij het ontwikkelen van een klimaatadaptieve wijk?*
3. *Wat zijn incentives/aansporingen om klimaatadaptieve maatregelen toe te passen?*
4. *Is het convenant werkbaar?*
5. *Bij welk van de drie klimaataspecten (hittestress, wateroverlast, droogte) is het lastigste de normen te halen?*
6. *Hoe controleer je of je plannen wel echt de gestelde doelen halen?* vervolg: *Maak je gebruik van hulpmiddelen (online tools, kaarten, modellen, etc)*
7. *Wat is voor u de grootste drempel in het proces?*
8. *Wie zijn nog meer van belang in het project?*

### A.3.2. Poll questions

This section presents the questions and possible answers (in Dutch) that are used to structure the poll in the focus groups. For question 1, 2, 6 & 7 multiple answers were possible, for 3 & 4 only one answer.

1. *Het belangrijkste obstakel in het geval van klimaatadaptatie is?*
    - Financiële middelen
    - Ondergrondse infrastructuur
    - Gewoontes/cultuur
    - Onderhoud
    - Uitvoering aanleg klimaatadaptieve oplossing
    - Tegengestelde belangen verschillende klimaataspecten
    - Beperkte doorlaatbaarheid grond
2. *De belangrijkste stimulans voor klimaatadaptatie is?*
    - Integrale oplossingen voor klimaataspecten
    - Duidelijke normen
    - Normen die een doel voorschrijven
    - Een model of tool die de werking van het natuurlijke systeem visualiseert
    - Ecologische waarde
    - Ambitie
    - Klimaatrobuust zijn
    - Strenge normen
    - Communicatie
    - Beleid op maat
    - Netwerk voor kennis
3. *Normen die een doel voorschrijven zijn beter dan middelvoorschriften*
    - Ja
    - Nee
    - Niet altijd
4. *Strenge normen die wettelijk zijn vastgelegd zijn een obstakel of een stimulans?*
    - Obstakel
    - Stimulans
    - Beide
5. *Een ideale norm geeft veel creatieve vrijheid of is gespecificeerd?*
    - Creatieve vrijheid
    - Gespecificeerd
    - Beide
6. *Bij welk thema ervaar je de meeste obstakels?*
    - Politieke/intitutionele bereidheid
    - Beschikking tot (financiële) middelen
    - Kennis/bekwaamheid
    - Samenwerking tussen afdelingen/disciplines

7. *Bij welk thema ervaar je de meeste stimulansen?*
    - Politieke/intitutionele bereidheid
    - Beschikking tot (financiële) middelen
    - Kennis/bekwaamheid
    - Samenwerking tussen afdelingen/disciplines

# B

# Soil and crop parameters

Table B.1: Types of soil that can be simulated by the **UrbanWB** model with corresponding key number codes

| Soil name | Key number |
|---|---|
| Veengrond met veraarde bovengrond | 1 |
| Veengrond met veraarde bovengrond, zand | 2 |
| Veengrond met kleidek | 3 |
| Veengrond met kleidek op zand | 4 |
| Veengrond met zanddek op zand | 5 |
| Veengrond op ongerijpte klei | 6 |
| Stuifzand | 7 |
| Podzol (leemarm, fijn zand) | 8 |
| Podzol (zwak lemig, fijn zand) | 9 |
| Podzol (zwak lemig, fijn zand op grof zand) | 10 |
| Podzol (lemig keileem) | 11 |
| Enkeerd (zwak lemig, fijn zand) | 12 |
| Beekeerd (lemig fijn zand) | 13 |
| Podzol (grof zand) | 14 |
| Zavel | 15 |
| Lichte klei | 16 |
| Zware klei | 17 |
| Klei op veen | 18 |
| Klei op zand | 19 |
| Klei op grof zand | 20 |
| Leem | 21 |

Table B.2: Type of plants that can be simulated by the **UrbanWB** model with corresponding key number codes

| Crop name | Key number |
|---|---|
| Grass | 1 |
| Corn | 2 |
| Potatoes | 3 |
| Sugarbeet | 4 |
| Grain | 5 |
| Miscellaneous | 6 |
| Non-arable land | 7 |
| Greenhouse area | 8 |
| Orchard | 9 |
| Bulbous plants | 10 |
| Foliage forest | 11 |
| Pine forest | 12 |
| Nature | 13 |
| Fallow | 14 |
| Vegetables | 15 |
| Flowers | 16 |

# C

# PET reduction

Table C.1: Decrease in PET for measures in AST, *bron: ASTdocumentation* adapted from *Kluck2020*.

| **Adaptation interventions** | **PET reduction [%]** |
|---|---|
| Adding trees | 75 |
| Bioretention cell | 10 |
| Bioswales (with drainage) | 10 |
| Cool building materials | 10 |
| Cooling with water elements: ponds | 10 |
| Create extra surface water | 10 |
| Creating shade | 75 |
| Deep groundwater infiltration | 0 |
| Ditch and swales | 10 |
| Drought resistance species | 0 |
| Extensive green roof | 10 |
| Extra intensive green roof | 10 |
| Floating puri-plants | 10 |
| Fountains, waterfalls, water facades | 25 |
| Green facades | 10 |
| Infiltration boxes | 0 |
| Infiltration field and strips with surface storage | 10 |
| Infiltration trench | 10 |
| Permeable pavement systems (storage) | 0 |
| Permeable pavement systems (infiltration) | 0 |
| Private green garden | 25 |
| Rain barrels | 0 |
| Rain gardens | 10 |
| Rainwater detention pond (wet pond) | 10 |
| Rainwater storage below buildings | 0 |
| Remove pavement to plant green | 10 |
| Urban agriculture | 10 |
| Urban forest | 75 |
| Urban parks | 75 |
| Urban wetland | 25 |
| Water roof | 10 |
| Water square | 0 |
| Wetting surfaces (of gardens, roofs, roads) | 25 |

# D

# Input files

## D.1. Neighbourhood input file

```
# This is a TOML-format neighbourhood (base) configuration file.
# [-] indicates fraction, please type 0.75 to represent 75%.


title = ”Neighbourhood config Amstelwijck I”

###########
# overall #
###########

# timestep length [s]
timestep = 3600

# soil type and crop type
soiltype = 18
croptype = 1

# total area of study area[m2]
tot_area = 74795
# area input type [0: fraction(default), 1: area]
area_type = 1


##############
# paved roof #
##############

# total area of paved roof [m2]
# paved roof fraction of total [-]
# part of buildings above Groundwater [-]
# part of paved roof disconnected from sewer system [-]
# interception storage capacity on paved roof [mm]
# initial interception storage on paved roof (at t=0) [mm]

tot_pr_area = 12878
pr_frac = 0.172
frac_pr_aboveGW = 1
discfrac_pr = 0
```

```
intstorcap_pr = 1.6
intstor_pr_t0 = 0


################
# closed paved #
################

# total area of closed paved [m2]
# closed paved fraction of total [-]
# part of closed paved disconnected from sewer system [-]
# interception storage capacity on closed paved [mm]
# initial interception storage on closed paved (at t=0) [mm]

tot_cp_area = 18259
cp_frac = 0.244
discfrac_cp = 0
intstorcap_cp = 1.6
intstor_cp_t0 = 0


##############
# open paved #
##############

# total area of open paved [m2]
# open paved fraction of total [-]
# part of open paved disconnected from sewer system [-]
# interception storage capacity on open paved [mm]
# infiltration capacity on open paved [mm/d]
# initial interception storage on open paved (at t=0) [mm]

tot_op_area = 6482
op_frac = 0.087
discfrac_op = 0
intstorcap_op = 1.6
infilcap_op = 10.9
intstor_op_t0 = 0


###########
# unpaved #
###########

# total area of unpaved [m2]
# unpaved fraction of total [-]
# interception storage capacity on unpaved [mm]
# infiltration capacity on unpaved [mm/d]
# initial final remaining interception storage on unpaved (at t=0) [mm]

tot_up_area = 31069
up_frac = 0.415
intstorcap_up = 20
infilcap_up = 480
fin_intstor_up_t0 = 0
```

```
####################
# unsaturated zone #
####################

# parameters for unsaturated zone are endogenous


###############
# groundwater #
###############

# groundwater area is endogenous, calculated from the formula
# tot_gw_area = tot_area * gw_frac = tot_area * (pr_frac * frac_pr_aboveGW
# + cp_frac + op_frac + up_frac + ow_frac * frac_ow_aboveGW)
# drainage resistance from groundwater to open water (w) [d]
# seepage to deep groundwater defined as either constant downward flux
# or dynamic computed flux determined by head difference and resistance [0=flux; 1=level]
# constant downward flux from shallow groundwater to deep groundwater [mm/d]
# hydraulic head of deep groundwater [m-SL]
# vertical flow resistance from shallow groundwater to deep groundwater (vc) [d]
# initial groudwater level (at t=0), usually taken as
# target water level, relating to ”storcap_ow” [m-SL]

w = 100
seepage_define = 1
down_seepage_flux = -0.5
head_deep_gw = 0.2
vc = 4000
gwl_t0 = 1.50


##############
# open water #
##############

# total area of open water [m^2]
# open water fraction of total [-]
# part of open water above Groundwater [-]
# storage capacity of open water (divided by 1000 is target open water level) [mm]
# predefined discharge capacity from open water (internal) to
# outside water (external) [mm/d over total area]

tot_ow_area = 6107
ow_frac = 0.082
frac_ow_aboveGW = 0
storcap_ow = 1600
q_ow_out_cap = 14.4


################
```

## D.2. Measure input file

```
# This is a TOML-format configuration file that contains
# all the input parameters of measure.
# Measure can be implemented as 1-layer, 2-layer or 3-layer structure.
# A 3-layer measure has interception layer (1), top storage layer (2)
# and bottom storage layer (3).
# Since there are many buttons in Measure, 0-1 is applied to represent No-
Yes, except for ”measure_applied” button which uses false-true.

title = ”Bioswale Amstelwijck I”


##################
# Apply measure? #
##################

# Apply measure or not [true: applied, false: not applied]
measure_applied = true

# Greenroof-alike measure is different from a general measure
greenroof_type_measure = false

####################
# Area information #
####################

# total area of measure [m^2]
tot_meas_area = 2410

# area of xx with measure (xx --> PR, CP, OP, UP, UZ, GW, SWDS, MSS, OW) [m2]
pr_meas_area = 0
cp_meas_area = 0
op_meas_area = 410
up_meas_area = 2000
uz_meas_area = 0
gw_meas_area = 0
swds_meas_area = 0
mss_meas_area = 0
ow_meas_area = 0

# runoff inflow area from xx to measure,
# i.e. measure inflow area from xx (xx --> PR, CP, OP, UP, OW) [m^2],
# OW not yet possible.
pr_meas_inflow_area = 7215
cp_meas_inflow_area = 8999
op_meas_inflow_area = 5589
up_meas_inflow_area = 21508
ow_meas_inflow_area = 0


#####################################
# Number of layer, Active processes #
#####################################

# number of storage layers [1, 2 or 3]
num_stor_lvl = 3
```

```
# Selection at which measure layer runoff from other area is stored,
# interception layer (1) or bottom storage layer (3) [1 or 3]
runoff_to_stor_layer = 1

# Selection if evaporation from measure (interception layer)
# is possible (1) or not (0) [0 or 1]
EV_evaporation = 1

# Selection if transpiration from measure (bottom layer, top layer if applicable)
# is possible (1) or not (0) [0 or 1]
ET_transpiration = 1

# Selection if infiltration from measure is possible (1) or not (0) [0 or 1]
IN_infiltration = 1

# Selection if slow drainage (delay) from measure is possible (1) or not (0) [0 or 1]
SD_delay = 1

# Selection if fast drainage (pumping) from measure is possible (1) or not (0) [0 or 1]
FD_pumping = 0

###############################
# Water from measure flows to #
###############################

# Water from measure flows to xx [0: No, 1: Yes]

# surface runoff from measure interception layer to OW
# runoff from measure bottom storage layer to OW
# overflow from measure bottom storage layer to OW

# surface runoff from measure interception layer to UZ
# runoff from measure bottom storage layer to UZ
# overflow from measure bottom storage layer to UZ

# surface runoff from measure interception layer to GW
# runoff from measure bottom storage layer to GW
# overflow from measure bottom storage layer to GW

# surface runoff from measure interception layer to SWDS
# runoff from measure bottom storage layer to SWDS
# overflow from measure bottom storage layer to SWDS

# surface runoff from measure interception layer to MSS
# runoff from measure bottom storage layer to MSS
# overflow from measure bottom storage layer to MSS

# surface runoff from measure interception layer to Out
# runoff from measure bottom storage layer to Out
# overflow from measure bottom storage layer to Out

surf_runoff_meas_OW = 0
ctrl_runoff_meas_OW = 1
overflow_meas_OW = 1
```

```
surf_runoff_meas_UZ = 0
ctrl_runoff_meas_UZ = 0
overflow_meas_UZ = 0

surf_runoff_meas_GW = 0
ctrl_runoff_meas_GW = 1
overflow_meas_GW = 0

surf_runoff_meas_SWDS = 0
ctrl_runoff_meas_SWDS = 0
overflow_meas_SWDS = 0

surf_runoff_meas_MSS = 0
ctrl_runoff_meas_MSS = 0
overflow_meas_MSS = 0

surf_runoff_meas_Out = 0
ctrl_runoff_meas_Out = 0
overflow_meas_Out = 0

#####################
# Measure structure #
#####################

# Measure can be defined as 1-layer (only interception layer), 2-layer
# (interception layer + bottom storage layer), or 3-layer (interception layer
# + top storage layer + bottom storage layer).

######################
# Interception layer #
######################

# storage capacity of interception layer of measure [mm]
# infiltration capacity of interception layer of measure [mm/d]
# initial storage in interception layer of measure (at t=0) [mm]

storcap_int_meas = 20
infilcap_int_meas = 2000
intstor_meas_t0 = 0

#####################
# Top storage layer #
#####################

# area of top storage layer of measure [m2]
# storage capacity of top storage layer of measure [mm]
# infiltration capacity of top storage layer of measure [mm/d]
# initial storage in top storage layer of measure (at t=0) [mm]

top_meas_area = 2410
storcap_top_meas = 100
infilcap_top_meas = 2000
stor_top_meas_t0 = 0

########################
# Bottom storage layer #
```

```
########################

# area of bottom storage layer of measure [m2]
btm_meas_area = 2410

# storage capacity of bottom storage layer of measure [mm]
storcap_btm_meas = 310

# percolation (connection) from measure bottom storage layer to
# groundwater is possible (1) or not (0) [0 or 1]
connection_to_gw = 1

# limitation of percolation from measure to groundwater if groundwater level
# is below measure bottom level, limited (1) or unlimited (0) [0 or 1]
limited_by_gwl = 0

# bottom level of measure [m-SL]
btm_level_meas = 1.18

# selection if transpiration from bottom storage layer of measure
# is possible (1) or not (0) [0 or 1]
btm_meas_transpiration = 1

# discharge type from bottom storage layer of measure [0: flux or 1: level]
btm_discharge_type = 0

# runoff capacity from bottom storage layer of measure [mm/d]
runoffcap_btm_meas = 600

# discharge level from bottom storage layer of measure [mm]
dischlvl_btm_meas = 430

# hydraulic resistance for level induced discharge from
# bottom storage layer of measure [d]
c_btm_meas = 2

# initial storage in bottom storage layer (at t=0) [mm]
stor_btm_meas_t0 = 0

# evaporation factor of measure [-]
evaporation_factor_meas = 0.8982


#################
# Other Buttons #
#################
```

