Heat-Down: Integrated modelling of stormwater and urban heat for cooling cities

1 SUMMARY OF RESEARCH PLAN

There is growing evidence that heatwaves are becoming more frequent. Exacerbated in urban areas due to highly impervious surfaces, limited air humidity, anthropogenic heat, and reduced ventilation, this effect is also frequently referred to as Urban Heat Islands. Urban heat presents a major threat to public health, increased energy consumption for cooling, reduction in economic productivity, increased heat related damage on infrastructure and a reduction of overall people's well-being. Also associated with climate change and intensified by the increasing level of urbanization is the challenge of stormwater management. Urban pluvial flooding can cause larger damages when compared to other natural hazards. In adapting and minimizing flooding risks, cities have been adopting *Blue-Green Infrastructure*, such as green roofs, infiltration basins and rain gardens, and reducing the reliance on grey infrastructure (e.g. building underground reservoirs or pipelines, such as the *Chicago Deep Tunnel Shaft*[1] or the *London Tideway*[2] projects). Blue-Green Infrastructure in cities can also contribute to mitigate urban heat effects. However, with the exception of a few studies, the urban heat mitigation potential of these systems and its relation to the water requirements has not yet been thoroughly quantified.

With this project, we aim to understand how elements of urban stormwater systems can contribute to mitigate urban heat, to improve urban thermal comfort and to identify the extent of implementation required to create a significant impact. Hybrid solutions such as the digitalisation and smart control of stormwater systems, namely smart urban stormwater harvesting, reuse for irrigation, flood control and active operation of Blue-Green Infrastructure also create new opportunities for new stormwater systems urban functions. We will analyse the direct and indirect impact of stormwater system elements to mitigate urban heat effects in two diverse and unique urban areas: City of Zürich (Switzerland) and City of Melbourne (Australia). This project is divided into three core parts: (A) analysis of stormwater dynamics and the role of smart stormwater management and Blue-Green Infrastructure in urban heat mitigation; (B) development of an urban climate model suitable for simulating the active application of water on Blue-Green Infrastructure and urban pavements, and (C) integration of both stormwater and urban climate models to simulate fully dynamic scenarios of planning stormwater management options for urban heat mitigation at the broader district and city scale. These three parts will be supported by field measurements, in which we will collect data on the urban water balance and high-resolution urban surface temperature observations at the street and city scales.

The *Heat-Down* project will develop new best practices for quantifying and leveraging the multi-functional benefits of smart stormwater management and Blue-Green Infrastructure for urban heat stress control. The project will also realise their integration with local urban-climate models for exploratory modelling and spatial planning purposes as part of shaping more liveable cities in the face of future challenges.

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[1] The Chicago Deep Tunnel Shaft project: https://www.geoengineer.org/news/tunnel-in-chicago-prevents-an-area-from-flooding

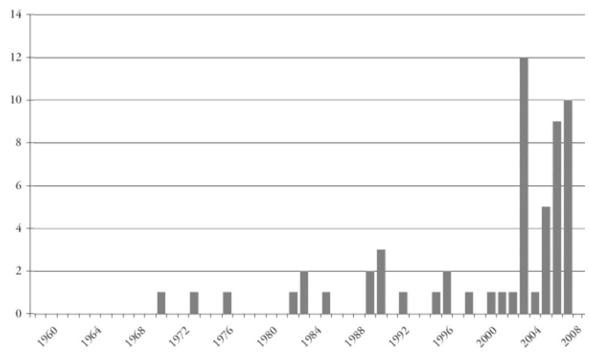
[2] The Thames Tideway project: https://www.tideway.london

2 RESEARCH PLAN

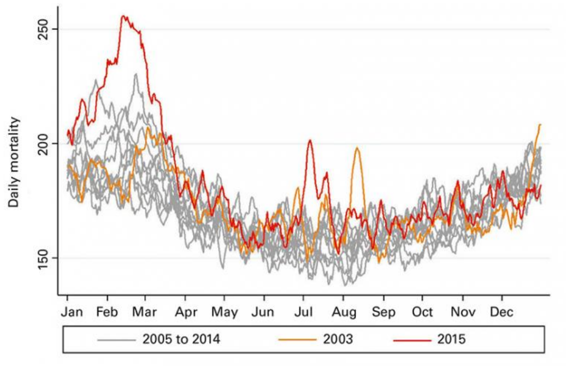
2.1 Current state of research on urban heat effects and urban water mitigation measures

2.1.1 The need for cooler cities: urban heat is already affecting population's health

Climate change is a pressing issue that requires understanding of its impact at many different scales. For example, there is growing evidence (see Figure 1a) that heatwaves are becoming more frequent (e.g. Alexander and Arblaster, 2009; Goner et al., 2010; Hartmann et al., 2013; Schleussner et al., 2017; Seneviratne et al., 2012). Climate simulations also project an increase in the number and intensity of heatwaves and hot extremes in many regions of the world (Fischer et al., 2014; Sillmann et al., 2013), even for global warming scenarios with a 1.5°C or 2°C temperature increase (Dosio et al., 2018; Seneviratne et al., 2016; Wartenburger et al., 2017). Heatwaves do not only contribute to general human discomfort; they can also cause respiratory difficulties, heat exhaustion and heat-related fatalities due to their impact on the human cardiovascular and respiratory system (Kovats et al., 2008). Sensitive populations (i.e. children, older adults, those with existing health conditions) are at particular risk during such heatwave events. For example, the Center for Disease Control and Prevention estimated that, from 1979 to 2003, excessive heat exposure contributed to more than 8,000 premature deaths in the United States (CDC, 2011), which exceeds the number of mortalities resulting from hurricanes, lightning, tornadoes, floods, and earthquakes combined. During the 2003 heatwave in Europe, more than 70,000 additional deaths were reported (Robine et al., 2008; Schär et al., 2004). Switzerland experienced significant heatwaves during the summers of 2003 and 2015 (Figure 1b), which were the two warmest summers in over 150 years. For these summers, an excess mortality of 6.9% (975 deaths) and 5.9% (804 deaths) was estimated, for each of the two years, respectively (Vicedo-Cabrera et al., 2016). Heat-related mortality is a growing public health concern that is further exacerbated by climate change, urbanisation and an aging population.



(a) Days per year with minimum temperatures above 32°C, 1948 to 2007 in the City of Phoenix, USA (adapted Gober et al., 2010)



(b) All-cause daily mortality (number of deaths) in Switzerland in 2003, from 2005 to 2014 and in 2015 (Vicedo-Cabrera et al., 2016)

Figure 1. *(a) Increase of heatwave frequency and (b) increased mortality caused by heatwaves*

Urban areas are where the effects of heatwaves are more significant. In addition to the generalised impacts of heatwaves, urban areas additionally experience urban heat island (UHI) effects characterised by higher air temperatures compared to the surrounding rural environment (Coutts et al. 2007; Moonen et al 2012; Oke 1987). Recently (Santamouris and Kolokotsa, 2016), UHI phenomena were reported in more than 400 cities around the world and their magnitude was found to vary by location, with intensities (i.e. air temperature differences between urban and rural areas) up to 7°C. While the suitability of UHI intensity as an indicator for urban heat mitigation has been criticised (Martilli et al., 2019), it is nonetheless clear that urban heat in cities is significant and demands attention. The large amount of impervious surfaces that do not retain water or humidity within urban areas in conjunction with traditional urban water management, made to drain water out of the city efficiently (Arnold, C. L. and Gibbons, 1996; Butler and Davies, 2018), can partly explain the adverse effects due to urban heat. Other contributing factors are, for example, lower surface reflectivity, reduced evapotranspiration, the anthropogenic heat generated by cooling systems or transportation combustion engines and lower wind speed when compared to neighbouring rural areas, resulting in larger sensible heat.

Solutions for city cooling could focus on the implementation of more reflective surfaces (i.e. increasing urban surface albedo) and increasing vegetated areas that create shaded areas and contribute to evapotranspiration (Li and Bou-Zeid, 2013; Mackey et al., 2012; Seneviratne et al. 2018). **A less investigated measure to mitigate the effects of urban heat is the direct application of water on Blue-Green Infrastructures and urban pavements to enhance evaporative cooling,** following, for example, the Japanese *Uchimizu* tradition (Solcerova et al., 2018a, b).

