Politecnico di Torino

Master's Degree in

Environmental And Land Engineering

Track: Climate Change

Climate change adaptation using low impact development solutions in an urban catchment

Supervisor:
Prof. Jost-Diedrich Graf von Hardenberg

Candidate:
Carla Maria Di Natale

Advisors:
Prof. Harri Juhani Koivusalo
Dr. Ottar Tamm

Academic Year 2021/2022

October 2022

ACKNOWLEDGEMENT

The study was part of the Eviban project (Evidence based assessment of NWRM for sustainable water management) funded by the EU Water JPI and the Academy of Finland (n:o 326787).

The HCLIM simulations (climate scenario used in this study) were performed by the NorCP (Nordic Convection Permitting Climate Projections) project group, a collaboration between the Danish Meteorological Institute (DMI), Finnish Meteorological Institute (FMI), Norwegian meteorological institute (MET Norway), and the Swedish Meteorological and Hydrological Institute (SMHI).

I am grateful for having had the opportunity to participate in the Erasmus + programme and for being hosted by Aalto University of Technology, which allowed me to work on this thesis.

I would like to thank my supervisors and advisor Prof. Jost-Diedrich Graf von Hardenberg, Prof. Harri Juhani Koivusalo and Dr. Ottar Tamm for giving me the possibility to work on this project and for their precious and constant guidance, advices and feedback related to this research and professional decisions.

Next, I would like to thank all my friends that have supported and encouraged me: the old and far ones for being close even if miles away; the new ones for making me feel at home even in Finland, especially the "library gang" for making days of intense study pleasant to deal with.

Last but not least, I want to thank my big family. In particular, I express my gratitude to my parents and to my brother Giovanni, who have been supporting all my choices during the entire master program. I hope I made you proud of me.

ABSTRACT

Climate change refers to the average long-term changes over the whole Earth. Regarding northern Europe, future climate projections show a general increase of temperature over all seasons. In cold conditions, this change will strongly affect the hydrological features over a year, such as precipitation, snow depth and runoff. Stormwater management is already essential to treat water in urban catchments. Because climate change is complicating urbanization impacts on hydrological features, current stormwater management systems will need to be adapted to altered conditions. Low Impact Development (LID) controls are seen as one option to adapt urban catchments to a changing hydrology.

In order to evaluate local climate change impacts on the hydrology and then realize a climate change adaptation, an urban catchment in Espoo, in southern Finland, was studied. The analysis was performed in three time windows: historical, mid- and far-future, according to the RCP8.5 emission scenario. Air temperature and precipitation time-series from HARMONIE-AROME regional climate model were used as input to simulate the hydrological processes in the study catchment using the Storm Water Management Model (SWMM). This study focuses on analyzing changes in urban runoff and snow dynamics. Their behavior was analyzed seasonally and within the water year together with air temperature and precipitation. When the projected mean air temperature increased, snow water equivalent reduced, leaving almost no snow in the far-future period. This in turn altered the seasonal runoff behavior both in mid- and far-future periods. In fact, mid-winter runoff was modelled to increase considerably, while spring runoff was expected to decrease with respect to historical period. The highest runoff volume and peak flows will still occur in summer. Thus, in order to alleviate for the climate change impacts on urban hydrology, the stormwater management can be used for adaption by installing LID solutions to reduce the total runoff volume in summer. The subcatchments of Vallikallio with the highest total runoff volumes were identified to select locations for LID implementation with high impacts on runoff. The performance of bio-retention cells, permeable pavements and green roofs was evaluated to investigate if and to what extent LID solutions can aid in the mitigation against climate change impacts on the urban runoff regime. All the selected LID scenarios achieved the total runoff volume reduction in summer, having an impact during the other seasons. While permeable pavements and bio-retention cells were projected to behave similarly within the water year, green roofs had a negligible runoff volume reduction in winter. Bio-retention cell scenario was the one that required the lowest LID coverage compared to the other scenarios, with the same scope.

Keywords: Climate change; Urban hydrology; Stormwater management; SWMM; LID.