# E

# Sensitivity analysis data

## E.1. Hydrological uncertainty

### E.1.1. Type of crop

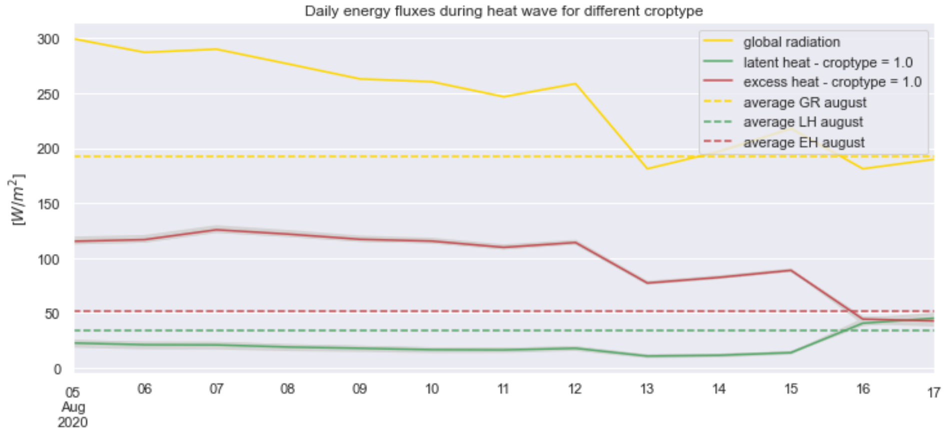


Figure E.1: Daily averages for energy fluxes during a heat wave and averages for the same period in August 2020 for different $croptype$: *global radiation*, *latent heat* flux and *excess heat* flux (= potential LH - actual LH).

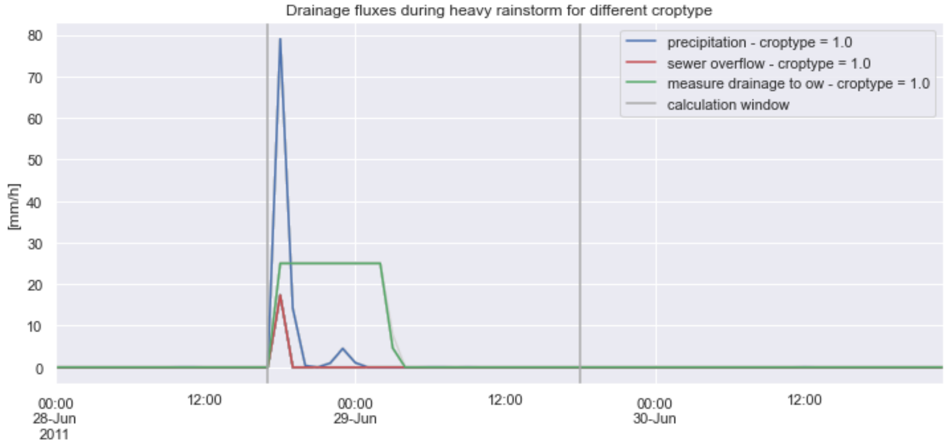


Figure E.2: Drainage fluxes during an extreme precipitation event (June 28, 2011) for different $croptype$: precipitation, **sewer** overflow and **measure** drainage.

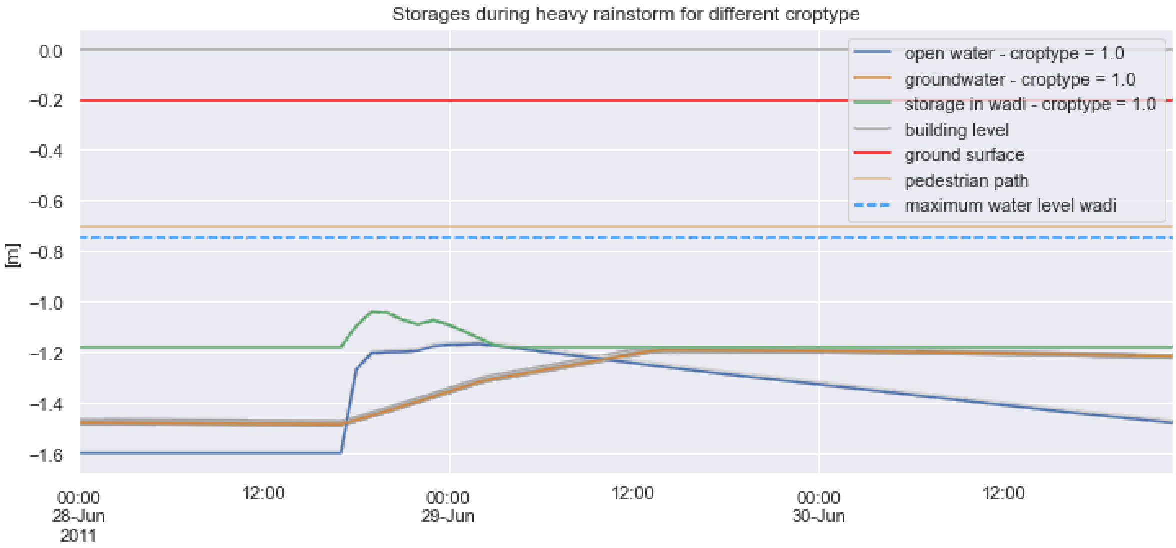


Figure E.3: Storage during an extreme precipitation event (June 28, 2011) for different $croptype$: **open water** level, **groundwater** level and water level in **measure**.

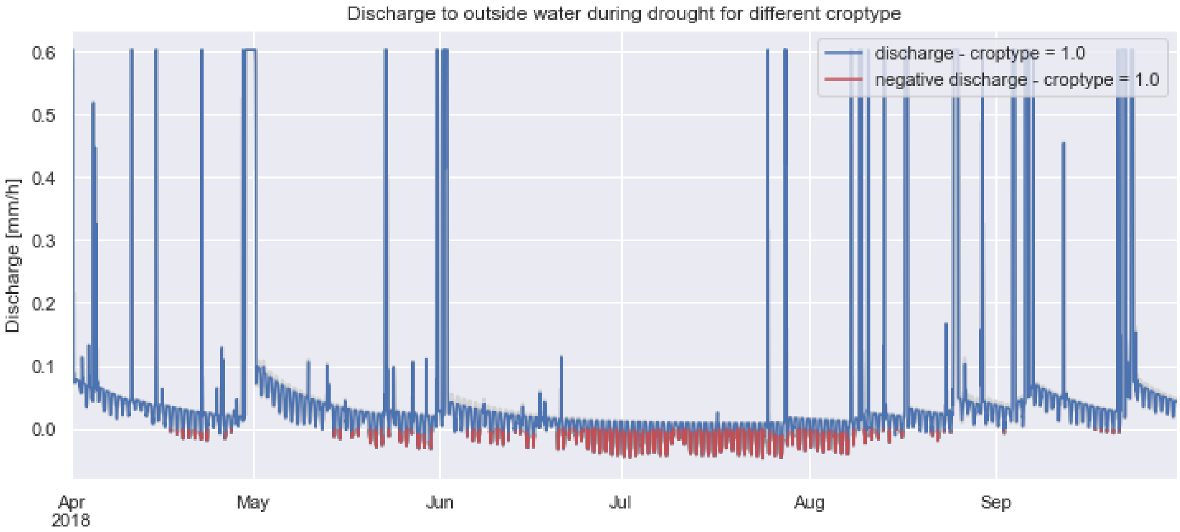


Figure E.4: Discharge from **open water** to **outside water** during drought year (2018) for different $croptype$: positive discharge, negative discharge (inlet) and **groundwater** influx.

Table E.1: *Heat stress* and *drought* indicators for different $croptype$.

| Crop type # | Crop type | Latent heat | Excess heat | Inlet | Disch. out |
|---|---|---|---|---|---|
| 1 | Grass | 21.1 $W/m^2$ | 97.7 $W/m^2$ | 15.8 $mm$ | 224.7 $mm$ |
| 2 | Corn | 21.2 $W/m^2$ | 97.6 $W/m^2$ | 15.7 $mm$ | 225.3 $mm$ |
| 3 | Potatoes | 21.8 $W/m^2$ | 96.9 $W/m^2$ | 15.8 $mm$ | 224.1 $mm$ |
| 4 | Sugarbeet | 21.8 $W/m^2$ | 96.9 $W/m^2$ | 15.8 $mm$ | 224.1 $mm$ |
| 5 | Grain | 21.4 $W/m^2$ | 97.2 $W/m^2$ | 15.8 $mm$ | 222.5 $mm$ |
| 6 | Miscellaneous | 21.4 $W/m^2$ | 97.4 $W/m^2$ | 15.8 $mm$ | 222.5 $mm$ |
| 7 | Non-arable land | 21.4 $W/m^2$ | 97.4 $W/m^2$ | 15.8 $mm$ | 222.5 $mm$ |
| 8 | Greenhouse area | 21.2 $W/m^2$ | 97.6 $W/m^2$ | 15.7 $mm$ | 225.3 $mm$ |
| 9 | Orchard | 21.1 $W/m^2$ | 97.7 $W/m^2$ | 15.8 $mm$ | 224.7 $mm$ |
| 10 | Bulbous plants | 21.1 $W/m^2$ | 97.7 $W/m^2$ | 15.8 $mm$ | 224.7 $mm$ |
| 11 | Foliage forest | 21.1 $W/m^2$ | 97.7 $W/m^2$ | 15.8 $mm$ | 224.7 $mm$ |
| 12 | Pine forest | 21.1 $W/m^2$ | 97.7 $W/m^2$ | 15.8 $mm$ | 224.7 $mm$ |
| 13 | Nature | 21.1 $W/m^2$ | 97.7 $W/m^2$ | 15.8 $mm$ | 224.7 $mm$ |
| 14 | Fallow | 19.8 $W/m^2$ | 98.9 $W/m^2$ | 14.0 $mm$ | 237.8 $mm$ |
| 15 | Vegetables | 20.8 $W/m^2$ | 98.0 $W/m^2$ | 15.5 $mm$ | 227.1 $mm$ |
| 16 | Flowers | 20.6 $W/m^2$ | 98.2 $W/m^2$ | 15.4 $mm$ | 228.4 $mm$ |

Table E.2: *Pluvial flooding* indicators for different $croptype$.

| Crop type # | Crop type | Tot. prec. | Tot. SO | Tot. drain. | Max. OW | Max. GW | Max. meas. |
|---|---|---|---|---|---|---|---|
| 1 | Grass | 100.4 $mm$ | 8.7 $mm$ | 7.4 $mm$ | -1.17 $m$ | -1.19 $m$ | -1.04 $m$ |
| 2 | Corn | 100.4 $mm$ | 8.7 $mm$ | 7.4 $mm$ | -1.17 $m$ | -1.19 $m$ | -1.04 $m$ |
| 3 | Potatoes | 100.4 $mm$ | 8.7 $mm$ | 7.4 $mm$ | -1.17 $m$ | -1.19 $m$ | -1.04 $m$ |
| 4 | Sugarbeet | 100.4 $mm$ | 8.7 $mm$ | 7.4 $mm$ | -1.17 $m$ | -1.19 $m$ | -1.04 $m$ |
| 5 | Grain | 100.4 $mm$ | 8.7 $mm$ | 7.4 $mm$ | -1.17 $m$ | -1.20 $m$ | -1.04 $m$ |
| 6 | Miscellaneous | 100.4 $mm$ | 8.7 $mm$ | 7.4 $mm$ | -1.17 $m$ | -1.20 $m$ | -1.04 $m$ |
| 7 | Non-arable land | 100.4 $mm$ | 8.7 $mm$ | 7.4 $mm$ | -1.17 $m$ | -1.20 $m$ | -1.04 $m$ |
| 8 | Greenhouse area | 100.4 $mm$ | 8.7 $mm$ | 7.4 $mm$ | -1.17 $m$ | -1.19 $m$ | -1.04 $m$ |
| 9 | Orchard | 100.4 $mm$ | 8.7 $mm$ | 7.4 $mm$ | -1.17 $m$ | -1.19 $m$ | -1.04 $m$ |
| 10 | Bulbous plants | 100.4 $mm$ | 8.7 $mm$ | 7.4 $mm$ | -1.17 $m$ | -1.19 $m$ | -1.04 $m$ |
| 11 | Foliage forest | 100.4 $mm$ | 8.7 $mm$ | 7.4 $mm$ | -1.17 $m$ | -1.19 $m$ | -1.04 $m$ |
| 12 | Pine forest | 100.4 $mm$ | 8.7 $mm$ | 7.4 $mm$ | -1.17 $m$ | -1.19 $m$ | -1.04 $m$ |
| 13 | Nature | 100.4 $mm$ | 8.7 $mm$ | 7.4 $mm$ | -1.17 $m$ | -1.19 $m$ | -1.04 $m$ |
| 14 | Fallow | 100.4 $mm$ | 8.7 $mm$ | 7.5 $mm$ | -1.16 $m$ | -1.19 $m$ | -1.04 $m$ |
| 15 | Vegetables | 100.4 $mm$ | 8.7 $mm$ | 7.4 $mm$ | -1.17 $m$ | -1.19 $m$ | -1.04 $m$ |
| 16 | Flowers | 100.4 $mm$ | 8.7 $mm$ | 7.4 $mm$ | -1.17 $m$ | -1.19 $m$ | -1.04 $m$ |