2.1.2 New opportunities for Blue-Green Infrastructure and smart stormwater management to mitigate urban heat

Historically, within the urban water cycle, management of stormwater management has focused on two main objectives: to reduce flooding and to control (or reduce) water pollution. To reduce the frequency and impact of floods in cities, grey engineering solutions, such as underground reservoirs (e.g. Cunha et al., 2017) and real-time control systems taking advantage of existing hydraulic capacity of sewer pipes (Leitão et al., 2018), have been investigated. Other types of solutions also aimed at minimising flooding in urban areas consider Blue-Green Infrastructures (see e.g. Fletcher et al., 2015; Winker et al., 2019; Oral et al., 2020). Both types of solutions have also been applied to reduce pollution of receiving water bodies as they can have: (i) impact on reducing the number of discharges from Combined Sewer Overflows (Joshi et al., in review), and (ii) can provide some level of stormwater treatment (green solutions only) before it is discharged to receiving water bodies.

Based on the concept of circular economy (Pearce and Turner, 1990), stormwater (and other urban water streams) should be seen as a resource and not as something to be disposed of (even if treated to a high standard). Since early times, rainfall harvesting cisterns (i.e. water reservoirs usually built underground) have been used to store rainwater for various applications, including potable uses. More recently, other uses for rainwater have been proposed: irrigation, toilet flushing, and mitigating urban heat (to irrigate green areas or simply watering impervious pavements to increase evaporative cooling). The idea of using stormwater to mitigate urban heat has received some attention over a decade ago (Probst et al., in review), but has been gaining resurgence in recent years (Richards and Edwards, 2018) with the focus on watering Blue-Green Infrastructure. Coutts et al. (2012, 2014) showed the relevance of Blue-Green Infrastructure (also frequently referred to as *Water Sensitive Urban Design* or *Climate Sensitive Urban Design)* to mitigate urban heat and highlighted the possibility of using them for both urban hydrology (to reduce floods) and microclimate objectives (to mitigate urban heat). The effectiveness of Blue-Green Infrastructure, however, depends on the presence of moisture in these systems during extreme heat days, which is a key design parameter that needs to be accounted for. It has been shown that Blue-Green solutions with low moisture content exhibit almost no cooling effect (Osmond and Sharifi, 2017; Coutts & Harris, 2013). Furthermore, **the timing of stormwater inflow and incidence of urban heat are often not concurrent, emphasising the need for smart stormwater management and stormwater storage in nearby Blue-Green assets.**

The presence of water bodies in urban areas is known to reduce air temperature and improve thermal comfort on city or regional scales (Chang et al., 2007; Spronken-Smith and Oke, 1999). Various studies have shown that the surface temperature of water bodies is usually lower than other urban surfaces during the day and warmer during the night (e.g. Seed Consulting Services, 2017). Also, the effect of pavement watering on increasing thermal comfort in cities has been practiced for many years - see the example of the *Uchimizu* tradition in Japan. Recently, few studies have attempted to quantify the effect of this tradition on reducing pavement surface and air temperatures and increasing thermal comfort (e.g. Kinouchi and Kanda, 1997; Yamagata et al., 2008; Li et al., 2013; Hendel et al., 2014; Hendel, 2015; Solcerova et al., 2018a; Ferrari et al., 2020).

Despite the evidence that water can have on mitigating urban heat, very few studies (Broadbent et al., 2018; Demuzere et al., 2014; Mitchell et al., 2008) have explored the potential of stormwater to influence urban microclimate and its long-term spatio-temporal dynamics. Mitchell et al. (2008), in particular looked into the link between stormwater and energy balance to analyse city planning options aimed at reducing urban heat. Their study focused on irrigating green areas, trees and Blue-Green Infrastructure, but not on the direct application of stormwater to pavement surfaces. **The consideration of smart stormwater management to enhance Blue-Green Infrastructure performance on reducing UH effects and to create new urban water related opportunities (such as surface watering) to increase evaporative cooling and thermal comfort in cities, is an opportunity that has not yet been thoroughly investigated**.

The combined analysis of stormwater dynamics (i.e. stormwater availability) and urban heat budget, is key for understanding its potential to mitigate adverse impacts of urban heat, before starting to build new or retrofit existing Blue-Green and grey urban water infrastructure. Other urban water sources (e.g. potable water) may also be used for urban heat mitigation; therefore a cost-benefit analysis on the use of stormwater to this end is also required to assess the value of this specific resource.

2.1.3 Microclimate models to support urban heat mitigation analyses of present and future scenarios

Urban climate modelling is essential to study variations of features in urban areas (buildings materials and orientations, vegetation, surface types, and water features) and their impact on urban climate in the present and projected into the future. Such types of models are generally classified into three to four broad categories based on scale (Murakami et al., 1999): (i) global-scale models, such as the General Circulation Models (GCMs) or Numerical Weather Prediction (NWP), which assess climate at a very coarse resolution, but across countries and the globe (e.g. Best, 2005); (ii) Local to meso-scale models, which can simulate variations in temperatures at the city and regional level down to the local neighbourhood (Murakami et al., 1999) – it is also usually at this scale, at the boundary layer interface, where urban heat effects can be investigated (Oke, 1987); and (iii) micro-scale models, some of which rely on Computational Fluid Dynamics (CFD) in solving the Navier-Stokes Equations (e.g. Bruse, 1999; Krayenhoff and Voogt, 2007), while others rely on high levels of parameterisation to adequately describe the urban geometry and simulate the microclimate within the urban canopy layer, i.e. a local street (Meili et al., 2020).

Whilst the global-level models are too coarse for the purpose of this project, local to meso-scale climate modelling on the other hand is generally well established and mature with a number of available models for research purposes e.g. LUMPS (Grimmond and Oke, 2002)/SUEWS (Järvi et al., 2011), WRF (Chen et al., 2004; Kusaka et al., 2001), CCSM (Vertenstein et al., 2004), JULES (JULES, 2011), and CABLE (Kowalczyk et al., 2006). It is also at this spatial scale that stormwater management strategies are often investigated (i.e. neighbourhood to catchment scale). As such, many local and meso-scale models have also considered the inclusion of vegetation and water in their model scope, allowing them to assess the impact that water and Blue-Green Infrastructure can have on the effects of UHI and other urban heat indicators (e.g. heat stress, characterised by the Urban Thermal Climate Index - Bröde et al., 2012, Back et al., in review). Street-level effects, however, are often simplified using "typified canyon geometry" based on the local area. For stormwater management practices, which can vary dynamically over time, such simplifications may not be ideal and thus simple, yet dynamic relationships may have to be sought.

Urban climate modelling at the micro-scale is far less mature and less options exist at this scale. However, there are a number of gains from modelling at this scale, such as the ability to more accurately determine human thermal comfort, to better understand the impact of canyon geometry and vegetation on the urban energy balance and, in particular, to investigate how local practices such as pavement watering or blue-green infrastructure can have an immediate effect on the surrounding environment. Examples of models include: ENVI-met (Bruse, 1999), SOLWEIG (Lindberg et al., 2008), VTUF-3D (Nice et al., 2018), FITNAH 3D (Gross, 2002) and more recently, Urban Tethys-Chloris (UT&C) (Meili et al., 2020). Some of these models (e.g. ENVI-met, VTUF-3D) are highly spatially explicit at the cost of high computational burden. Others (e.g. UT&C) are simplified, relying on their parameterisation and an idealised representation for producing a detailed time series of the energy balance at the local scale.

Many micro-, local- and meso-scale microclimate models, however, currently have several limitations for modelling the relationship between stormwater management and urban heat mitigation: the absence of water-related phenomena (e.g. watering green areas or pavement-watering), Blue-Green Infrastructure and their water balance are not explicitly considered and, instead, wet or vegetated land surface covers are used as proxies (Coutts et al., 2016; Broadbent et al, 2019), and their complexity (computational demand) is not suitable for long-term simulations, which is required to understand the timing between stormwater availability and extreme heat days. In the past, few studies have used numerical models to explore the potential of pavement-watering to reduce air temperature and consequently urban heat mitigation. One of the models, the National Integrated catchment-based Eco-hydrology (NICE) model that includes surface-unsaturated-saturated water processes was upgraded to represent the effect of urban geometry and anthropogenic heat generation to analyse the impact of using groundwater to mitigate the effects of UHI (Nakayama et al., 2012). Another study from Wei and He (2013), developed a thermal simulation tool to investigate different surface cooling strategies. These models are however too computationally demanding and therefore not suitable to investigate the long-term impact of the urban heat at the broad district and city scales.

The best attempt at capturing stormwater management related aspects in a microclimate model to the investigators' knowledge is the TARGET model (Broadbent et al., 2019), examples of which undertaken by the investigators are shown in Figure 2. It is a simple model designed to calculate surface temperature at street-scale (30-100 m) and assess UHI effects at city-scale level (> 500 m). TARGET was specifically developed to assess the role of Blue-Green Infrastructure on mitigating urban heat effects. However, as previously mentioned, the representation of these infrastructure is still only accomplished by proxy of alternative static land cover classes. Due to its simple modelling approach, TARGET is suitable for long-term simulations to assess, for example, cumulative impact of UHI effects. This is a suitable starting point for incorporating missing model features including horizontal advection, effects of pavement-watering, more detailed water balance and improved representation of stormwater management systems and practices.