TABLE OF CONTENTS

List of Figures

List of Tables

1. Introduction

During the last decades, we have been facing climate change and urbanization, two megatrends that affect urban hydrology and modify the water cycle and its mechanisms (Pang, Gu, Launiainen, & Guan, 2022). Because climate change and urbanization are projected to increase, it is important to adapt the current stormwater management systems to better mitigate against pressures on urban catchments, such as urban floods, traffic interruption, economic losses, pollution and health issues (Qin, Li, & Fu, 2013). One type of stormwater management that seems to be a promising adaptation solution to climate change impacts on urban catchments are the low impact development (LID) controls (Eckart, McPhee, & Bolisetti, 2017).

1.1. Climate change

Climate change is a trend that refers to the average long-term changes over the whole Earth. Because of climate change, in Europe a shift toward a warmer or drier climate has already occurred, depending on the region and the climate zone. Changes in air temperature and precipitation have more or less direct impacts on hydrological features. Main changes in the climate zones are projected to occur in the northeastern Europe, and are seen as a shift to a warmer and wetter climate zone. In fact, by the end of the century, the climate zone in southern Finland is projected to shift from cold and snowy winters and rather rainy, short and cool summers to mild winters and rather rainy, long and warm summers (Jylhä, et al., 2010).

Climate change is going to increase air temperature and altering the thermal seasons in Finland. The thermal winter is projected to become shorter, while the thermal summer to become longer in the whole Finland, because spring and summer will start earlier and autumn and winter will start later than today; moreover, autumn is projected to become even longer, shortening the winter. In fact, in the southern Finland, the thermal growing season (characterized by a temperature higher than 5°C) usually starts in the end of April and ends in October, having a length of about 6 months. Due to climate change, the thermal growing season is projected to increase approximately by about 30% or less, depending on the emission scenario taken into account. In fact, by the end of the century, the thermal season will start in the beginning of April and end in November, having a length of 8 months. This will cause earlier and longer spring, summer and autumn, delaying and reducing winter. In particular, the length of spring is projected to increase between 0-60%, thermal summer will increase of about 30%, autumn is assumed to increase about 2 months up to 100% and thermal winter is projected to decrease by about 4 months or even more, so much that it will fade within the end of this century. Thus, in southern Finland, the future seasons are projected to resemble the central Europe (Ruosteenoja, Räisänen, & Pirinen, 2011).

The projected change in the thermal seasons will directly affect the hydrological seasonal cycle in Finland, which is characterized by snow accumulation in winter and snow melt in spring. In fact, snow cover depth and duration are projected to decrease by the end of this century. Due to higher air temperature, the snow bulk temperature is projected to increase towards the melting point, leading to more frequent melt-freeze cycles in the snow pack and increasing the density and grain-size of snow (Rasmus, Räisänen, & Lehning, 2004). Thus, in southern Finland, due to rising temperature, snow accumulation will decrease significantly in winter, leading to snow melt already in winter. As a direct consequence, runoff and water levels will increase in winter, while runoff and snowmelt floods will decrease during spring. Therefore, by the end of this century, permanent winter with air temperature below freezing threshold is projected to become exceptional in the southern Finland, bringing important changes in seasonal runoff dynamics (Veijalainen, Lotsari, Alho, Vehviläinen, & Käyhkö, 2010; Veijalainen, 2012).

1.2. Urbanization

Urbanization is the other trend that affects hydrology. It changes the characteristics and properties of natural catchments by increasing paved and impervious surfaces and drainage. As a consequence, the water balance is modified. (Sillanpää, 2013)

The increment of impervious surfaces modifies the water balance in urban areas. In southern Finland, one of the greatest changes regards the storm water runoff. In fact, catchment lag decreases during warm periods of the year, while both runoff volume and peak flows increase, because of the high extent of impervious surfaces. In particular, the highest peak flows are detected to occur because of rainfall events in summer and autumn. The impacts of higher runoff are hazardous floods and erosion. Moreover, the higher the imperviousness, the lower the quality of receiving waters (Metsäranta, Kotola, & Nurminen, 2005; Sillanpää, 2013). Moreover, urbanization reduces water storage capacity, which is strictly related to floods (Khadka, et al., 2020).