## E.1.2. Type of soil

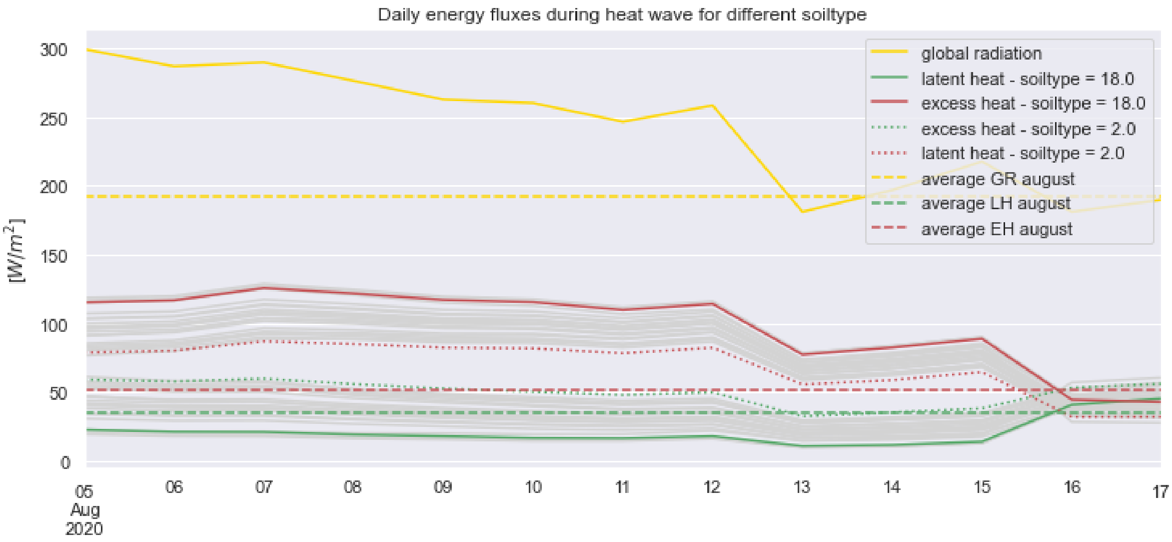


Figure E.5: Daily averages for energy fluxes during a heat wave and averages for the same period in August 2020 for different $soiltype$: *global radiation*, *latent heat* flux and *excess heat* flux (= potential LH - actual LH).

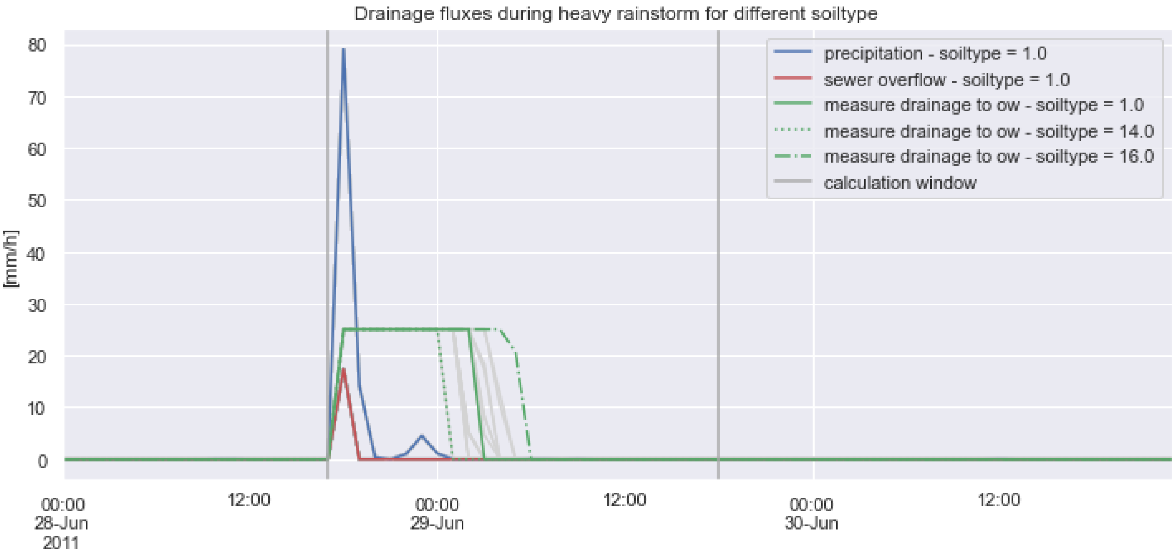


Figure E.6: Drainage fluxes during an extreme precipitation event (June 28, 2011) for different $soiltype$: precipitation, **sewer** overflow and **measure** drainage.

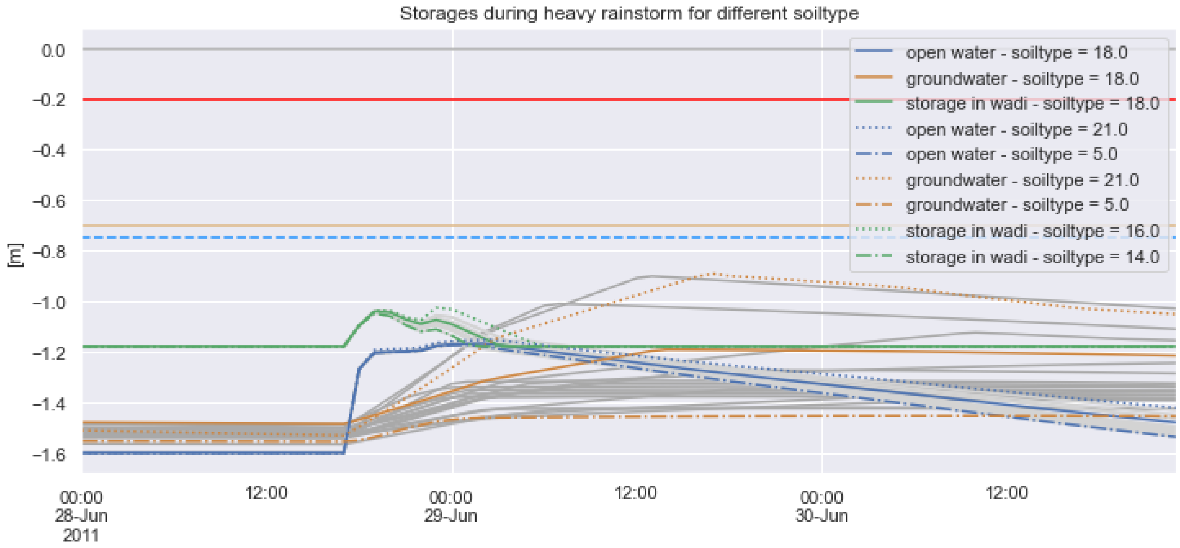


Figure E.7: Storage during an extreme precipitation event (June 28, 2011) for different $soiltype$: **open water** level, **groundwater** level and water level in **measure**.

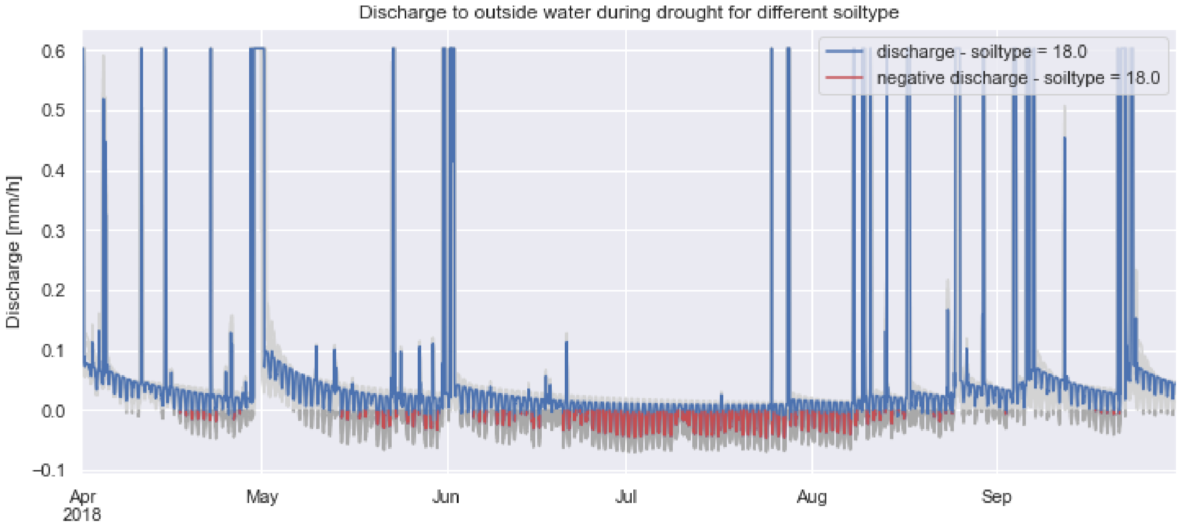


Figure E.8: Discharge from **open water** to **outside water** during drought year (2018) for different $soiltype$: positive discharge, negative discharge (inlet) and **groundwater** influx.

Table E.3: *Heat stress* and *drought* indicators for different $soiltype$.

| **Soil type #** | **Soil type** | **Latent heat** | **Excess heat** | **Inlet** | **Disch. out** |
|---|---|---|---|---|---|
| 1 | Peat mixed | 36.4 $W/m^2$ | 82.4 $W/m^2$ | 24.0 $mm$ | 189.6 $mm$ |
| 2 | Peat/sand mixture | 49.8 $W/m^2$ | 69.0 $W/m^2$ | 33.9 $mm$ | 172.5 $mm$ |
| 3 | Peat with clay | 31.6 $W/m^2$ | 87.2 $W/m^2$ | 23.6 $mm$ | 200.0 $mm$ |
| 4 | Peat with clay on sand | 38.2 $W/m^2$ | 80.6 $W/m^2$ | 32.9 $mm$ | 187.5 $mm$ |
| 5 | Peat on sand | 41.1 $W/m^2$ | 77.6 $W/m^2$ | 26.9 $mm$ | 170.7 $mm$ |
| 6 | Peat on clay | 25.8 $W/m^2$ | 92.9 $W/m^2$ | 18.9 $mm$ | 213.6 $mm$ |
| 7 | Loose sand | 25.5 $W/m^2$ | 93.2 $W/m^2$ | 19.5 $mm$ | 191.4 $mm$ |
| 8 | Fine sand | 33.2 $W/m^2$ | 85.6 $W/m^2$ | 25.1 $mm$ | 167.8 $mm$ |
| 9 | Fine sand, loamy | 43.0 $W/m^2$ | 75.8 $W/m^2$ | 35.7 $mm$ | 169.8 $mm$ |
| 10 | Fine sand on coarse sand | 35.9 $W/m^2$ | 82.8 $W/m^2$ | 24.3 $mm$ | 177.5 $mm$ |
| 11 | Boulder clay | 28.5 $W/m^2$ | 90.2 $W/m^2$ | 19.1 $mm$ | 189.4 $mm$ |
| 12 | Enkeerd | 46.4 $W/m^2$ | 72.4 $W/m^2$ | 41.3 $mm$ | 168.7 $mm$ |
| 13 | Beekeerd | 33.6 $W/m^2$ | 85.2 $W/m^2$ | 24.7 $mm$ | 178.5 $mm$ |
| 14 | Coarse sand | 19.3 $W/m^2$ | 99.5 $W/m^2$ | 11.1 $mm$ | 211.3 $mm$ |
| 15 | Coarse sand with clay | 44.0 $W/m^2$ | 74.8 $W/m^2$ | 49.4 $mm$ | 193.3 $mm$ |
| 16 | Light clay | 34.4 $W/m^2$ | 84.4 $W/m^2$ | 31.2 $mm$ | 205.7 $mm$ |
| 17 | Heavy clay | 19.6 $W/m^2$ | 99.1 $W/m^2$ | 16.9 $mm$ | 233.2 $mm$ |
| 18 | Clay on peat | 21.1 $W/m^2$ | 97.7 $W/m^2$ | 15.8 $mm$ | 224.7 $mm$ |
| 19 | Clay on sand | 46.9 $W/m^2$ | 71.9 $W/m^2$ | 42.6 $mm$ | 184.0 $mm$ |
| 20 | Clay on coarse sand | 29.0 $W/m^2$ | 89.8 $W/m^2$ | 15.5 $mm$ | 212.4 $mm$ |
| 21 | Loam | 42.3 $W/m^2$ | 73.5 $W/m^2$ | 60.6 $mm$ | 198.4$mm$ |

Table E.4: *Pluvial flooding* indicators for different $soiltype$.