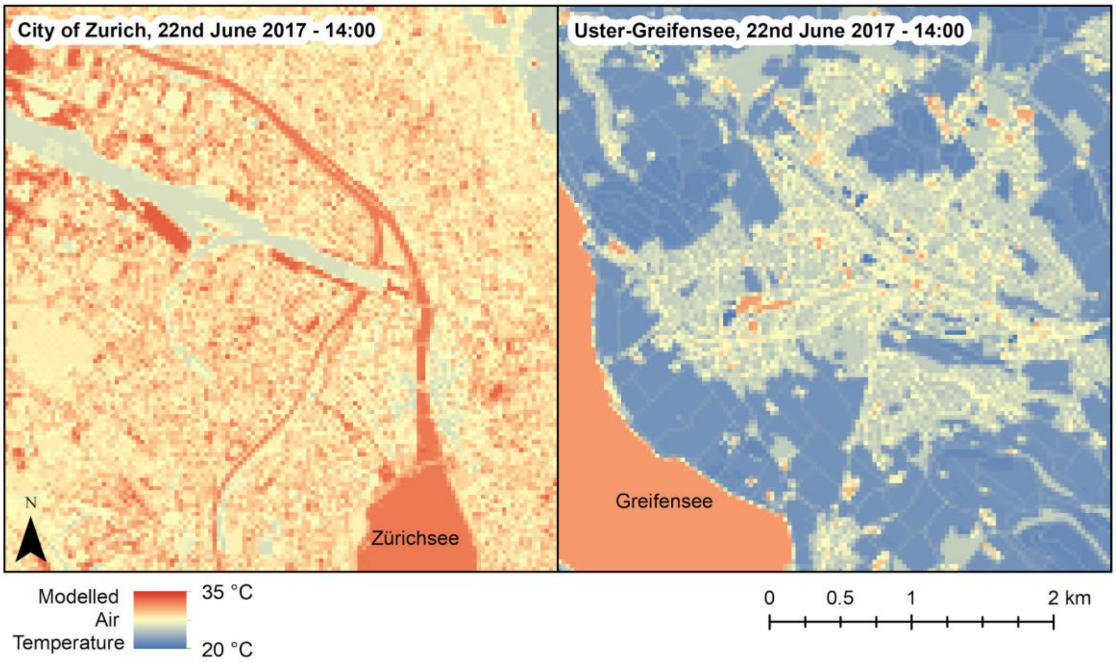


Figure 2. *TARGET urban climate simulation results for parts of two Swiss Cities: City of Zurich (left) and City of Uster (right); part of preliminary analyses conducted by PI Leitão and CI Bach to identify key limitations of TARGET such as erroneous surface temperature results in the lake areas (TARGET is not able to simulate deep water bodies e.g. Zürichsee, Greifensee), limited land surface classification (e.g. railway tracks in Zürich), absence of horizontal advection (seen in lack of radius of influence in both maps).*

2.1.4 Conclusion and research needs

In summary, the research needed to investigate urban heat mitigation taking advantage of new developments in smart stormwater systems and Blue-Green Infrastructure represents a new opportunity to make cities more comfortable, now and in the future. Two key knowledge gaps will be investigated in this project:

- Among urban heat mitigation strategies, the potential of blue-green infrastructure combined with smart stormwater management has not yet been quantitatively studied. Stormwater dynamics, i.e. spatio-temporal availability, will be investigated and the results will allow estimating the stormwater heat budget and associated potential to reduce surface and air temperatures in urban areas.

- In regards to urban climate modelling, recent microclimate models are simple and fast and can be used to assess urban heat over a long time period at the city-scale. However, such models do neither consider the effect of horizontal advection (i.e. wind direction and speed) and deep lakes nor are they able to simulate the effect of direct application of stormwater (or other water sources) over urban surfaces such as Blue-Green infrastructure and pavements, nor can they evaluate the cumulative long-term impacts of urban heat. Such models still need to be developed and tested for typical urban climate conditions and also for future scenarios.

2.2 Current state of own research

Principal Investigator: Dr. João P. Leitão *(Department Urban Water Management, Eawag)*

João P. Leitão is a senior urban hydrology researcher at the Department of Urban Water Management of Eawag. His research has focused on the development of urban flood (stormwater) models, based on dual-drainage and one-dimensional concepts, designed for urban flood forecasting and real-time control (Leitão et al., 2010, 2013; Maksimović et al., 2009). João's research focus has also been focused on the adequate consideration of model input data to improve urban flood modelling using conventional sensors (Leitão and de Sousa, 2018; Leitão et al., 2016; Leitão et al., 2009) and alternative data sources, such as Unmanned Aerial Vehicles (UAVs) (Leitão et al., 2016; Tokarczyk et al., 2015), surveillance cameras (Leitão et al., 2018) and social media images (Chaudhary et al., 2019).

More recently and directly relevant to the tasks proposed in this project, João developed a simple location model and efficient algorithm to identify the best location(s) to install in-sewer flow limiters (Leitão et al., 2018). This advanced stormwater storage technology aims primarily to reduce stormwater peaks and consequently mitigate floods and reduce sewer overflows. Another application of this type of flow control devices that has not yet been explored is to store stormwater to be used for urban heat mitigation - the research focus of the proposed project. This experience on urban stormwater modelling and management is found to be relevant to accurately evaluate the temporal and spatial dynamics of stormwater and assess its potential for urban heat mitigation. Also recently, João has started to investigate the multi-functionality of urban stormwater systems, in particular, the potential of Blue-Green Infrastructure to reduce combined sewer overflow discharges (Joshi et al., in review) and to mitigate urban heat. These early investigations have led to a critical review currently under review (Probst et al., in review). He currently also co-supervises a masters project on total urban water cycle modelling together with CI van de Ven and CI Bach.

Co-Investigator: Dr. Peter M. Bach *(Department of Urban Water Management, Eawag)*

Peter M. Bach is a researcher in Blue-Green Infrastructure and integrated urban water modelling at the Department of Urban Water Management of Eawag. Peter's work has focused extensively on the development of spatio-temporal simulation models for the planning Blue-Green Infrastructure for multiple objectives including stormwater management, urban amenity and, more recently, urban heat mitigation. He is best known for his developed modelling platform that encompasses a broad range of aspects of Blue-Green Infrastructure planning, known as the

Urban Biophysical Environments and Technologies Simulator (UrbanBEATS) (Bach et al., 2019, 2020). UrbanBEATS can model the implementation and adaptation of Blue-Green Infrastructure in urban environments over time and associated stormwater balance. Peter's most impactful interdisciplinary research has focussed on improving model integration (Bach et al., 2014) and their adoption in practice (Kuller et al., 2018), improving the modelling of Blue-Green Infrastructure planning and their integration with the urban form (Bach et al., 2018) to achieve multiple-benefits (Kuller et al., 2017; Joshi et al., in review) and how they are to be adapted in future (Rauch et al., 2017). He is currently deeply involved in a critical review on Blue-Green Infrastructures for urban heat mitigation with PI Leitão (Probst et al., in review) and on rapid assessment models of urban bioclimatic conditions (Back et al. in review) and the total urban water cycle (with PI Leitão and CI van de Ven).

In addition to his modelling research, Peter has also investigated the use of infrared thermography in urban environments, detecting buried pipe leaks beneath grassed surfaces (Bach and Kodikara, 2017) and assessing UHI using ground-based thermography (unpublished work). In terms of microclimate research, from 2015 to 2017, Peter led the development of an industry software tool for urban microclimate mapping known as the *Water Sensitive Cities Toolkit*, funded by the Cooperative Research Centre (CRC) for Water Sensitive Cities in Australia. This work also involved the application and analysis of UHI in key Australian cities in conjunction with industry collaborators and researchers from the Monash University climate modelling group[3], among others CI Nice. Peter's integrated modelling platform, UrbanBEATS, his experience in infrared thermography and work in the microclimate space are all highly relevant to the integration of stormwater and microclimate science, which this project proposes.