Sillanpää (2013) listed findings about urbanization impacts on snow in catchments in the southern Finland. It was assessed that urbanization does not modify the total runoff generation during the cold season, but the way it occurs in time, because of changed snow properties and spatial distribution. In fact, snowmelt starts earlier and it is separated into a higher number of runoff events with a shorter duration, compared to snowmelt in natural catchments. Thus, urbanization causes the generation of smaller snowmelt runoff volume events. In urban catchments, due to earlier snowmelt combined with warm period contribution to runoff, runoff is generated in a more evenly distributed way during the year (Sillanpää, 2013).

1.3. Stormwater management

Both climate change and urbanization have significant effects on the urban hydrology. While urbanization affects the hydrological response of the catchment because of the increase of impervious surfaces, climate change affects generation and distribution of runoff during the seasons. In cold regions like Finland, their combined effects will lead to significant increase mostly in low flows, followed by moderate and high flows (Pang, Gu, Launiainen, & Guan, 2022). Floods will become more extreme, with increasing frequency and duration and with a higher geographical distribution (Berggren, Olofsson, Viklander, & Svensson, 2012), reduce the snow water equivalent and anticipate snowmelt, which will decrease both runoff and groundwater level in spring (Okkonen & Bjørn, 2010). Because these megatrends are projected to increase in the future, threatening infrastructures and urban life, it is crucial to manage urban hydrology in order to improve quality and quantity of storm water, mitigate climate change impacts and adapt urban catchments to upcoming risks.

There are different types of solutions that potentially reduce urban flood risk and/or pollutant concentration. Examples of such solutions include upgraded drainage systems, best management practices (BMPs) and LIDs. The solution of expanding and upgrading existing drainage systems is the approach that has been applied to drain surface runoff from urban areas. Nevertheless, this approach is not the most efficient among the different solutions. The reason is that the traditional drainage systems are designed to only drain surface runoff, without affecting the imperviousness of urban surfaces. Thus, excess stormwater easily exceeds the drainage capacity and causes floods. Moreover, increasing impervious areas and expanding the drainage system are unsustainable, expensive and unpractical in densely urbanized areas (Qin, Li, & Fu, 2013). Previously, BMPs were designed to reduce soil erosion and sediment load entering waterways (Rao, et al., 2009). More recently, BMPs have been implemented as structural stormwater treatment devices used for pollutant removal (Barrett, 2005) both infield and off-site, as stormwater runoff from impervious surfaces contributes to large quantities of pollutants to waterbodies close to urban areas (Yu, Yu, & Xu, 2013). LID controls are designed to manage urban stormwater in order to bring urban hydrology to the pre-development conditions, dealing with both water quality and quantity. The peculiarity of these solutions is that they work by mimicking processes involved in the natural water cycle. By reducing the percentage of impervious surfaces within urban catchments, LIDs improve infiltration and evapotranspiration, and reduce volume runoff, peak flows and pollutant loads. Recently, LIDs have been used to reduce stress on urban stormwater infrastructures and provide a certain level of resiliency to adapt the catchment to climate change. Thus, they are considered promising solutions for sustainable stormwater management (Eckart, McPhee, & Bolisetti, 2017).

1.3.1. Low Impact Development solutions

Many different studies have been carried out in order to understand the hydrological functioning and the pollutant removal performance of LIDs. For example, Qin et al. (2013) studied the performance of different LID designs on managing floods under different rainfall characteristics in China. They assessed that LID performance is affected by the percentage of LID coverage, percentage of LID drainage area and the effective storage capacity. In general, all LID scenarios evaluated in their study were effective in flood reduction during heavier and shorter rainfall events, while it was reccomended to combine the scenarios with conventional flood control to be effective also during heavier and longer rainfall events. However, according to the process on which the solution is based on (i.e. infiltration, storage and transpiration), each type of LID performs in a singular way: swales have the least impact on flood reduction, but the most effective storage capacity; permeable pavements have the highest impact on flood reduction in most of storm events; green roofs have an effective storage capacity that may allow to totally store stormwater in most of storm events.