| **Soil type** | **Tot. prec.** | **Tot. SO** | **Tot. drain.** | **Max. OW** | **Max. GW** | **Max. meas.** |
|---|---|---|---|---|---|---|
| Peat mixed | 100.4 $mm$ | 8.7 $mm$ | 7.3 $mm$ | -1.17 $m$ | -1.33 $m$ | -1.04 $m$ |
| Peat/sand mixture | 100.4 $mm$ | 8.7 $mm$ | 7.3 $mm$ | -1.17 $m$ | -1.42 $m$ | -1.04 $m$ |
| Peat with clay | 100.4 $mm$ | 8.7 $mm$ | 7.5 $mm$ | -1.17 $m$ | -1.27 $m$ | -1.04 $m$ |
| Peat with clay on sand | 100.4 $mm$ | 8.7 $mm$ | 7.5 $mm$ | -1.17 $m$ | -1.35 $m$ | -1.04 $m$ |
| Peat on sand | 100.4 $mm$ | 8.7 $mm$ | 6.6 $mm$ | -1.17 $m$ | -1.45 $m$ | -1.04 $m$ |
| Peat on clay | 100.4 $mm$ | 8.7 $mm$ | 7.3 $mm$ | -1.16 $m$ | -1.01 $m$ | -1.04 $m$ |
| Loose sand | 100.4 $mm$ | 8.7 $mm$ | 6.4 $mm$ | -1.17 $m$ | -1.35 $m$ | -1.04 $m$ |
| Fine sand | 100.4 $mm$ | 8.7 $mm$ | 5.6 $mm$ | -1.17 $m$ | -1.38 $m$ | -1.05 $m$ |
| Fine sand, loamy | 100.4 $mm$ | 8.7 $mm$ | 6.6 $mm$ | -1.17 $m$ | -1.38 $m$ | -1.04 $m$ |
| Fine sand on coarse sand | 100.4 $mm$ | 8.7 $mm$ | 6.6 $mm$ | -1.17 $m$ | -1.42 $m$ | -1.04 $m$ |
| Boulder clay | 100.4 $mm$ | 8.7 $mm$ | 6.4 $mm$ | -1.17 $m$ | -1.32 $m$ | -1.04 $m$ |
| Enkeerd | 100.4 $mm$ | 8.7 $mm$ | 6.6 $mm$ | -1.17 $m$ | -1.36 $m$ | -1.04 $m$ |
| Beekeerd | 100.4 $mm$ | 8.7 $mm$ | 6.4 $mm$ | -1.17 $m$ | -1.36 $m$ | -1.04 $m$ |
| Coarse sand | 100.4 $mm$ | 8.7 $mm$ | 5.6 $mm$ | -1.17 $m$ | -1.34 $m$ | -1.05 $m$ |
| Coarse sand with clay | 100.4 $mm$ | 8.7 $mm$ | 8.4 $mm$ | -1.16 $m$ | -1.12 $m$ | -1.04 $m$ |
| Light clay | 100.4 $mm$ | 8.7 $mm$ | 9.5 $mm$ | -1.16 $m$ | -1.25 $m$ | -1.03 $m$ |
| Heavy clay | 100.4 $mm$ | 8.7 $mm$ | 7.4 $mm$ | -1.16 $m$ | -0.90 $m$ | -1.04 $m$ |
| Clay on peat | 100.4 $mm$ | 8.7 $mm$ | 7.4 $mm$ | -1.17 $m$ | -1.20 $m$ | -1.04 $m$ |
| Clay on sand | 100.4 $mm$ | 8.7 $mm$ | 8.5 $mm$ | -1.17 $m$ | -1.36 $m$ | -1.04 $m$ |
| Clay on coarse sand | 100.4 $mm$ | 8.7 $mm$ | 7.8 $mm$ | -1.17 $m$ | -1.39 $m$ | -1.04 $m$ |
| Loam | 100.4 $mm$ | 8.7 $mm$ | 7.8 $mm$ | -1.15 $m$ | -0.89 $m$ | -1.04 $m$ |

### E.1.3. Drainage resistance in groundwater

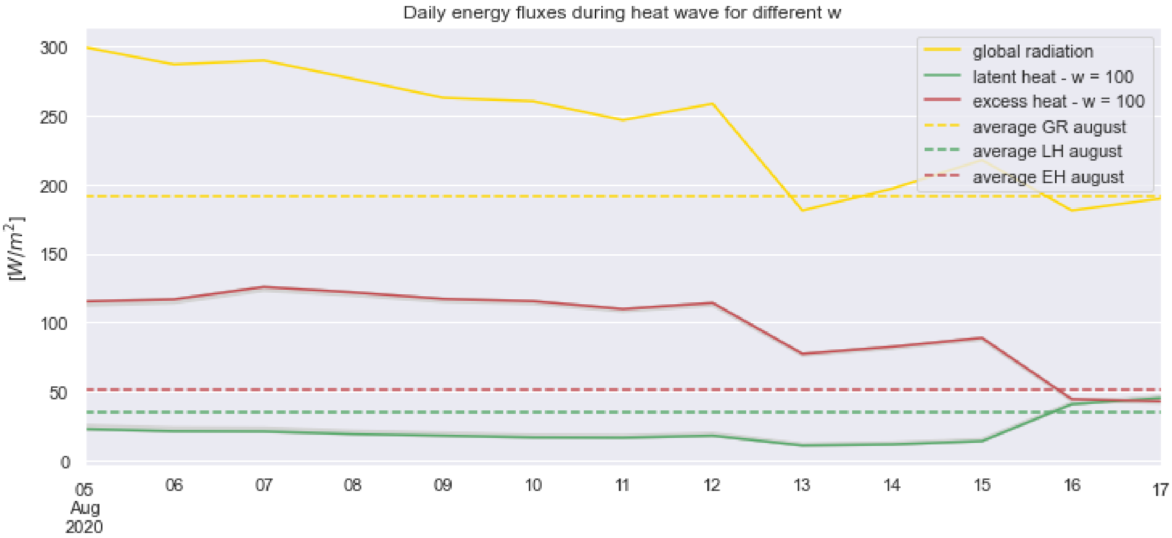


Figure E.9: Daily averages for energy fluxes during a heat wave and averages for the same period in August 2020 for different $w$: *global radiation*, *latent heat* flux and *excess heat* flux (= potential LH - actual LH).

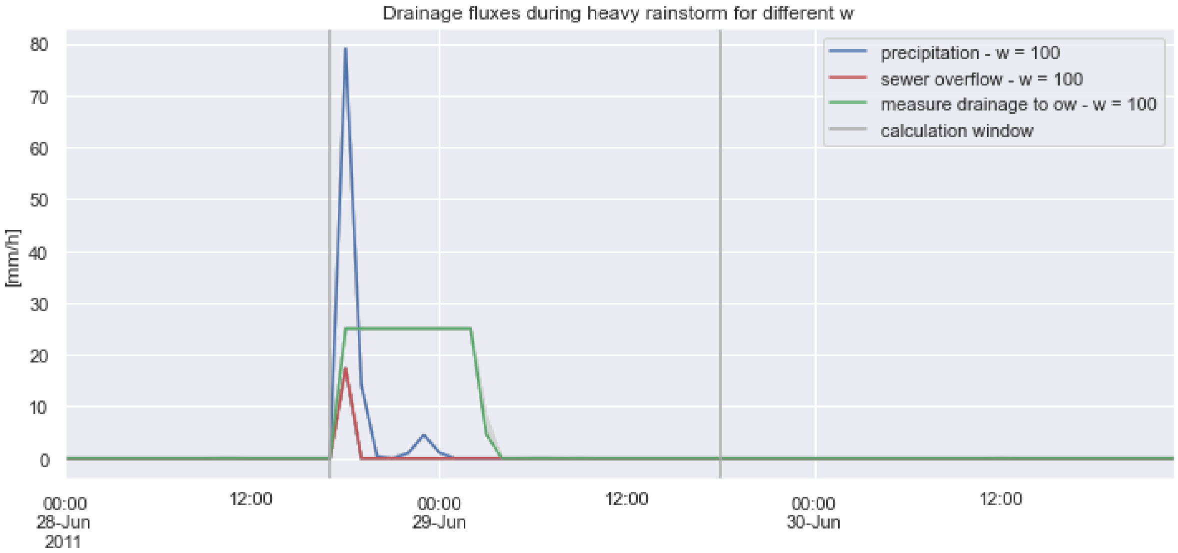


Figure E.10: Drainage fluxes during an extreme precipitation event (June 28, 2011) for different $w$: precipitation, **sewer** overflow and **measure** drainage.

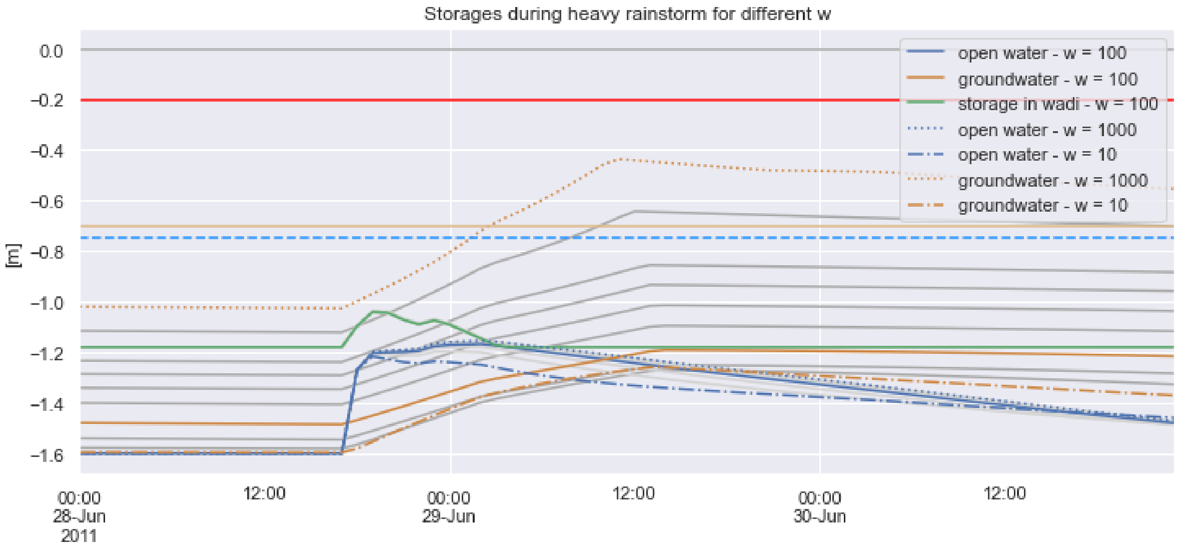


Figure E.11: Storage during an extreme precipitation event (June 28, 2011) for different $w$: **open water** level, **groundwater** level and water level in **measure**.

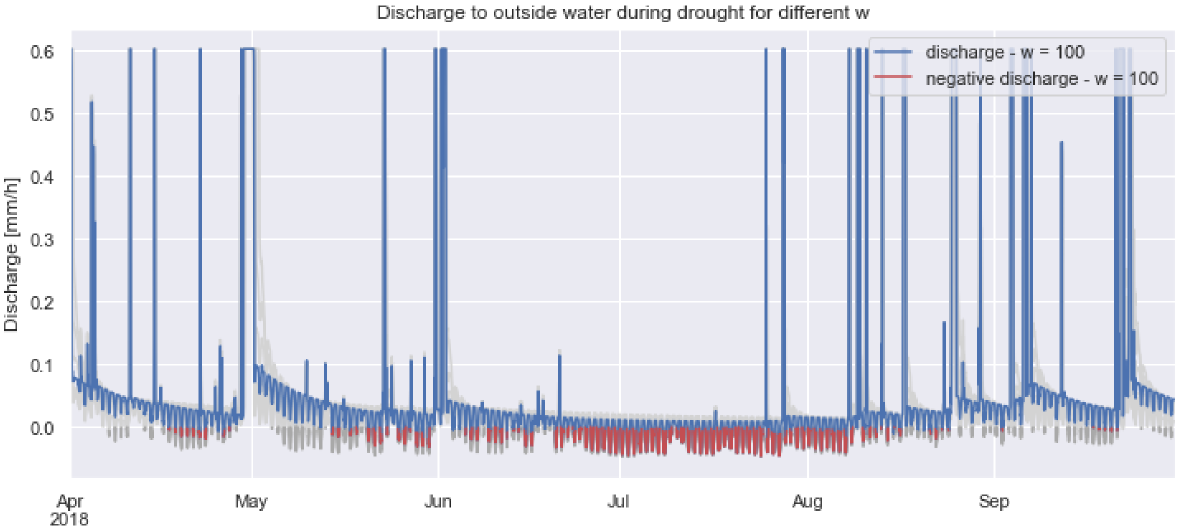


Figure E.12: Discharge from **open water** to **outside water** during drought year (2018) for different $w$: positive discharge, negative discharge (inlet) and **groundwater** influx.