Co-Investigator: Dr. Kerry Nice *(University of Melbourne/Monash Uni/CRC for Water Sensitive Cities, Australia)*
Kerry Nice is a research fellow at the University of Melbourne in the Transport, Health, and Urban Design Lab, Melbourne School of Design. He is also a research fellow with Monash University and the CRC for Water Sensitive Cities. Following a 13 year career as a senior level software engineer, he completed a PhD at Monash University in urban climate modelling. He developed one of the first models, VTUF-3D (Nice et al. 2018), to examine the cooling benefits of urban vegetation at a micro-climate scale. This work led to co-development of two other models, TARGET and UT&C (Broadbent et al. 2019; Meili et al. 2020) to examine similar questions at micro- and local-scales. His research using modelling has concentrated on micro-scale human thermal comfort assessments of urban design types (Todorovic et al. 2019; Gál & Nice 2020). He is also engaged in supervision of two PhD students examining the cooling impacts of irrigation.

His research has also expanded to include the utilisation of computer vision techniques and neural networks to take advantage of large amounts of imagery to study and plan the transformation of urban areas for better public health outcomes. Finally, he is a co-investigator on the UKRI-NHMRC Built Environment And Prevention Research Scheme, "A Vision of Healthy Urban Design for NCD Prevention", utilising many of the methods above to identify and redesign urban areas that lead to poor health outcomes.

[3] Ideanthro Ep 175 - Urban heat and the water sensitive city https://youtu.be/zpcG196D7Vw and a news article on *Sustainability Matters* https://bit.ly/2nFNrPR

Co-Investigator: Dr. ir. Frans van de Ven *(TU Delft and Deltares, The Netherlands)*

Frans van de Ven is team leader Urban Land & Water Management at Deltares, the Netherlands institute for delta technology, and he is associate professor Urban Water Management at the Faculty of Civil Engineering and Geosciences of Delft University of Technology. Dr. van de Ven is working on attractive, flood robust and climate resilient cities, while aiming at reduction of the environmental footprint of urban systems. This includes research into (1) concepts for resilient urban land & water management, (2) methods for engineering urban water systems and for control of water quantity, quality, demands and supply and (3) urban planning support tools to implement these improved concepts in practice. His major fields of expertise include: Sustainable urban land & water management systems; how to make the most out of urban surface water, groundwater, stormwater runoff, parks and green infrastructure; *Effectiveness, planning and design of Blue-Green Infrastructure for reducing the impact of extreme rainfall, drought and heat; Climate resilience of urban areas; adaptation strategies and urban planning support systems; improving urban land & water system modelling for adaptation planning; Urban heat stress control and Blue-Green Infrastructure, and* Transition management to realise resilient and sustainable urban systems.

Project partner: Dr. Cintia Dotto *(City of Melbourne, Australia)*

Cintia is the Senior Sustainability Officer at the Climate Resilience team, City of Melbourne. Cintia has over 15 years of experience with environmental projects and urban water management, including a diverse range of roles including academic researcher, consulting and local government. Prior to CI Bach's involvement, Cintia led the early development of a multidisciplinary integrated modelling tool - the *Water Sensitive Cities Modelling Toolkit*, which aimed to quantify the multiple benefits of water sensitive urban design in the urban environment, including its Microclimate Module (Dotto et al., 2012). In her current role at City of Melbourne she explores novel solutions combining integrated water management and urban cooling principals to support policy making and climate change adaptation outcomes. In her former role as research support manager for the CRC for Water Sensitive Cities, she supported research synthesis in the form of software tools, including the adoption of the TARGET model (proposed to be refined in this project) to estimate urban cooling benefits associated with Blue-Green Infrastructure.

2.3 Detailed research plan

2.3.1 Overview, research goals and research questions

The *Heat-Down* project tackles the challenge of urban heat mitigation and the opportunities that are created through multi-functional urban stormwater systems, such as Blue-Green Infrastructure. This not only includes the collection, storage and direct application of stormwater to urban surfaces at intermittent intervals to drive evaporative cooling processes, but also the use of stormwater to maintain and enhance the function of Blue-Green Infrastructure solutions (encompassing both so-called 'Sustainable Urban Drainage Systems' or 'Water Sensitive Urban Design' and existing natural assets, e.g. trees, urban green spaces and water bodies), which drive cooling through evapotranspiration. For this purpose, this project investigates two of the main challenges when considering stormwater to mitigate urban heat: (i) stormwater dynamics and availability in the urban environment and (ii) the lack of fast, simple urban climate models able to assess stormwater Blue-Green and grey solutions and able to run long-term simulations at the district and city scales. The overall practical outcome of the project is an improved understanding and means of assessment of how the combination of Blue-Green Infrastructure and smart and effective stormwater application to natural and anthropogenic surfaces can significantly impact urban heat. The research planned in the *Heat-Down* project is articulated around these issues according to the following research questions:

A. What are the temporal (availability), spatial (infrastructure placement) and temperature dynamics of stormwater and how do they relate to heatwaves and hotspot occurrence (present and future)? (WP A)

B. To what extent can Blue-Green Infrastructure effectiveness be enhanced by smart stormwater management to mitigate local urban heat effects? (WP B)

C. What are the essential requirements for an effective stormwater management strategy at the city scale (i.e. distributed infrastructure, policy and operational requirements) to maximise urban heat mitigation? (WP C)

2.3.2 Project case studies

Two unique case studies (Figure 3) representing two highly contrasted spatial scales, urban densities, climates and infrastructure will be used to validate the *Heat-Down* project model developments. The City of Zurich in Switzerland may face a significant increase (up to 3º C[4]) in day and night temperature, according to climate scenario simulations (Funk et al., 2018). It is the largest city in Switzerland and continues to experience urban expansion; it is located next to a major natural water body (the lake Zurich), which may have a positive impact on reducing UH effects. Recently, the City of Zurich published a plan to mitigate urban heat impacts (Stadt Zurich, 2020), in which different approaches are proposed and preliminarily assessed. In contrast, the second case study, the City of Melbourne (Australia), has ambitious integrated water management and climate adaptation targets that will not be achieved through current practices. Novel approaches that see stormwater as a precious resource are imperative (City of Melbourne, 2017). It faces hot and relatively dry summer climate, has a separate sewer system suitable for in-sewer stormwater storage and a few unique stormwater management and urban heat mitigation facilities (known as the *Innovation Districts*).

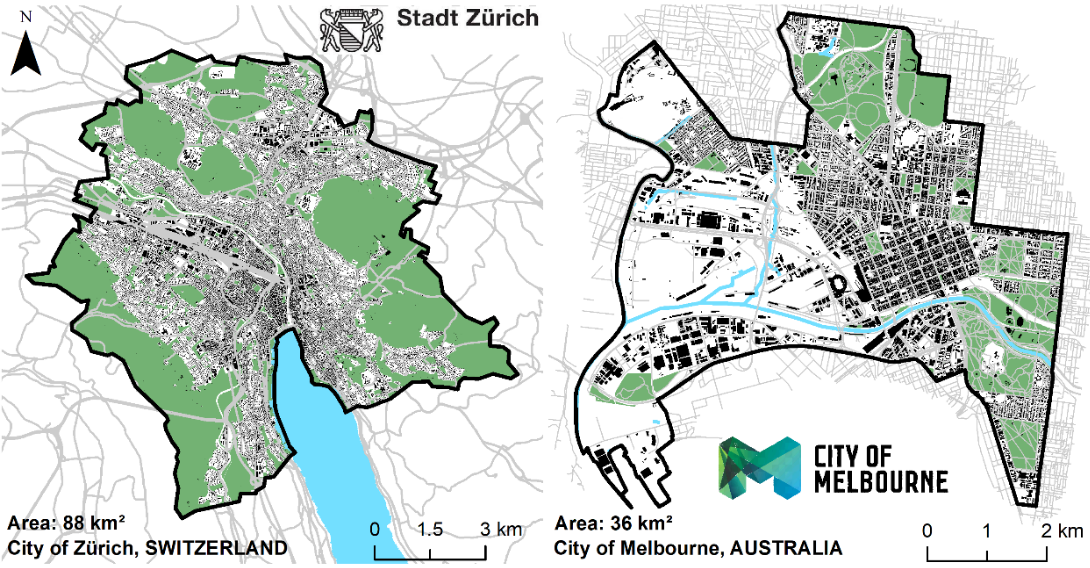


Figure 3. Proposed case studies for Heat-Down, maps depict green and blue spaces and built environment (Sources: Swiss GIS Data from Kanton of Zurich, Australian GIS Data from data.vic.gov.au, Logos - City of Zurich from stadt-zuerich.ch, City of Melbourne from melbourne.vic.gov.au)

[4] Climate analysis map (Klimaanalysekarte) available at http://maps.zh.ch

2.3.3 Project work packages

Much of this project centres around the development and application of an integrated model that couples stormwater dynamics and fast urban climate modelling ***to explore and assess city-wide urban heat mitigation strategies***. The proposed modelling framework and associated Work Packages (WP) are illustrated in Figure 4. Work Package C, in particular, ties the project together and is devoted to data collection for model development, calibration and validation and is present in all parts of the work. Details of each work package and the tasks involved are outlined below.