Palla et al. (2015) analysed the contribution of LIDs to restore the critical components of natural flow regimes in a small urban catchment in the northern Italy, under different rainfall event return periods. The LID scenarios chosen were green roofs and permeable pavements and their performance was analysed through peak flow reduction, volume reduction and hydrograph delay. The results of their study showed that the volume reduction strictly depended on the retention capability of the catchment, which is modified by the characteristics of LIDs, such as void ratio and storage layer depth. Moreover, the effectiveness of LID controls required a minimum land use conversion area and that the hydrological performance linearly increased with increasing the effective impervious area reduction percentage. Thus, reducing the imperviousness of the urban catchment was a possible method to transform the catchment close to the pre-development hydrological condition.

Zahmatkesh et al. (2015) focused on understading the impacts of climate change on rainfall intesities and stormwater runoff volume and peak flows in New York city. They showed that runoff volume increased for future climate scenarios because of increase in rainfall, but the use of LIDs was able to decrease the long-term average runoff volume and peak flows. Among porous pavements, bio-retetion cells and rainwater harvesting, the pavements were noted to provide the highest peak flow reduction. Therefore, LIDs were found to be promising climate change mitigation solutions.

Some studies that combine the evaluation of LID impact on both quality and quantity have been performed too. One example was shown by Tuomela (2017), who modelled LID controls and assessed their impact on runoff and pollution reduction in an urban catchment in southern Finland. After estimating that impermeable surfaces, such as parking lots, walkways, roads and roofs, contributes most of the stormwater loads, and that precipitation affects the load generation, bio-retention cells and permeable pavements were chosen to control pollutant loads. If LIDs are designed to only reduce runoff volume, they achieve the goal by improving infiltration and evapotranspiration within the catchment, providing some pollutant load removal too. If pollutant removal rates are included in the design, LIDs succeed removing pollutant at the catchment scale. The different LID scearios perform the runoff volume and pollutant reduction in a different way, according to the mechanisms involved, the location and the pollutant. Therefore, similarly to Qin et al. (2013), a combination of different LID types in Tuomela (2017) would be a more effective management option than a LID scenario composed of single LID type, targeting most of pollutants.

1.4. Objectives

This study was motivated by climate change impacts on urban hydrology and by the consequent need to adapt urban catchments through sustainable stormwater management systems. The study had two main goals: to investigate climate change impacts on urban hydrology and to understand how to adapt an urban catchment through LID solutions.

Regarding the first main goal, a climate model result is given as input to the Storm Water Management Model (SWMM) (2022) in order to investigate climate change impacts on the urban catchment of interest. SWMM was the main tool used to simulate the hydrologic features in three time windows (historical, mid- and far-future), in order to quantify how urban runoff and snow dynamics are projected to change within time. Their behavior was analyzed seasonally and within the water year together with air temperature and precipitation.

For the second main goal, SWMM was used to model three LID scenarios, in order to reduce the total runoff volume in the urban catchment of interest. After choosing the LID types according to the mechanisms through which they perform, i.e. evapotranspiration, infiltration and/or storage, the location of the LIDs was evaluated to place them in those subcatchments where LIDs yielded the highest runoff volume reduction. Then, because climate change is going to exaggerate the effects of urbanization, the goal was to understand how the different LID scenarios perform during mid- and far-future periods and if it would be possible to totally mitigate climate change impacts in both future periods, with each LID scenario, and eventually to evaluate how differently the three LID scenarios perform according to the same scope to achieve. Therefore, the intention was not to bring the urban hydrology to the pre-development condition, but to understand performance of different LID scenarios under an extreme future climate change scenario.