Table E.5: *Heat stress* and *drought* indicators for different $w$

| w | Latent heat | Excess heat | Inlet | Disch. out |
|---|---|---|---|---|
| 10 | 25.1 $W/m^2$ | 97.9 $W/m^2$ | 25.1 $mm$ | 239.6 $mm$ |
| 25 | 25.1 $W/m^2$ | 97.8 $W/m^2$ | 20.7 $mm$ | 235.6 $mm$ |
| 50 | 25.1 $W/m^2$ | 97.8 $W/m^2$ | 17.9 $mm$ | 230.9 $mm$ |
| 100 | 25.0 $W/m^2$ | 97.7 $W/m^2$ | 15.8 $mm$ | 224.7 $mm$ |
| 200 | 24.8 $W/m^2$ | 97.5 $W/m^2$ | 13.8 $mm$ | 217.6 $mm$ |
| 300 | 24.6 $W/m^2$ | 97.2 $W/m^2$ | 12.8 $mm$ | 214.0 $mm$ |
| 400 | 24.5 $W/m^2$ | 97.0 $W/m^2$ | 12.4 $mm$ | 210.8 $mm$ |
| 500 | 24.4 $W/m^2$ | 96.8 $W/m^2$ | 12.5 $mm$ | 207.5 $mm$ |
| 750 | 24.3 $W/m^2$ | 96.2 $W/m^2$ | 13.7 $mm$ | 198.2 $mm$ |
| 1000 | 24.6 $W/m^2$ | 95.6 $W/m^2$ | 15.8 $mm$ | 189.1 $mm$ |

Table E.6: *Pluvial flooding* indicators for different $w$.

| w | Tot. prec. | Tot. SO | Tot. drain. | Max. OW | Max. GW | Max. meas. |
|---|---|---|---|---|---|---|
| 10 | 100.4 $mm$ | 8.7 $mm$ | 7.4 $mm$ | -1.22 $m$ | -1.26 $m$ | -1.04 $m$ |
| 25 | 100.4 $mm$ | 8.7 $mm$ | 7.4 $mm$ | -1.20 $m$ | -1.27 $m$ | -1.04 $m$ |
| 50 | 100.4 $mm$ | 8.7 $mm$ | 7.4 $mm$ | -1.18 $m$ | -1.25 $m$ | -1.04 $m$ |
| 100 | 100.4 $mm$ | 8.7 $mm$ | 7.4 $mm$ | -1.17 $m$ | -1.19 $m$ | -1.04 $m$ |
| 200 | 100.4 $mm$ | 8.7 $mm$ | 7.4 $mm$ | -1.16 $m$ | -1.10 $m$ | -1.04 $m$ |
| 300 | 100.4 $mm$ | 8.7 $mm$ | 7.4 $mm$ | -1.16 $m$ | -1.01 $m$ | -1.04 $m$ |
| 400 | 100.4 $mm$ | 8.7 $mm$ | 7.5 $mm$ | -1.16 $m$ | -0.93 $m$ | -1.04 $m$ |
| 500 | 100.4 $mm$ | 8.7 $mm$ | 7.5 $mm$ | -1.16 $m$ | -0.86 $m$ | -1.04 $m$ |
| 750 | 100.4 $mm$ | 8.7 $mm$ | 7.5 $mm$ | -1.16 $m$ | -0.64 $m$ | -1.04 $m$ |
| 1000 | 100.4 $mm$ | 8.7 $mm$ | 7.5 $mm$ | -1.15 $m$ | -0.44 $m$ | -1.04 $m$ |

### E.1.4. Unpaved infiltration capacity

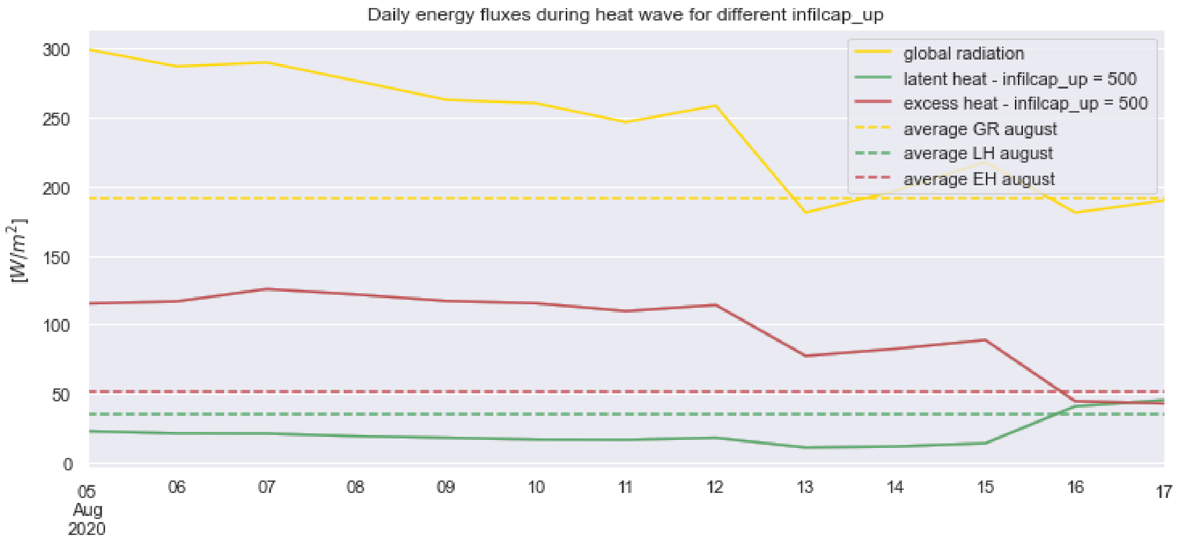


Figure E.13: Daily averages for energy fluxes during a heat wave and averages for the same period in August 2020 for different $infilcap\,up$: *global radiation*, *latent heat* flux and *excess heat* flux (= potential LH - actual LH).

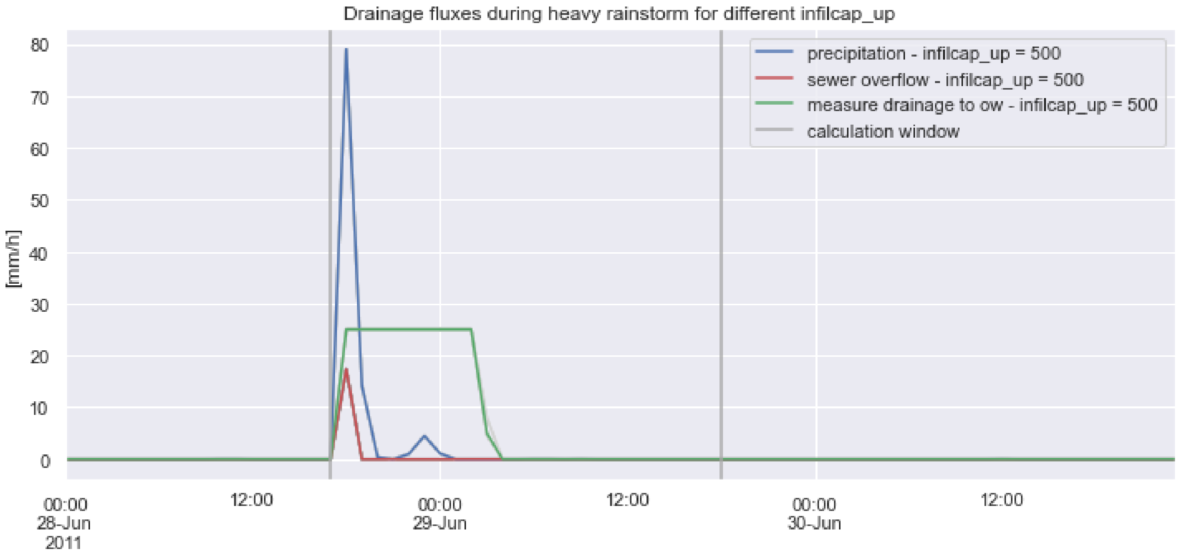


Figure E.14: Drainage fluxes during an extreme precipitation event (June 28, 2011) for different $infilcap\,up$: precipitation, **sewer** overflow and **measure** drainage.

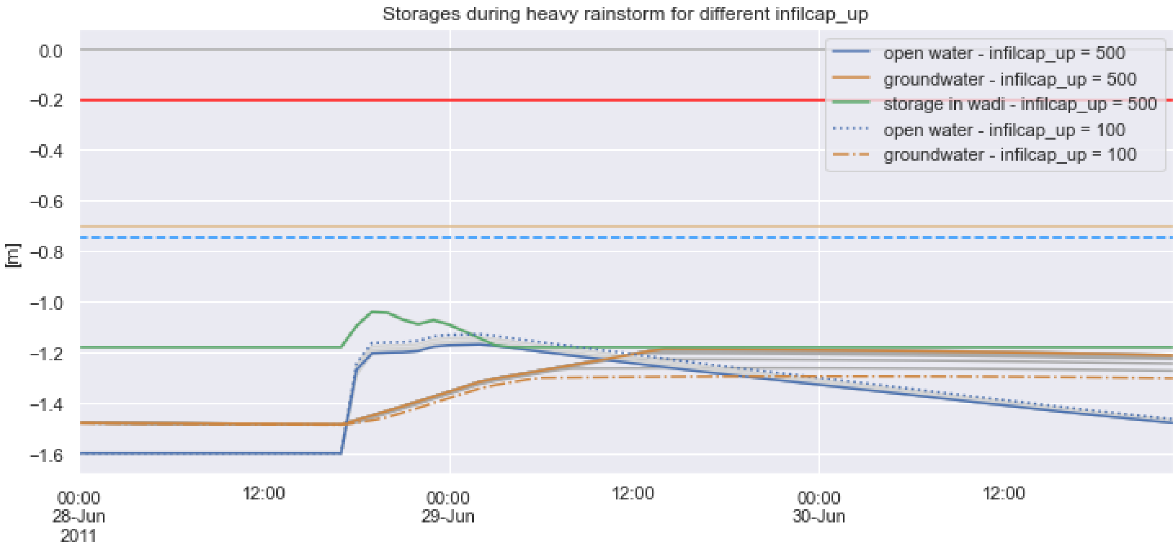


Figure E.15: Storage during an extreme precipitation event (June 28, 2011) for different $infilcap\ up$: **open water** level, **groundwater** level and water level in **measure**.

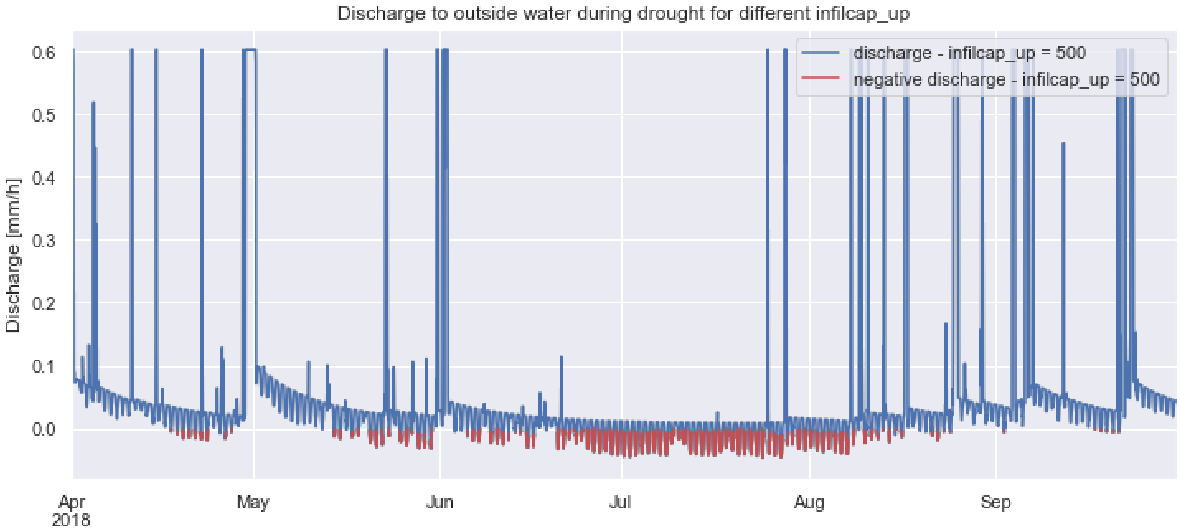


Figure E.16: Discharge from **open water** to **outside water** during drought year (2018) for different $infilcap\ up$: positive discharge, negative discharge (inlet) and **groundwater** influx.

Table E.7: *Heat stress* and *drought* indicators for different $infilcap\ up$.

| Infiltration capacity | Latent heat | Excess heat | Inlet | Disch. out |
|---|---|---|---|---|
| 100 | 21.0 $W/m^2$ | 97.8 $W/m^2$ | 15.8 $mm$ | 224.4 $mm$ |
| 200 | 21.0 $W/m^2$ | 97.7 $W/m^2$ | 15.8 $mm$ | 224.6 $mm$ |
| 300 | 21.1 $W/m^2$ | 97.7 $W/m^2$ | 15.8 $mm$ | 224.6 $mm$ |
| 400 | 21.1 $W/m^2$ | 97.7 $W/m^2$ | 15.8 $mm$ | 224.7 $mm$ |
| 500 | 21.1 $W/m^2$ | 97.7 $W/m^2$ | 15.8 $mm$ | 224.7 $mm$ |
| 600 | 21.1 $W/m^2$ | 97.7 $W/m^2$ | 15.8 $mm$ | 224.7 $mm$ |
| 700 | 21.1 $W/m^2$ | 97.7 $W/m^2$ | 15.8 $mm$ | 224.7 $mm$ |
| 800 | 21.1 $W/m^2$ | 97.7 $W/m^2$ | 15.8 $mm$ | 224.7 $mm$ |
| 900 | 21.1 $W/m^2$ | 97.7 $W/m^2$ | 15.8 $mm$ | 224.7 $mm$ |
| 1000 | 21.1 $W/m^2$ | 97.7 $W/m^2$ | 15.8 $mm$ | 224.7 $mm$ |

Table E.8: *Pluvial flooding* indicators for different $infilcap\ up$.

| Infiltration capacity | Tot. prec. | Tot. SO | Tot. drain. | Max. OW | Max. GW | Max. meas. |
|---|---|---|---|---|---|---|
| 100 | 100.4 $mm$ | 8.7 $mm$ | 7.4 $mm$ | -1.13 $m$ | -1.30 $m$ | -1.04 $m$ |
| 200 | 100.4 $mm$ | 8.7 $mm$ | 7.4 $mm$ | -1.14 $m$ | -1.26 $m$ | -1.04 $m$ |
| 300 | 100.4 $mm$ | 8.7 $mm$ | 7.4 $mm$ | -1.15 $m$ | -1.23 $m$ | -1.04 $m$ |
| 400 | 100.4 $mm$ | 8.7 $mm$ | 7.4 $mm$ | -1.16 $m$ | -1.21 $m$ | -1.04 $m$ |
| 500 | 100.4 $mm$ | 8.7 $mm$ | 7.4 $mm$ | -1.17 $m$ | -1.19 $m$ | -1.04 $m$ |
| 600 | 100.4 $mm$ | 8.7 $mm$ | 7.5 $mm$ | -1.17 $m$ | -1.19 $m$ | -1.04 $m$ |
| 700 | 100.4 $mm$ | 8.7 $mm$ | 7.5 $mm$ | -1.17 $m$ | -1.19 $m$ | -1.04 $m$ |
| 800 | 100.4 $mm$ | 8.7 $mm$ | 7.4 $mm$ | -1.17 $m$ | -1.20 $m$ | -1.04 $m$ |
| 900 | 100.4 $mm$ | 8.7 $mm$ | 7.4 $mm$ | -1.17 $m$ | -1.20 $m$ | -1.04 $m$ |
| 100 | 100.4 $mm$ | 8.7 $mm$ | 7.4 $mm$ | -1.17 $m$ | -1.20 $m$ | -1.04 $m$ |