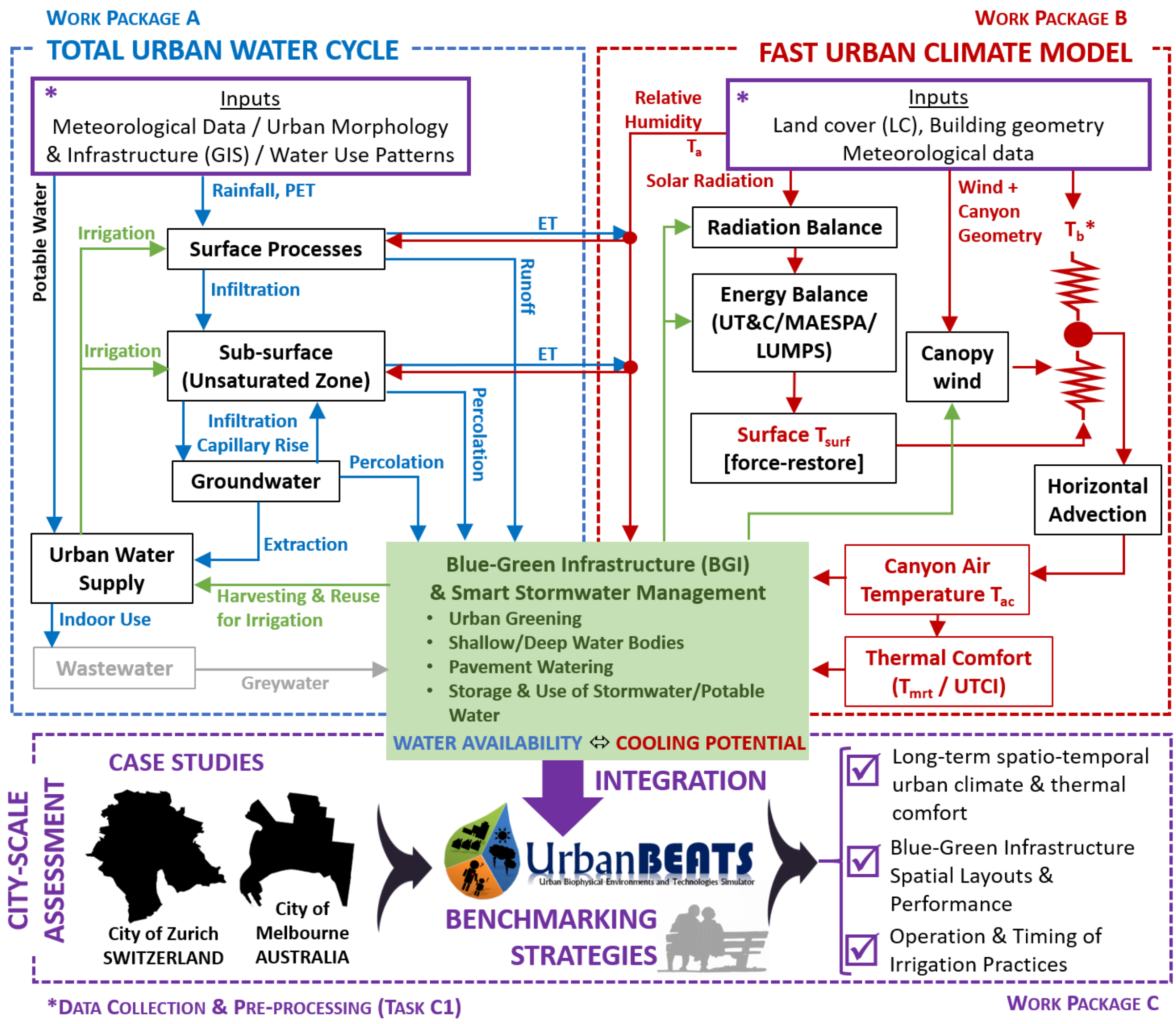


Figure 4. Proposed Integrated Modelling Framework illustrating the linkage between Work Packages and the coupling of Total Urban Water Cycle model with stormwater management options, the modified TARGET Model, which constitute the Fast Urban Climate Model (diagram partly adapted from Broadbent et al., 2019) - ET stands for Evapotranspiration, T_{ac} is the street level air temperature, T_b^* is the air temperature above the urban canopy layer, T_{surf} is the surface temperature, RH is the relative humidity, T_a is the reference air temperature.

WORK PACKAGE A: ASSESS SMART STORMWATER MANAGEMENT POTENTIAL FOR URBAN HEAT MITIGATION (Lead: PI Leitão, CI van de Ven)

Water plays an important role in active (e.g. pavement watering and spraying) and passive (rain) evaporative cooling and in vegetation maintenance, which are considered as important local urban heat mitigation measures. In a previous study, Nakayama et al. (2012) showed that surface-watering using groundwater can reduce surface temperatures but can have a negative impact on groundwater availability, which is used as a source of drinking water in some cities. **Stormwater should therefore be considered as an alternative water resource to reduce urban heat stress.** This work package focuses on the need to understand stormwater dynamics and its temporal relation to extreme heat days. Stormwater availability and its smart(er) management, both temporal and spatial, will play an important role in its potential to mitigate urban heat. To address this as well as the potential cost-benefits (e.g. versus potable water), total urban water cycle modelling needs to be conducted.

Modelling the urban water cycle in a fast and efficient manner has already been investigated over a decade ago (Mitchell et al., 2001) and provides a good foundation for this work. However, concepts and algorithms will need to be adapted to capture the more intricate dynamics of the urban water cycle, in particular: (1) the pipe network infrastructure and the combined drainage systems prevalent in Switzerland (and elsewhere globally), (2) more explicit consideration of Blue-Green Infrastructure and practices (e.g. pavement watering) within the modelling, (3) applying the algorithms in a more spatially explicit manner using a suitable Geographic Information Systems (GIS) framework, and (4) enable urban water balance modelling at high temporal resolution to align with the urban climate model's sub-daily time steps. Table 1 outlines the scope of Blue-Green and grey infrastructure and water-related practices we propose to investigate as part of this project. The first task (A1) investigates the dynamics of these systems while the second task (Task A2) incorporates these into the Total Urban Water Cycle model (Figure 4).

Table 1. Blue-green / Grey measures to mitigate urban heat in Heat-Down, categorisation and multi-functionality

SYSTEM / PRACTICE	INFRASTRUCTURE TYPE	FUNCTION(S)
Rain barrels	Blue-Green Infrastructure	Storage / Flood Mitigation
Rain Gardens / Tree Pits	Blue-Green Infrastructure	Flood and urban heat mitigation
Wetlands / Ponds	Blue-Green Infrastructure	Storage / Flood and urban heat mitigation
Green Walls / Facades	Blue-Green Infrastructure	Urban heat mitigation
Underground storage tanks	Grey Infrastructure	Flood Mitigation
In-sewer storage (e.g. CENTAUR[5])	Grey Infrastructure	Flood Mitigation / CSO mitigation / Storage
Green Space Irrigation	-	Urban heat mitigation
Pavement Watering	-	Urban heat mitigation

TASK A1. Modelling the dynamics of stormwater management systems and practices

To assess stormwater availability to be used in reducing local urban heat via active evaporative cooling or Blue-Green Infrastructures irrigation, a thorough analysis on stormwater storage potential in cities will be performed, providing answers to the following question: *Is stormwater volume sufficient and available when and where required to mitigate UH effects?* Specifically, this task will establish how different systems in Table 1 should be spatially represented and modelled from a stormwater quantity (i.e. water balance) perspective to allow their integration with a broader integrated urban climate model. This evaluation will be supported by incorporating GIS-based representations of the urban environment and using stormwater numerical models, such as EPA SWMM (Rossman, 2015), that are able to include representation of both blue-green and grey infrastructure. On a system-by-system basis, we will analyse storage possibilities of stormwater and its long-term dynamics. In addition, we will investigate

[5] https://www.sheffield.ac.uk/centaur

the available stormwater heat budget, considering the different systems presented in Table 1 to provide a first quantification of the maximum stormwater potential for decreasing surface and air temperatures in urban areas.