The analysis was limited to the suburban area of Vallikallio in the city of Espoo. The meteorological input was from one regional climate model HARMONIE-AROME (Bengtsson, et al., 2017), which is forced by simulations of the EC-Earth Global Climate Model (GCM). Even if the same analysis should be ideally performed by using more than one GCM and Regional Climate Model (RCM), the objective of this study is to demonstrate that the whole chain of computation can be adopted as a methodology, later explained in Section 3, to evaluate the possibility of climate change adaptation of urban catchments through LID solutions.

2. Site description and data

2.1. Study area

The study area of interest is located in southern Finland (Figure 1), where climate is typical of the Baltic areas. According to the Finnish Meteorological Institute (FMI), winter is the longest season and lasts for about 100 days, during which temperature remains below 0 °C. The coolest days occur in the beginning of February, reaching -25 °C and the permanent snow starts covering the surface after a couple of weeks after the season begins. Spring starts in early April, one month earlier than the rest of Finland and the temperature rises above 0 °C up to 10 °C. The thermal growing season begins once the mean daily temperature is higher than 5 °C and the snow melts, depending on the elevation and relative position to the sea. From late May to mid-September there is summer, during which the temperature stays above 10 °C and the warmest days can reach 30 °C; summer thunderstorms occur between 4 and 8 days. Once autumn begins, daily temperature is on the average lower than 10 °C and the thermal growing seasons ends once temperature do not exceed 5 °C anymore, around late October (Seasons in Finland, 2022). The weather rapidly changes in Finland, so there are irregular precipitations during the year. The season that shows a sort of orderliness in rainfall is summer, with rain occurring mostly in the afternoon and early evening. Summer is the rainiest season together with autumn. In fact, starting from March, which is the driest month, precipitation increases until late summer and then decreases toward winter and spring. The annual precipitation in southern Finland is about 700 mm (Climate elements, 2022).

Vallikallio catchment is located in Leppävaara district in the city of Espoo, in the region of Uusimaa (Figure 1). The catchment area is about 11.4 ha and its ground height varies from 29 to 50 m above the sea level. It is a medium-density residential area with about 12300 pop/km^2, mainly built between 1980 and 1990. Half of Vallikallio surface area is impervious; in fact, the catchment is mostly composed by flats and the asphalt covers all the surfaces devoted to the traffic. The study catchment is totally covered by a subsurface storm sewer network that drains the whole area and has direct connections to traffic areas and most of the roofs. The stormwater runoff at the outlet discharges further untreated to Monikonpuro Brook water body. The impervious area that is directly connected to the stormwater system is about 29% of the total catchment area (Metsäranta, Kotola, & Nurminen, 2005; Sillanpää, 2013).