## E.2. Climate change

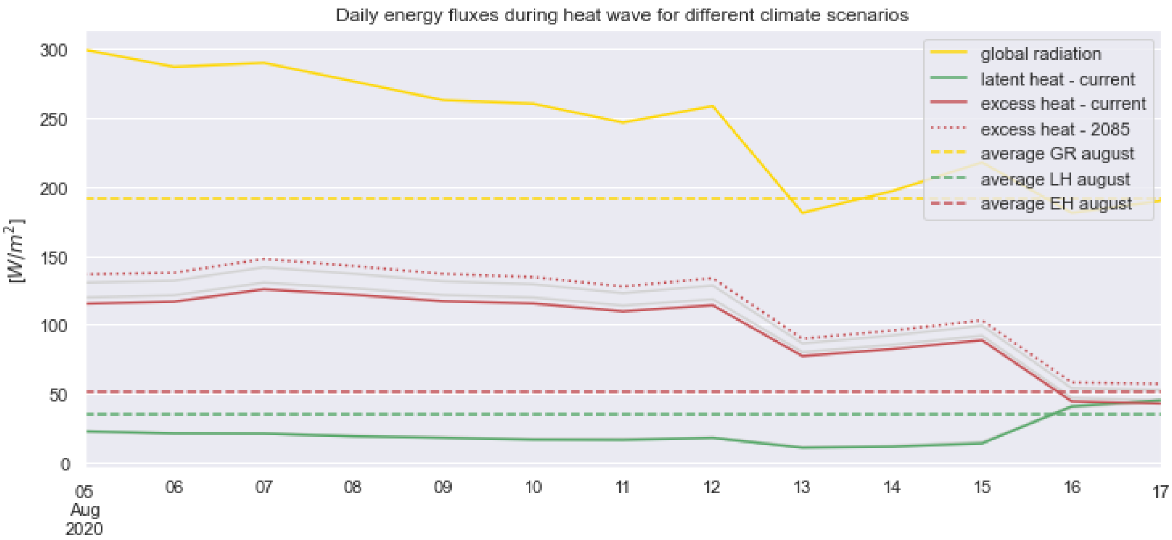


Figure E.17: Daily averages for energy fluxes during a heat wave and averages for the same period in August 2020 for different climates: *global radiation*, *latent heat* flux and *excess heat* flux (= potential LH - actual LH).

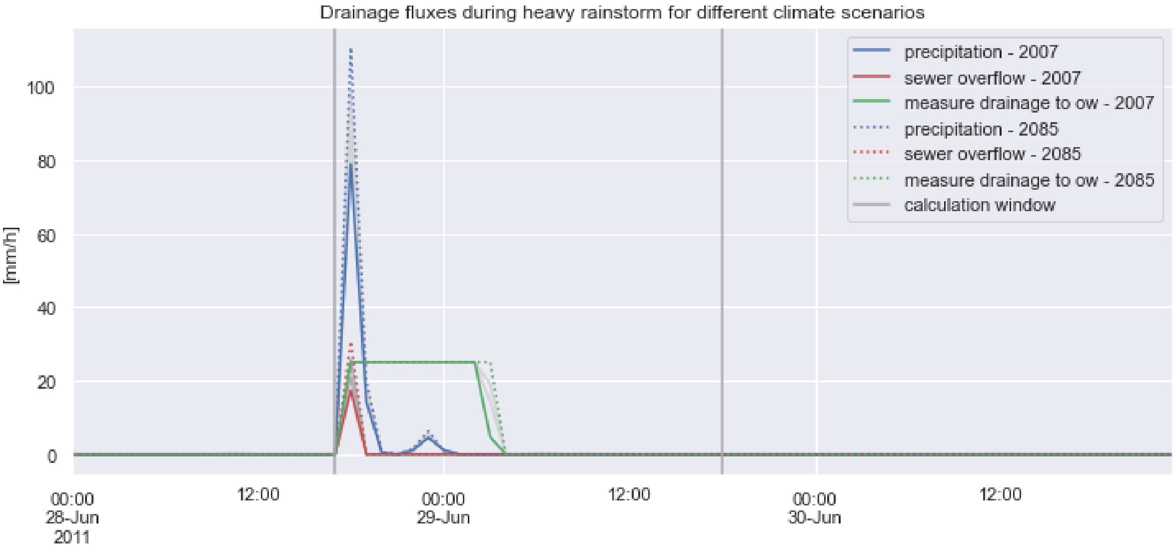


Figure E.18: Drainage fluxes during an extreme precipitation event (June 28, 2011) for different climates: precipitation, **sewer** overflow and **measure** drainage.

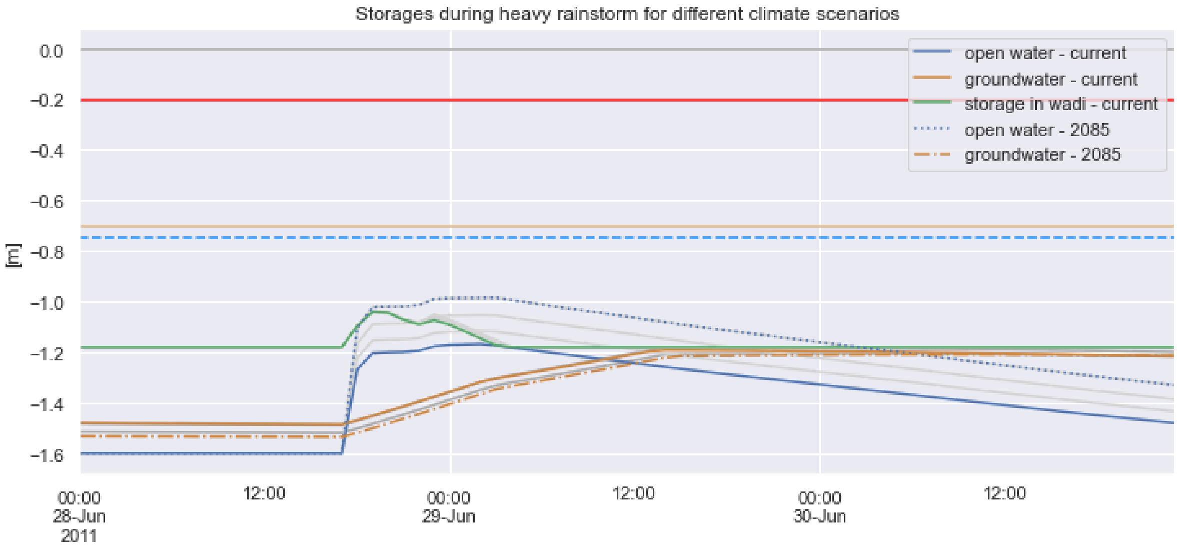


Figure E.19: Storage during an extreme precipitation event (June 28, 2011) for different climates: **open water** level, **groundwater** level and water level in **measure**.

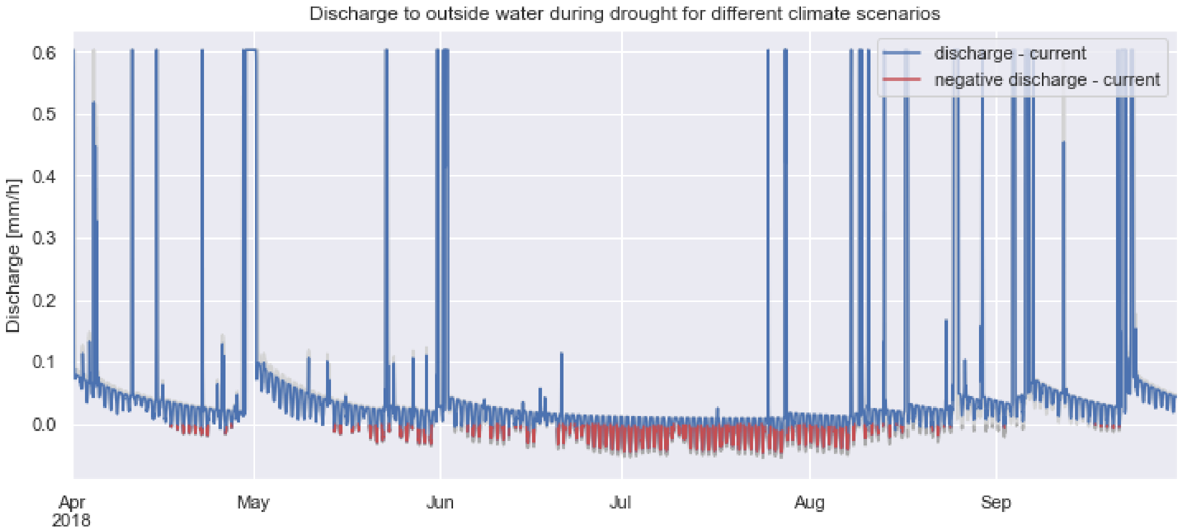


Figure E.20: Discharge from **open water** to **outside water** during drought year (2018) for different climates: positive discharge, negative discharge (inlet) and **groundwater** influx.

Table E.9: *Heat stress* and *drought* indicators for different climates.

| | **Latent heat** | **Excess heat** | **Inlet** | **Disch. out** |
|---|---|---|---|---|
| 2007 | 21.1 $W/m^2$ | 97.7 $W/m^2$ | 15.8 $mm$ | 224.7 $mm$ |
| 2030 | 21.3 $W/m^2$ | 101.6 $W/m^2$ | 16.4 $mm$ | 234.8 $mm$ |
| 2050 WH | 21.3 $W/m^2$ | 110.5 $W/m^2$ | 19.1 $mm$ | 224.5 $mm$ |
| 2085 WH | 21.2 $W/m^2$ | 115.4 $W/m^2$ | 20.8 $mm$ | 220.7 $mm$ |

Table E.10: *Pluvial flooding* indicators for different climates.

| | **Tot. prec.** | **Tot. SO** | **Tot. drain.** | **Max. OW** | **Max. GW** | **Max. meas.** |
|---|---|---|---|---|---|---|
| 2007 | 100.4 $mm$ | 8.7 $mm$ | 7.4 $mm$ | -1.17 $m$ | -1.19 $m$ | -1.04 $m$ |
| 2030 | 111.3 $mm$ | 10.6 $mm$ | 7.7 $mm$ | -1.12 $m$ | -1.18 $m$ | -1.04 $m$ |
| 2050 WH | 125.0 $mm$ | 12.9 $mm$ | 7.9 $mm$ | -1.05 $m$ | -1.21 $m$ | -1.04 $m$ |
| 2085 WH | 139.8 $mm$ | 15.4 $mm$ | 8.1 $mm$ | -0.99 $m$ | -1.21 $m$ | -1.04 $m$ |

# E.3. Spatial planning

## E.3.1. Private property

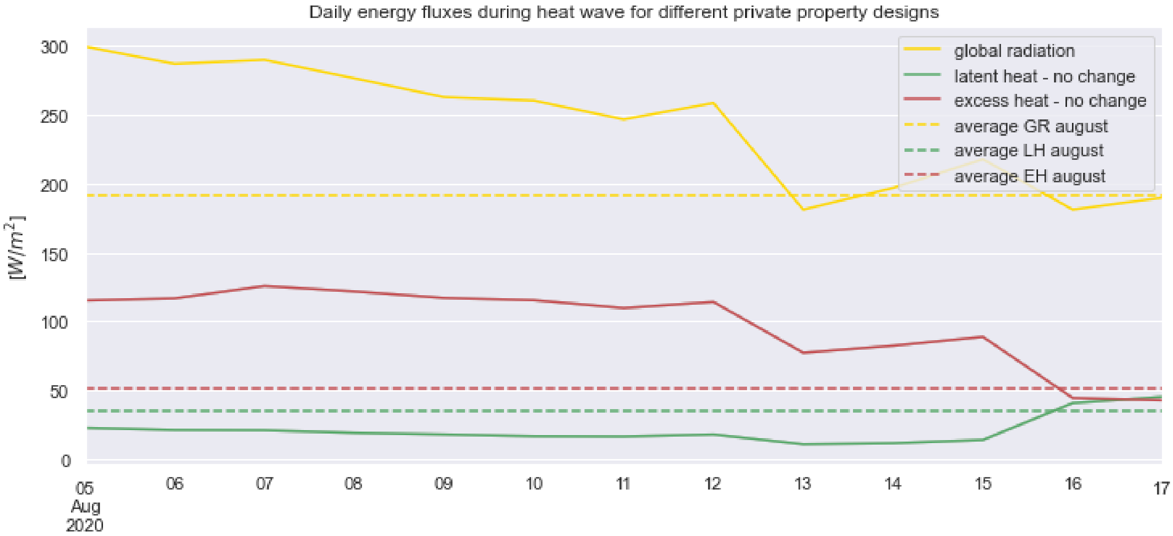


Figure E.21: Daily averages for energy fluxes during a heat wave and averages for the same period in August 2020 for different *private property* designs: *global radiation*, *latent heat* flux and *excess heat* flux (= potential LH - actual LH).