TASK A2. Assembling the Total Urban Water Cycle Model

Having established suitable model conceptualisations of the different systems and practices in Table 1, Task A2 will assemble the adapted Total Urban Water Cycle Model and create its link with the Blue-Green Infrastructure (see Figure 4). We will use the Aquacycle water balance model as a starting point (Mitchell et al., 2001), which is capable of representing the urban water cycle at a range of spatial scales (from a household to a catchment), allowing for linking with urban climate models (Mitchell et al., 2008). However, Aquacycle is not spatially explicit and also limited in its representation of soil moisture and sub-surface processes. As such, we propose to adapt elements from another model, known as the Urban Water Balance Model from the Adaptation Support Tool by Deltares[6] (van de Ven, 2016), which better represents the unsaturated soil matrix and interactions with underlying groundwater and uses more rigorous methods for calculating evapotranspiration, which is a key link between the urban water balance and the fast microclimate model (see Figure 4). We will then adapt the model to be spatially explicit, using the integrated modelling framework UrbanBEATS (Bach et al., 2020), developed by CI Bach as its foundation. UrbanBEATS (see Figure 5 for model overview) already has a suitable GIS modelling framework (allowing for different spatial representations of urban data) and an automated procedure for identifying urban catchment characteristics (Bach et al., 2018). This speeds up parameter estimation and the model setup process and allows us to test different scenarios and strategies as part of Task C3 later in the project. The model can also efficiently interface with pipe network infrastructure through EPA SWMM.

A further advantage of using UrbanBEATS for this project is that it already has an available algorithm for automatically generating different Blue-Green Infrastructure layouts in urban catchments for runoff volume reduction, stormwater harvesting and water quality control (Bach et al., 2020) and, thus, will be able to assess the variability in stormwater volumes and storage requirements across the catchment. Detailed model testing will be conducted as part of Task C3 using the case studies from Switzerland and Australia.

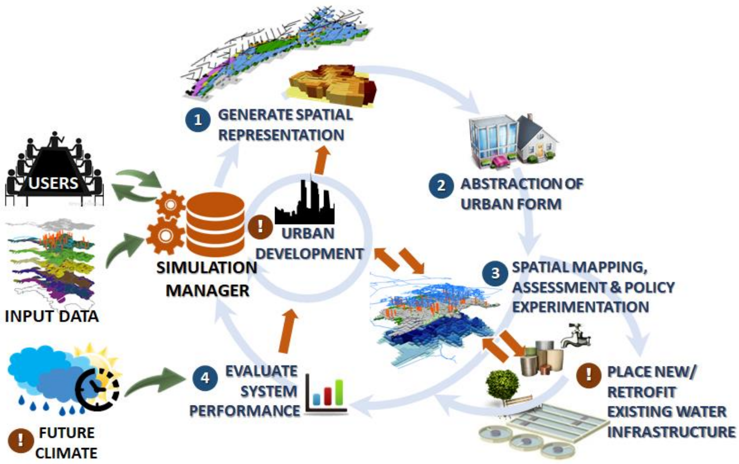


Figure 5. The Urban Biophysical Environments and Technologies Simulator (UrbanBEATS) Framework (adapted from Deletic et al., 2019)

WORK PACKAGE B: DEVELOP A FAST URBAN CLIMATE MODEL TO ASSESS CITY-SCALE IMPACT OF BLUE-GREEN INFRASTRUCTURE ON URBAN HEAT (Lead: CI Nice and PI Leitão)

In WP B, we will develop a fast urban climate model suitable for simulating long multi-year periods alongside the Total Urban Water Cycle (WP A). This urban climate model will not be built from scratch, but instead will rely on

[6] https://publicwiki.deltares.nl/display/AST/Urban+Water+balance+model

enhancing the existing TARGET model (Broadbent et al., 2019). Components from the Urban Tethys-Chloris (UT&C) (Meili et al., 2020) and MAESPA (Duursma & Medlyn, 2012) will be used to augment the hydrology and vegetation modules in TARGET and assist in supplying the functionality for the enhancements described in Tasks B1 and B2.

TASK B1. Modelling Blue-Green Infrastructure, green space irrigation and pavement-watering urban heat impacts

This task aims to upgrade processes that are currently not sufficiently represented in TARGET to make it suitable for simulating the full range of smart stormwater management infrastructure and practices (Table 1). We will utilise two existing models to add these missing components. The first is MAESPA (Duursma and Medlyn, 2012), which is a soil-plant-atmosphere model that has been previously coupled by CI Nice with the TUF-3D model (Krayenhoff et al., 2007) to create the VTUF-3D urban climate model (Nice et al., 2018). This coupling provides the hydrology and physiological processes of a single tree, a stand of trees, or vegetated irrigated surface cover (i.e. turf) that are currently parameterised in TARGET. To add additional surface types (deep water, swales, misting fountains, porous and/or watered pavements), modules from a second model, the Urban Tethys-Chloris (UT&C) (Meili et al., 2020) (co-developed by CI Nice) will be utilised. UT&C provides a wide range of urban hydrology processes (interception, ponding, vadose zone dynamics, runoff, and soil hydrology) and plant water and biophysical relations. It also allows modelling of many different arrangements of vegetation within the urban canyon including green roofs and green walls.

In addition, TARGET will be upgraded to include a simple horizontal advection scheme. These processes are currently neglected for computational reasons (Broadbent et al., 2019) and grid cells are modelled independently of each other. With the addition of this new scheme, wind direction, wind speed, and terrain features will be used to distribute temperature fluxes to nearby grid cells at the end of each timestep. TARGET currently has other limitations outlined earlier that restricts its use to a few climatic conditions (e.g. clear sky days). To this end, another aim of this task is to explore specifically how TARGET behaves under conditions of high cloud cover and rainfall and test its sensitivity to parameters relating to the water balance (e.g. relative humidity, evapotranspiration, soil moisture). These modifications should significantly improve our preliminary model runs (shown in Figure 2). Evaluation of modelled results from the improved model will be validated against air and surface temperature measurements collected with temperature sensors and thermal cameras at street level during different times of the day (see Task C1 for further details). In addition, sensitivity tests will be run on the different types of new infrastructure as well as deriving simple functions and/or lookup tables for use in as an alternative method to parameterise these surface types in TARGET.

TASK B2. Improving the computational efficiency of local-scale urban climate modelling

The resulting model developed in Task B1 will provide the opportunity to simulate a range of infrastructure/practice configurations at the street level and to derive emulators and/or empirical relationships to enable these processes being parameterised into a new faster local-scale model as part of Task B2. Through analysing the results from different configurations, this will help us to understand the level of complexity that needs to be considered for each system/practice. This will also be enabled using similar principles as our previous work in flood modelling (Jamali et al., 2019)[7] to incorporate the algorithms and findings from Task B1 into the model. This allows an option during model runs to use the data-driven relations instead of MAESPA/UT&C code for maximum efficiency. For example, we can translate the results from pavement watering from the improved model into simple surface temperature functions. Blue-Green Infrastructure may exhibit different energy balance behaviours that we can better capture through dynamic modification of surface cover proxies. In addition, these models were originally designed to model shorter duration periods (days to months). Some additional validation will be required to ensure they are suitable for longer periods (1 to 10 years) and to handle a wide variety of climatic conditions, modelling larger areas, and driven by spatial variable forcing data. Validations of the enhanced model from Task B1 and the faster emulator based model from Task B2 and comparisons between the models will be performed using the data sets (see Task C1) from City of Zürich and the City of Melbourne case studies (using their air temperature sensor network). Finally, a sensitivity analysis will be performed to gain a better understanding of the relative impacts of different types of Blue-Green Infrastructure.

WORK PACKAGE C: EXPLORING CITY-SCALE SCENARIOS AND INTEGRATED STRATEGIES FOR URBAN HEAT MITIGATION (Lead: CI Bach and PI Leitão)

The third work package runs parallel to both Work Packages A and B. WP C encompasses data collection and pre-processing for model development, calibration and validation (Task C1). With these data, we then propose to setup the integrated stormwater-urban climate model for our two case studies (Task C2) in order to fully investigate the dynamics of stormwater management for urban heat mitigation (Task C3). The crux of this work package is building a newfound understanding of how to best improve current stormwater management to incorporate the additional benefit of urban heat mitigation in a spatial (infrastructure) and temporal (operation) manner.

TASK C1. Data collection for model development, calibration and validation

The aim of this task is to collect meteorological, stormwater and local air and surface temperature data to support (i) the investigations about the stormwater dynamics in WP A, (ii) the development and validation of the urban climate model in WP B, and (iii) benchmarking urban heat mitigation strategies in WP C (Tasks C2, C3). Most of these data sets to be used in the project are open-source (e.g. the data for the Swiss case study are freely accessible from Canton Zürich) or the access to them has already been granted (e.g. thermal imagery surveys and air temperature records from the City of Melbourne). All these measurements will provide a solid basis to better understand the urban climate phenomena, to evaluate the accuracy and uncertainties of surface and air temperatures simulated by the urban climate model and, to evaluate the impact of stormwater on mitigation of urban heat. The data sets to be collected and pre-processed in the *Heat-Down* project are summarised in Table 2.