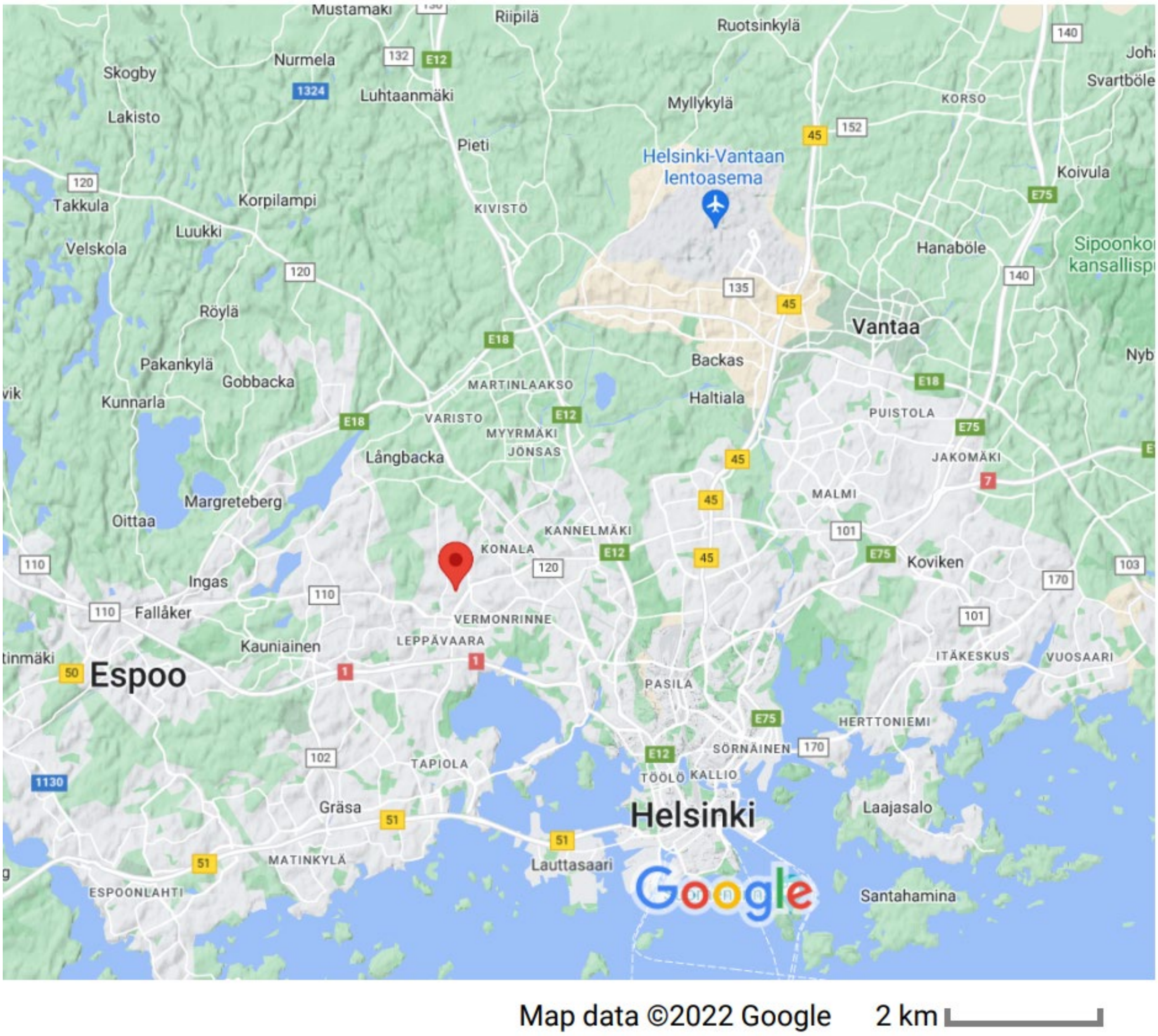

Figure 1: Location of Vallikallio catchment area, indicated with the red pin in the map. The image is taken from google maps.

2.2. Data and materials

In order to perform the simulation of the hydrological processes in the study catchment, the time-series chosen as input to the SWMM were air temperature and precipitation, which were downscaled and bias corrected by (Tamm, 2022) for this study. These time-series have an hourly resolution and come from the HARMONIE-AROME RCM. This model is also used as Numerical Weather Prediction (NWP) model to perform short-range weather forecasts and used in some countries such as Finland. It is developed as part of the ALADIN-HIRLAM system (Bengtsson, et al., 2017). This regional climate model is a state of the art in Finland, but can well replicate extreme rainfall events and provide accurate precipitation data. This regional climate model is forced by simulations of the EC-Earth GCM.

Among the future scenarios, the one that was chosen is the Representative Concentration Pathways defined for the Climate Model Intercomparison Project 5 (CMIP5) by different expert groups. Precisely, the RCP8.5 scenario was selected to perform the analysis. According to this high emission scenario, the radiative forcing is projected to reach values greater than 8.5 W/m^2 by the end of this century, compared to the pre-industrial level, and it will continue to rise for some time. The reason behind this choice is that RCP8.5, being the worst case scenario in terms of radiative forcing, allows to demonstrate if climate change impacts can be quantified and managed.

The analysis was performed in three time windows: historical that goes from 1986 to 2005; mid-future from 2041 to 2060; far-future from 2081 to 2100. In this way, it was possible to evaluate the evolution of climate change impacts in Vallikallio, by comparing the hydrological features that were observed to their future projections, according to a specific scenario.