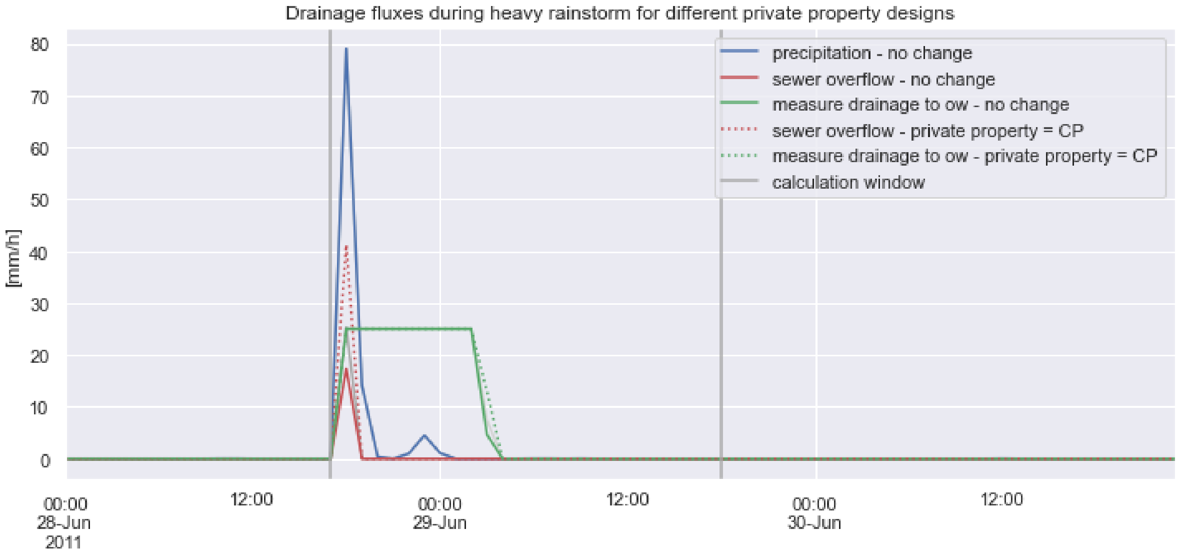


Figure E.22: Drainage fluxes during an extreme precipitation event (June 28, 2011) for different *private property* designs: precipitation, **sewer** overflow and **measure** drainage.

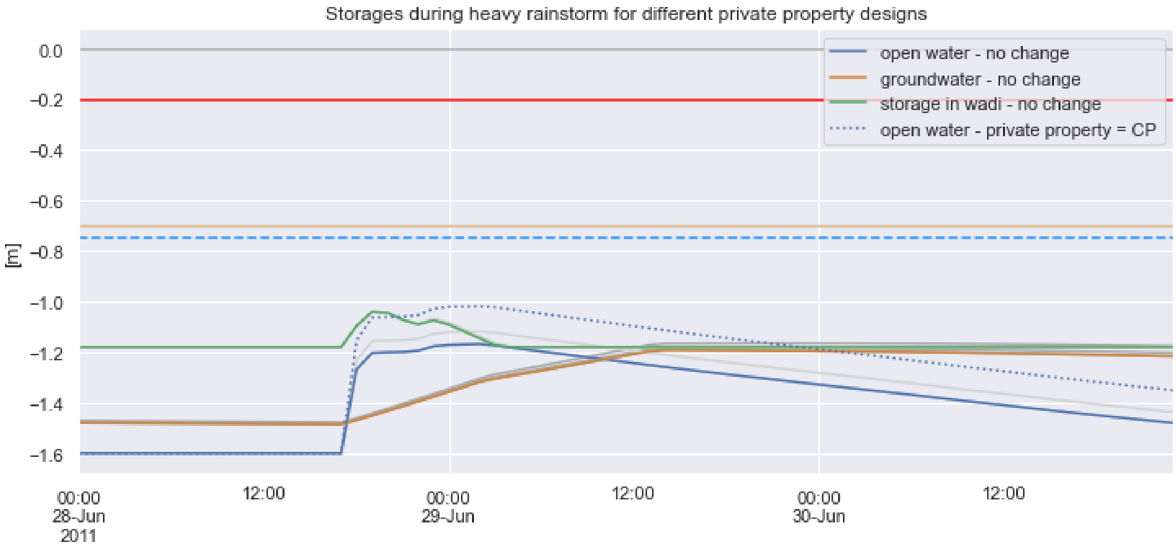


Figure E.23: Storage during an extreme precipitation event (June 28, 2011) for different *private property* designs: **open water** level, **groundwater** level and water level in **measure**.

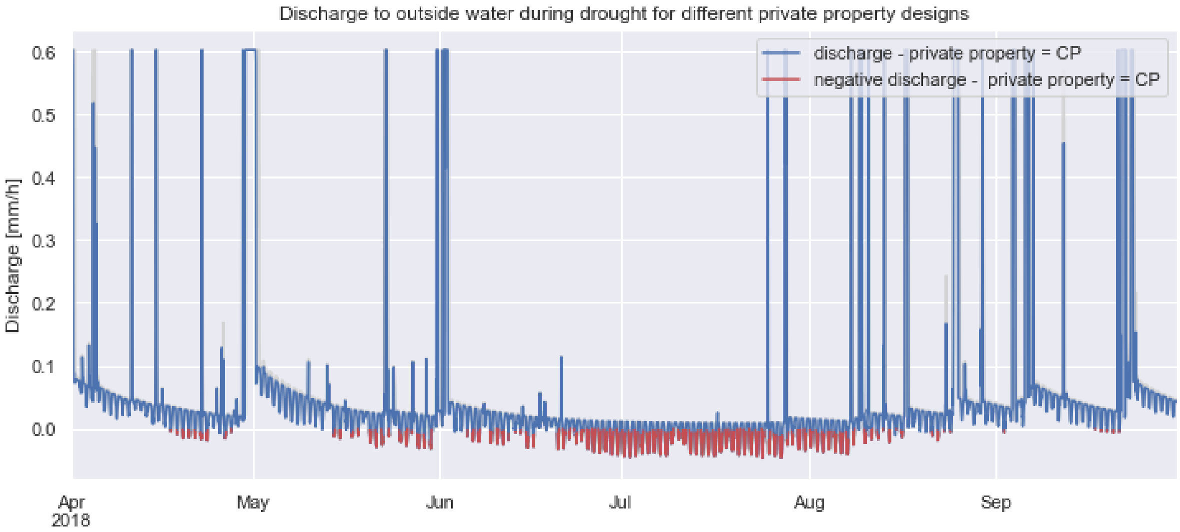


Figure E.24: Discharge from **open water** to **outside water** during drought year (2018) for different *private property* designs: positive discharge, negative discharge (inlet) and **groundwater** influx.

Table E.11: *Heat stress* and *drought* indicators for different *private property* designs.

| | **Latent heat** | **Excess heat** | **Inlet** | **Disch. out** |
|---|---|---|---|---|
| No change | 21.1 $W/m^2$ | 97.7 $W/m^2$ | 15.7 $mm$ | 223.7 $mm$ |
| Private property = CP | 21.1 $W/m^2$ | 97.7 $W/m^2$ | 14.9 $mm$ | 273.3 $mm$ |
| Private property = UP | 21.1 $W/m^2$ | 97.7 $W/m^2$ | 15.5 $mm$ | 240.3 $mm$ |

Table E.12: *Pluvial flooding* indicators for different *private property* designs.

| | **Tot. prec.** | **Tot. SO** | **Tot. drain.** | **Max. OW** | **Max. GW** | **Max. meas.** |
|---|---|---|---|---|---|---|
| No change | 100.4 $mm$ | 8.7 $mm$ | 7.4 $mm$ | -1.17 $m$ | -1.19 $m$ | -1.04 $m$ |
| Private property = CP | 100.4 $mm$ | 20.7 $mm$ | 7.7 $mm$ | -1.17 $m$ | -1.17 $m$ | -1.04 $m$ |
| Private property = UP | 100.4 $mm$ | 12.7 $mm$ | 7.5 $mm$ | -1.12 $m$ | -1.18 $m$ | -1.04 $m$ |

### E.3.2. Design choices

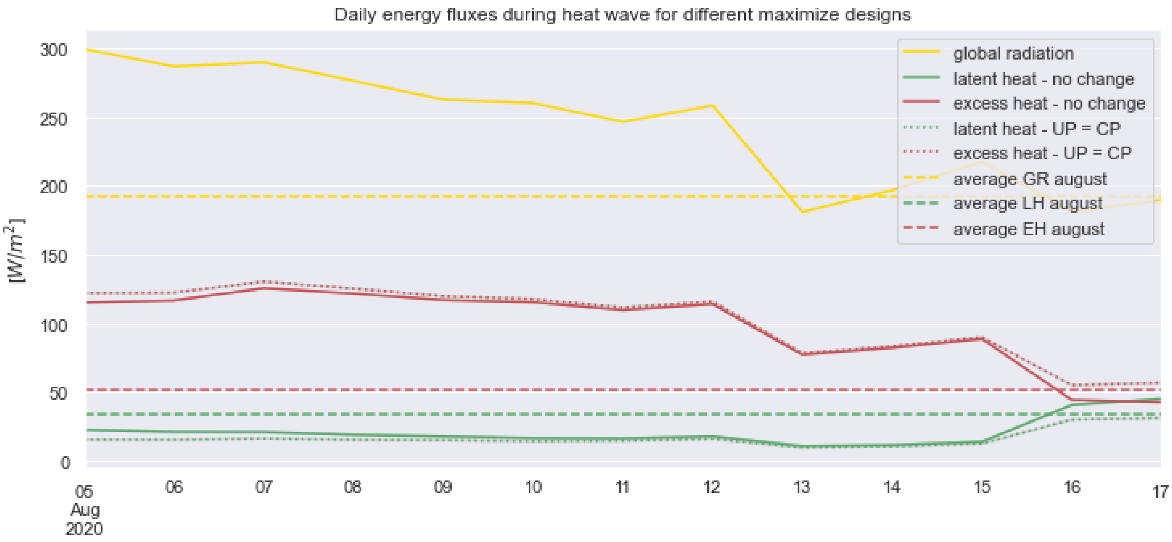


Figure E.25: Daily averages for energy fluxes during a heat wave and averages for the same period in August 2020 for different maximized designs: *global radiation*, *latent heat* flux and *excess heat* flux (= potential LH - actual LH).

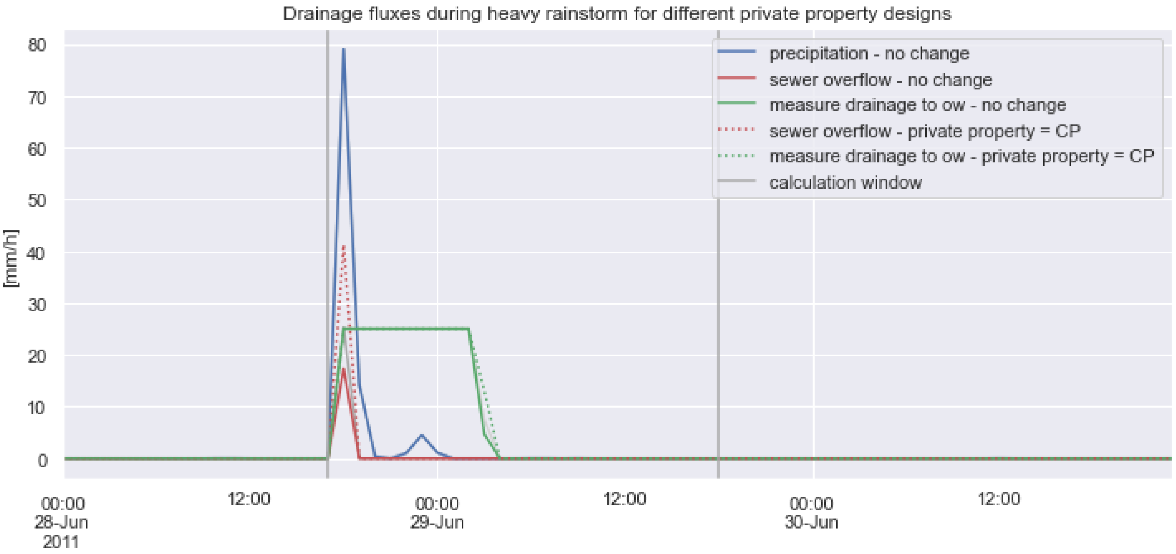


Figure E.26: Drainage fluxes during an extreme precipitation event (June 28, 2011) for different maximized designs: precipitation, **sewer** overflow and **measure** drainage.

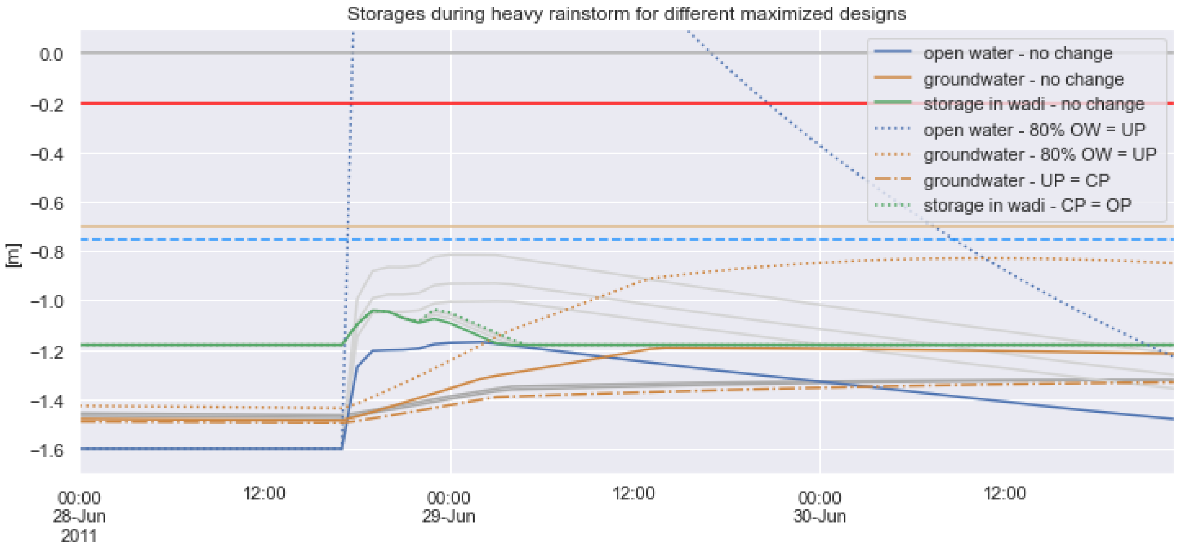


Figure E.27: Storage during an extreme precipitation event (June 28, 2011) for different maximized designs: **open water** level, **groundwater** level and water level in **measure**.