Data from stormwater systems are more frequently available than high temporal and spatial resolution thermographic data of urban surfaces. To support the development of the urban-climate model, we will (i) conduct temperature street-level transects across the City of Zurich during day time, night time, clear sky, cloud cover, rain

[7] The study simulated 80 years of 6-minute timestep climate data in SWMM coupled with a water balance model to assess long-term flood mitigation benefits of raintanks. SWMM was run in a semi-continuous mode using boundary conditions from other models as part of its setup.

and during different seasons of the year to get a thorough picture of the thermal behaviour of the urban surfaces. The temperature transects will be obtained using thermal cameras and will cover different urban layout typologies and orientations. For each of the selected areas (minimum five), the transects will be conducted for a period of two years, at least once every month. As a result of the street-level transects, and based on the knowledge of the existing stormwater infrastructure, we will identify an interesting streetscape for the project proposed tasks, where we can explore the potential of blue-green systems and pavement watering. Using GIS, we will map acquired land surface data to our cadastre map of the region. The data will also be used to set up a database of land cover temperatures for the City of Zurich case study. Ground-based thermographic data will also assist in correcting errors in the obtained satellite thermal imagery.

Table 2. *Data sets to be collected and used in the Heat-Down project*

DATA SET	TYPE	SOURCE(S)	PURPOSE
Meteorological data (e.g. rainfall, evaporation, solar radiation, air temperature)	Time series	Meteoswiss.ch bom.gov.au netatmo.com	**WP A and WP B** Model development/ calibration/validation
Surface temperature imagery	Street-level thermal cameras images Satellite imagery	Ground-based transects LANDSAT Aster	**WP B** Model development/ calibration/validation
Building and Street Layout	GIS Data	swisstopo.ch data.vic.gov.au	**WP B** Model development/ calibration/ validation
Local Air temperature measurements	Time series	City of Melbourne stormX project[8]	**WP C** Assessment of urban heat mitigation

TASK C2. Full integration of stormwater and the urban climate models and model setup of case studies

Having reworked the urban climate model to be more computationally efficient and scalable, both spatially and temporally, Task C2 will couple the Total Urban Water Cycle model developed in Task A2 with the fast microclimate model in Task B2. Preliminary integration aspects (outlined in Figure 4) include the propagation of the water balance dynamics of Blue-Green Infrastructure and stormwater management practices into the microclimate model as variations in surface types, changes to evapotranspiration and as emulators that contribute to the overall energy balance calculated within the urban climate model. The integration will be carried out, once again, using the UrbanBEATS platform since many spatial characteristics calculated by the model will also be required as input to simulate urban heat (land covers, building information). As we are investigating the impact of Blue-Green Infrastructure and stormwater management measures on urban heat mitigation, the integration will be mostly sequential (see e.g. Bach et al., 2014) to maintain simplicity and computational efficiency. As such, the total urban water cycle model (Task A2) will inform the urban water and energy balance, but no interaction in the opposite direction is foreseen except in the evapotranspiration relationships and through Blue-Green Infrastructures and smart stormwater practices. Once again, it is also in this task, where we will fully test the proposed simplified methods derived in Task B2, by calling the fast urban climate model under specific conditions during the long-term simulation using water balance outputs as boundary conditions.

[8] StormHeatX project funded by internal Eawag resources (01/2020 to 12/2021) that will deploy a dense network of temperature sensors to measure the heat balance between rainfall, surface and stormwater in urban areas.

To allow benchmarking of urban heat mitigation scenarios, either for present or future conditions, we require a 'Business As Usual' (BAU) scenario to compare against. Task C2 therefore also involves setting up and calibrating the integrated model for the two case studies based on the current state of the urban environment. Model calibration will be undertaken using data sets collected in Task C1, in particular, spatial air temperature measurements obtained from the existing National (Swiss and Australian) and private (e.g. Netatmo network[9]) weather stations, soil moisture measurements from these case studies, thermal imagery data of land surface covers obtained from the street-level transects to be conducted the City of Zürich (Task C1) and already available from the City of Melbourne, and also urban water-related information available for the two case studies (e.g. water consumption, current irrigation volumes, runoff volumes, flow rates in combined sewer systems). To assess model performance, we will conduct both a temporal and spatial validation of outputs using statistical measures such as the Nash-Sutcliffe coefficient of efficiency (Nash and Sutcliffe, 1970) and comparison of frequency distributions in temperatures as well as spatial metrics for comparing GIS outputs of modelled temperatures with validation data.

TASK C3. Benchmarking urban heat mitigation strategies

This final task will specifically explore effective stormwater management strategies, comprising infrastructure and practices, to maximise urban heat mitigation at the city-scale over a period of 10-years. The BAU scenarios that were set up for each case study and validated in Task C2 will be used as the benchmark. Through exploratory modelling (Bankes, 1993), we will then use UrbanBEATS with its newly integrated modules to generate various scenarios of Blue-Green Infrastructure layouts and smart stormwater practices (i.e. alternative water sources, irrigation rules, spatial policies of where and when to irrigate). Given the complexity of this scenario generation process, we will rely on the help of the Climate Resilient City Toolbox (van de Ven, 2016) to guide the scenario generation process. Our proposed scenario experiments include:

- **Infrastructure & Operational Scenarios:** Using combinations of Blue-Green infrastructure options vs. one infrastructure type at a time at multiple scales (e.g. small highly distributed systems vs. single large centralised assets) and operational variables (timing and water source for irrigation, conditions and locations for watering pavements, availability of and leveraging in-pipe storage)
- **Future Climate Scenarios:** Various future climate scenarios to obtain an ensemble of future layouts (e.g. the CH2018 dataset for Switzerland: CH2018 (2018) and CI Bach's dataset on high-resolution down-scaled bias-corrected climate data for the Melbourne region published in Zhang et al., 2019)
- **Planning & Policy Scenarios:** Testing how robust these infrastructure and operational scenarios are to changes in population density across the case study region (derivable from local planning documents) and changes in land uses and/or major water policy (e.g. water use restrictions due to drought or more stringent runoff management due to flood risk)

To fully understand and compare scenarios, we propose a set of performance indicators targeting a range of local, regional, long and short-term aspects (see Table 3). Specifically, being able to simulate long-term urban heat impacts, we also suggest new forms of KPIs that can be calculated from long-term simulation data (e.g. exceedance

[9] Netatmo.com

probabilities). Based on the suite of KPIs and the combinations of model layouts, we will conduct a meta-analysis of model results to identify:

- Overall city-scale impact of urban heat and performance of mitigation measures
- Key hotspots in each case study where urban heat mitigation is most sensitive, essential and most beneficial
- Dominant types of infrastructure layouts and practice combinations for urban heat mitigation
- Maximum achievable mitigation in each case study and their associated costs

Table 3. *Proposed Key Performance Indicators to be used in Benchmarking and understanding the extent to which different stormwater management strategies can mitigate urban heat across the case study regions*

KPI^	CATEGORY	DESCRIPTION & RELEVANCE
Universal Thermal Climate Index - UTCI [ ]*	Human Thermal Comfort	Indicates different levels of heat stress, based on the mean radiant temperature, which is calculated from air and surface temperatures (Bröde et al., 2012), allows benchmarking of high heat-stress areas
Reduction in % of affected vulnerable population [%]	Human Thermal Comfort	Spatial analysis of population likely to suffer heat-related mortality, identifies hot spots for stormwater management, puts UTCI into demographic context.
Reduction in Air Temperatures [°C]*	Urban Heat Mitigation	Extent to which cooling is provided in urban environments by reducing air temperature.
Exceedance probabilities for Air Temperatures [°C]	Urban Heat Mitigation	Understanding the long-term dynamics: the likelihood of exceeding specific air temperatures or heat stress thresholds (definable by e.g. UTCI)
Water Volume Requirement for urban heat mitigation [m^3]	Cost-benefit analysis / Water Management	Understanding how much water is required to achieve the desired UHI mitigation effect.
Potable Water Use Reduction for urban heat mitigation [% and $]	Cost-benefit analysis / Water Management	Cost savings by substituting potable water with stormwater for UHI mitigation.
Cost of Mitigation Strategy (Capital + O&M) [$]	Cost-benefit analysis / Water Management	Total life cycle cost of stormwater infrastructure/practices.