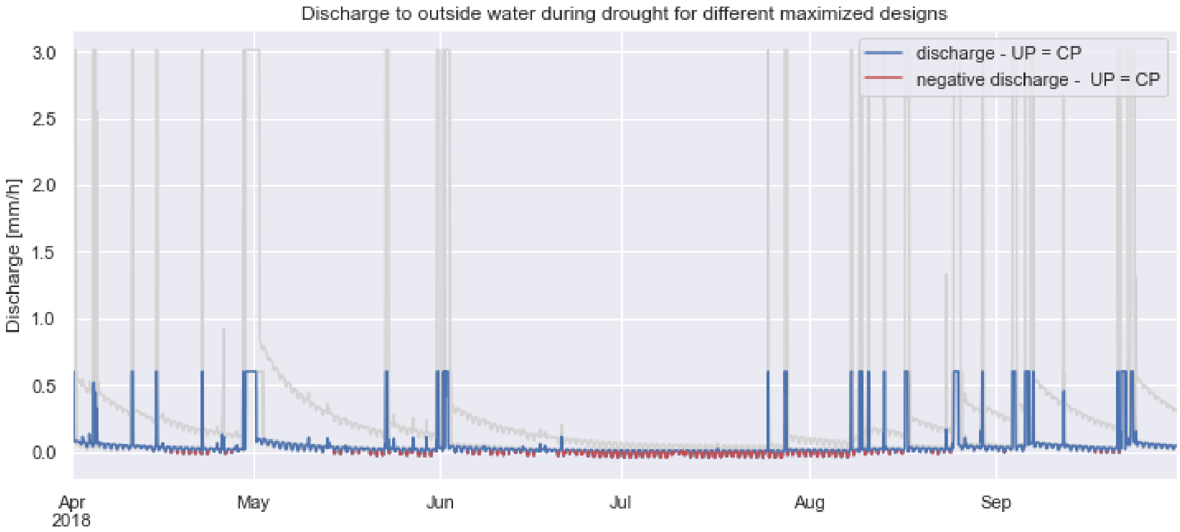


Figure E.28: Discharge from **open water** to **outside water** during drought year (2018) for different maximized designs: positive discharge, negative discharge (inlet) and **groundwater** influx.

Table E.13: *Heat stress* and *drought* indicators for different maximized designs.

| | **Latent heat** | **Excess heat** | **Inlet** | **Disch. out** |
|---|---|---|---|---|
| No change | 21.1 $W/m^2$ | 97.7 $W/m^2$ | 15.7 $mm$ | 223.7 $mm$ |
| UP = CP | 16.6 $W/m^2$ | 102.2 $W/m^2$ | 14.9 $mm$ | 306.9 $mm$ |
| CP = OP | 16.6 $W/m^2$ | 102.2 $W/m^2$ | 12.9 $mm$ | 320.3 $mm$ |
| OP = CP | 16.6 $W/m^2$ | 102.2 $W/m^2$ | 13.4 $mm$ | 319.7 $mm$ |
| 80% OW = UP | 21.1 $W/m^2$ | 97.7 $W/m^2$ | 0.02 $mm$ | 358.1 $mm$ |

Table E.14: *Pluvial flooding* indicators for different different maximized designs.

| | **Tot. prec.** | **Tot. SO** | **Tot. drain.** | **Max. OW** | **Max. GW** | **Max. meas.** |
|---|---|---|---|---|---|---|
| No change | 100.4 $mm$ | 8.7 $mm$ | 7.4 $mm$ | -1.17 $m$ | -1.19 $m$ | -1.04 $m$ |
| UP = CP | 100.4 $mm$ | 37.6 $mm$ | 8.0 $mm$ | -0.81 $m$ | -1.33 $m$ | -1.04 $m$ |
| CP = OP | 100.4 $mm$ | 23.6 $mm$ | 8.7 $mm$ | -1.00 $m$ | -1.32 $m$ | -1.04 $m$ |
| OP = CP | 100.4 $mm$ | 28.5 $mm$ | 8.5 $mm$ | -0.93 $m$ | -1.32 $m$ | -1.04 $m$ |
| 80% OW = UP | 100.4 $mm$ | 28.5 $mm$ | 8.5 $mm$ | 1.11 $m$ | -0.83 $m$ | -1.04 $m$ |

# F

# Case Implementation

Section 3.1.2 explained the most important parts of the case study implementation: what forcing was used in the atmospheric boundary and how fractions of land use classes were extracted from urban plans. However, local hydrological conditions are important as well, since they determine *how* the system functions. For this reason a more elaborate description of these parameters and assumptions is provided. First boundary parameters, then internal parameters, and lastly, assumptions for the sewer system.

The lower boundary of the model is governed by the **deep groundwater** dynamics. As mentioned in the section 3.1.1, there are two ways to define this boundary. Used in these case studies is the first method where an external head is defined with a flow resistance. The definition of the external head is relative to the ground surface (fig. F.1). In Amstelwijck I most of the surface lies $0.2\,m$ above NAP. With the assumption that the river level (at NAP) determines the external head, a value of $0.2\,m$ is used as input. Amstelwijck II has a lower surface level of $0.3\,m$ below NAP, so $head\ deepgw$ is set as $-0.3\,m$. The flow resistance ($vc$) depends on the thickness and hydraulic conductivity of the soil layers. To determine this parameter, the supposed seepage, or in this case upwell, is checked with the model calculation of seepage ($s\ gw\ out$). The yearly upwell is indicated to be around $0.1 - 0.5\,m$ (CAS, 2021 & Brouwer, 2016), so $vc$ is found to be around $4000\,days$.

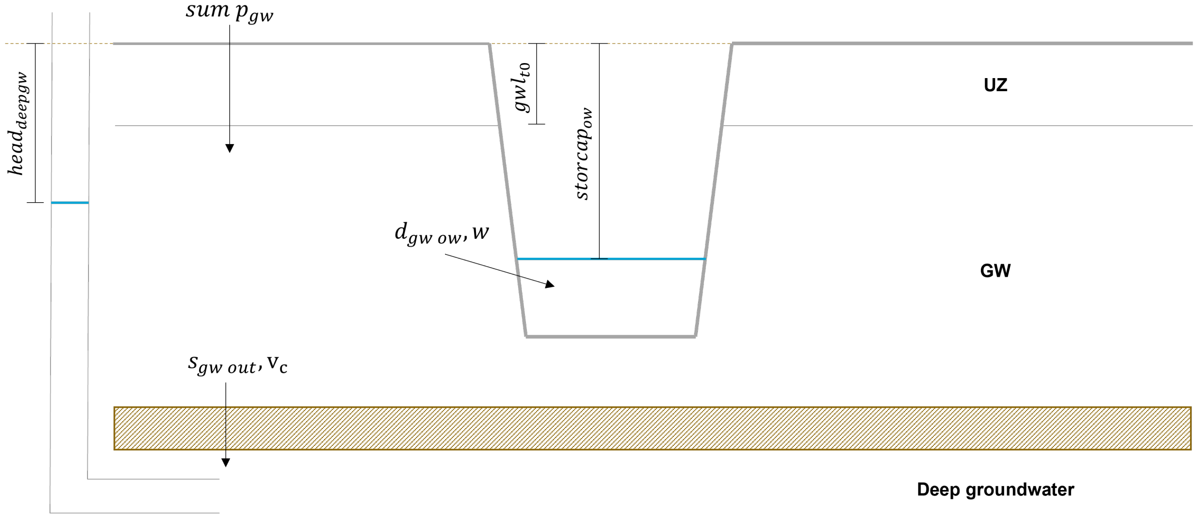


Figure F.1: Definition of head and water levels as used in the **UrbanWB** model, adapted from Vergroesen (2020).

The last boundary component, **outside water** is governed by the water level in **open water** and pumping capacity. If water rises above the set **open water** level ($storcap\ ow$) pumping starts, when lower than this level, external water is let in. The first case area is part of the large hydrological unit of *'Loudon'* with $15.1\,mm/d$ pumping capacity (fig. 2.4). The second is a smaller hydrological unit pumping to the larger *'Loudon'* unit. Here pumping capacity is $26.9\,mm/d$. The **open water** level is, again, relative to the surface level. $storcap\,ow$ is $1.6\,m$ in Amstelwijck **I** and $1.1\,m$ in Amstelwijck **II**.

Soil parameters determine how water moves inside the system. Chapter 2 describes how the area was formed and which soil characteristics are the result of that history. As mentioned the soil consists mainly of clay and fine sand, but there is also a peat layer present. These characteristics are captured by parameters in the **unsaturated zone**, **groundwater** and **open paved** and **unpaved** components. The parameters in the **unsaturated zone** affect how plants grow and take up their water, and in turn their transpiration. The type of soil ($soiltype$) and the type of plants ($croptype$) can be adjusted as input to select the right parameter sets. There are lists of predefined sets that can be used (see appendix B). An extensive explanation of calculations in the **unsaturated zone** can be found in the model documentation (Vergroesen, 2020). For the situation in Amstelwijck the $soiltype$ is clay on peat $(18)$ and $croptype$ is assumed to be grass $(1)$.

For the **groundwater** component the boundary flux to **deep groundwater** has already been discussed above. Additionally, there is a flux towards the **open water** controlled by a drainage resistance $(w)$. High drainage resistance results in slower drainage. This flux is a retention compared to sewer drainage and overland flow, which makes it a preferable option for climate-adaptive purposes. Considering the soil composition, the size of the project areas and **open water** area, $w$ is set to $100\,days$ for both cases. Lastly, **open paved** ($infilcap\,op$) and **unpaved** ($infilcap\,up$) components allow infiltration. The possibilities for infiltration are increased with higher infiltration capacities or with larger fractions of **open paved** and **unpaved**. Because there are large uncertainties for this parameter in spatial heterogeneity and behaviour under different conditions and because of the lack of knowledge about true values, standard, conservative values are used in the model ($infilcap\,op$ is $10.9mm/day$ & $infilcap\,up$ is $480mm/day$).

In Amstelwijck, like most new-built residential areas, the sewer system is separated, so the option of stormwater drainage system fraction ($swds\,frac$) is 1. The second option indicates what surfaces are connected to the **stormwater sewer**. Amstelwijck drains all surfaces that do not drain to the measures directly to the open water, so $discfrac\,pr$, $discfrac\,cp$, $discfrac\,op$ are all set to 0. There is one last parameter not yet specified, overflow rainfall intensity ($rainfall\,swds\,so$). Since the **stormwater sewer** is modeled as a direct discharge with a small storage term, this term does not reflect a physical property, but it can be determined empirically. For both cases the standard value of $rainfall\,swds\,so$ is $16.8mm/h$ is used. Lastly there is an option to include basements below **groundwater** ($frac\,pr\,aboveGW$). When the case, no **groundwater** exists below **paved roof**. There are no basements constructed in Amstelwijck, so $frac\,pr\,aboveGW$ is 1.

Climate-adaptive measures can be applied by manually changing parameters or boundary conditions. However, some are implemented into the model using an extra "measure" component. Amstelwijck **I** has implemented a *bioswale* or *wadi* that is connected to the area on the right side of the waterway in the centre (see Fig. 2.5). The inflow area of this measure is $43300m^2$). This is considered a 3-layer structure, where evaporation ($EV\,evaporation = 1$), transpiration ($ET\,transpiration = 1$), infiltration ($IN\,infiltration = 1$) and slow drainage ($SD\,delay$) are possible. This measure has runoff to the **open water** and **groundwater** from **bottom storage layer**. The *wadi* has a storage volume of $1025m^3$ over an area of $2410m^2$ with embankments and height differences. This is simplified in the model to a square "box" with a depth of $0.43m$ ($storcap\,int\,meas = 20mm$, $storcap\,top\,meas = 100mm$ & $storcap\,btm\,meas = 310mm$). Overflow can occur to **open water**.

The second measure implemented were *rain barrels*. These are connected to every roof in both Amstelwijck **I** and **II** (inflow areas are $12900\,m^2$ and $29800m^2$ respectively). A *rain barrel* is considered as a 2-layered structure with a dummy **interception layer** that allows "pumping" ($FD\,pumping = 1$). This measure has runoff to the **stormwater sewer** from **interception layer** and to the **open water** from **bottom storage layer**. The storage in one barrel is $1000mm$ ($storcap\,int\,meas = 0mm$, $storcap\,btm, meas = 1000mm$) and the total area covered is $180\,m^2$, resulting in $180\,m^3$ in total storage.

Lastly, in Amstelwijck I, the garden sheds in the area left of the waterway have *green roofs*. They replace $550\,m^2$ of roof (inflow area also $550\,m^2$) for a more climate adaptive solution. These roofs are modeled as a 3-layered structure with evaporation ($EV\,evaporation = 1$) and evapotranspiration ($ET\,transpiration = 1$). This measure has runoff to the **stormwater sewer** from **interception** and **bottom storage layer**. Water is mainly held in the **top storage layer** ($storcap\,int\,meas = 5mm$, $storcap\,top\,meas = 100mm$ & $storcap\,btm\,meas = 5mm$) and if this layer is filled, overflow occurs to the **stormwater sewer**.

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