^ KPIs are calculated relative to a ‘Business As Usual’ scenario, where no active UHI mitigation measures are pursued
* These temperature indicators will be calculated and analysed as a frequency distribution rather than a single value since model outputs will be spatially explicit

2.4 Project organisation and milestones

2.4.1 Project organization

The *Heat-Down* project will be conducted by a PhD student (with a background on urban water engineering) for the full duration of the project. A PostDoc researcher with a background in microclimate modelling will join the project by the end of the first year of the project for the duration of two years. The Principal Investigator (Dr. Leitão) will be directly involved in the coordination of the project and, together with Dr. Bach, Dr. Nice and Dr. van de Ven, will take supervision responsibility of both the PhD student and the PostDoc researcher. The tasks of the project are organised in such a way that they can be conducted independently, but also promote exchanges between the PhD student and the PostDoc researcher. The synergies between the two researchers (PhD student and Postdoc researcher) and the four investigators will be fruitful when it comes to urban climate modelling, model integration, and analysis of the impact of stormwater on urban heat mitigation. A tentative project schedule is outlined in Figure 6. Assuming the project is accepted in April 2021, the project could start by the end of June 2021 with the PhD student. The project duration is 48 months, starting with the assessment of stormwater dynamics in, at least, one of the case studies (City of Zurich or City of Melbourne case studies). Intermediate and final project reports will be submitted on a yearly basis.

Final deliverables in the form of a formal Ph.D. thesis and several peer-reviewed journal publications (see Table 4) will be submitted for review. By the end of the project, all relevant data for the case studies will be published on an open platform, such as zenodo.org. Additional participation in international peer-reviewed scientific conferences (e.g. *International Conference on Urban Drainage, International Conference on Urban Climate*) is also planned. To evaluate and explore the practice potential of the developed methodologies and tools, meetings with the case study partners are planned (in the case of the City of Zurich, the project results will be presented and compared with recent urban heat mitigation measures (Stadt Zurich, 2020).

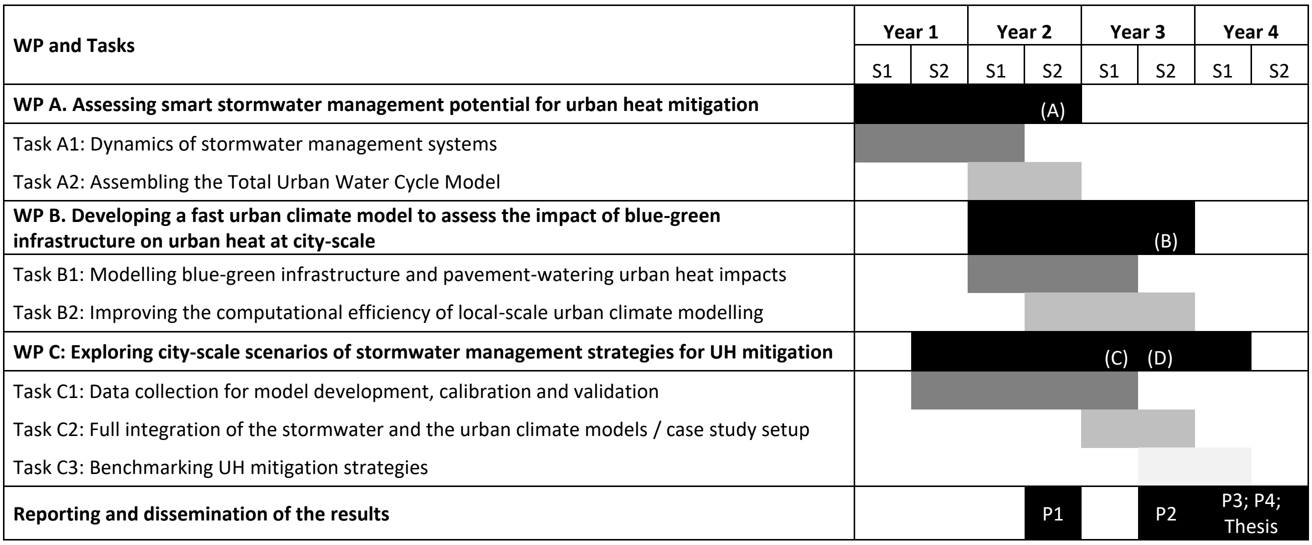


Figure 6. Proposed Schedule of the Heat-Down project, including milestones: (A) Urban water balance model; (B) Improved urban climate model, (C) Collected data completed, and (D) Integrated stormwater-urban climate model.

Table 4. List of planned publications for the Heat-Down Project

TENTATIVE TITLE OF PUBLICATION	TENTATIVE JOURNAL
P1: Is stormwater a valuable resource for mitigating urban heat effects: a supply-demand analysis	*Hydrological Processes*
P2: A new urban climate model to consider the urban water cycle on mitigating the effects urban heat	*Applied Thermal Energy*
P3: Assessing the potential of stormwater to increase evaporative cooling in urban areas and mitigate urban heat effects	*Landscape and Urban Planning*
P4: Identifying suitable placement strategies of Blue-Green Infrastructure for maximising urban heat mitigation along with stormwater management benefits	*Science of the Total Environment*

2.4.2 Risk management

Despite the experience, resources and commitment of project partners, circumstances may lead to a change of course in the *Heat-Down* project. In WP A, the main risk is the difficulty in accessing drainage network data. If this is to happen, the investigators have access to all these data for a small city located near the City of Zurich: Fehraltorf. Although smaller than the other two case studies, it ensures that the objectives will be achieved in the event the other case studies become difficult in terms of data availability. The other two case studies represent different urban realities (different scale and different climates), which can then be used to validate the findings obtained in the Fehraltorf case study. For WP B, no significant risks are identified. Both proposed urban climate models for improvement are open source, and CI Nice (project Co-Investigator) was involved in the development of two of the microclimate models (TARGET and UT&C) to be improved and used in our project. Task C1 involves data collection for the whole project. A significant amount of data is already accessible by the project team, in particular air temperature data from Swiss Meteorological Office and private weather stations, GIS data and the aerial thermal imagery for the City of Melbourne case study. Therefore, the only significant risks associated with data collection will involve the timing, logistics and acquisition of new thermographic data. Although the planning and execution of field trips does not pose any risks, the challenge may be to obtain a diverse enough thermal imagery data set as this is highly dependent on climatic conditions over the duration of the project. Tasks C2 and C3 are relatively dependent on all other project tasks. Therefore there is some amount of risk in the completion of the fully integrated model due to the complexity of sub-models. However, in the event that unforeseen issues arise with the modelling, we will still be able to conduct the fully integrated assessment using each of the models proposed as standalone and interfacing between them manually. The spatial integrated platform UrbanBEATS has been undergoing rigorous testing since 2014 and its development is supported by an international research consortium of five universities, therefore we do not foresee any risks with non-functional software.

2.5. Importance and impact

2.5.1 Scientific significance

The *Heat-Down* project will explore the potential of stormwater to mitigate urban heat. The first key aspect is related to the need of assessing how efficient the use of stormwater is mitigating urban heat; here the simple and fast urban climate model TARGET (Broadbent et al. 2019) will be improved. A second aspect will focus on stormwater spatio-temporal dynamics, i.e. to understand to what extent stormwater can be used to mitigate urban heat based on a spatial water supply-demand analysis. These developments will be applied to two different urban areas in different climate zones to gather a better understanding of urban heat in different contexts.

2.5.2 Social and economic impact

The year 2015 set many weather records, and it appears that extreme weather patterns will become increasingly frequent in the future. The cost of climate change to society will be especially large in urban areas, while the importance of infrastructure planning and management will grow accordingly. The *Heat-Down* project, with the aim of contributing to better understanding urban heat and explore the potential role of stormwater (Blue-Green Infrastructure and pavement-watering) to reducing its impact through rigorous data acquisition and model development and validation, will help urban planners and city managers to make better, evidence-based decisions. Mitigation of urban heat will result in less heat casualties, improve public health , increase in labour productivity, increased outdoor comfort in the urban environment on hot summer days – and hence outdoor recreational activities, reduce power consumption for air conditioning and other cooling. The research questions and associated tasks of the *Heat-Down* project are designed not only with the needs and challenges of urban planners and city managers in mind, but also to take advantage of recent technological developments. As the world becomes more interlaced with sensors and data, city managers and urban planners must learn to take full advantage of the changing environment. For example, street-level air and surface temperature transects can be further explored and contribute to more accurate urban climate modelling which, ultimately, will support the retrofit of existing and design of new more liveable and climate-safe cities.

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