The main tool used to simulate the hydrological features of Vallikallio catchment is SWMM. The catchment model that was used to run the simulations over the three time windows was provided by Koivusalo et al. (2022), who modified the model by Tuomela et al. (2019) in order to run it through all the seasons. For detailed information see Tuomela et al. (2019). Figure 2 presents the model of the Vallikallio catchment, which is discretised into 610 subcatchments according to their use, under the asusmption of homogeneous properties. The subcatchments are all linked together through 44 junctions and 43 conduits, forming the whole undergroud drainage system, whose outlet is also shown in the map. Table 1 lists the categories of subcatchments that compose Vallikallio: vegetation, sand, pavers, walkways, parking lots, roads, roofs and rocks. The subcatchment categories are characterised by a specific percentage of imperviousness that is shown in Figure 2 and Table 1. In general, almost 56% of the total surface area is impervious (see Section 2.1). More details about the Vallikallio catchment model are provided in Tuomela et al. (2019).

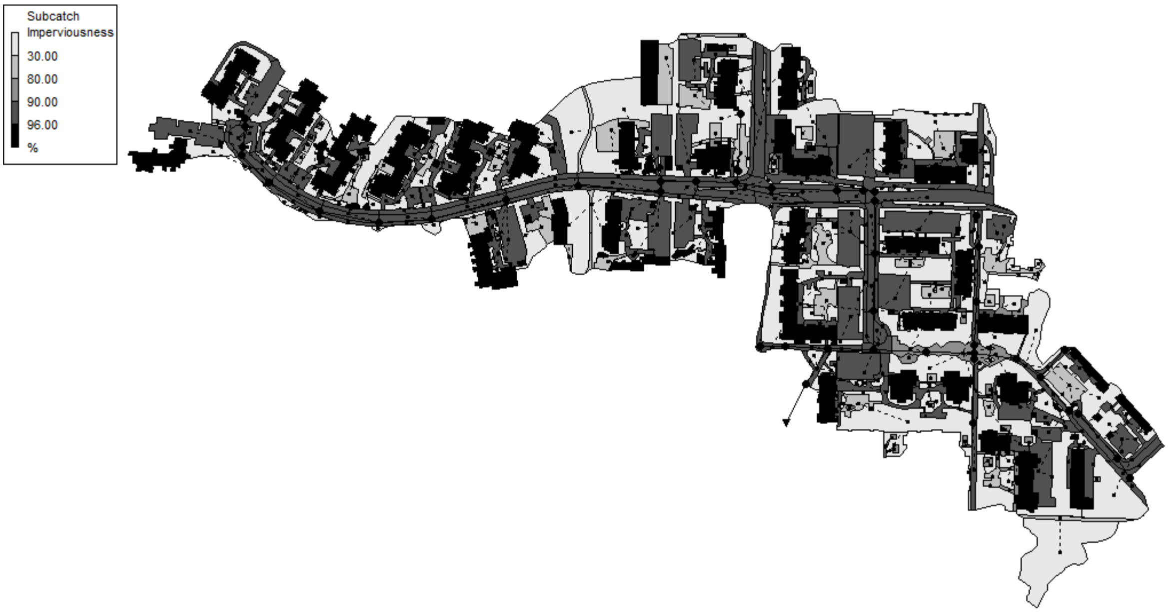

Figure 2: Model of Vallikallio catchment in SWMM with surface imperviousness, sewer network and its outlet. The legend indicates the percentage of imperviousness of each subcatchment.

Table 1: List of subcatchment's tag and respective area and imperviousness percentage. The colour map is related to the legend in Figure 3.

Subcatchment's tag	Area [%]	Imperviousness [%]	Level of grey
Vegetation	37.7	0	
Sand	6.4	33	
Paver	2.1	85	
Walkway	15.3	95	
Parking lot	12.8	95	
Road	6.4	95	
Roof	18.8	100	
Rock	0.4	100	

In Figure 3, it is clear how the daily mean air temperature is generally increasing in both future periods during the entire water year, according to the RCP8.5 scenario. The mean temperature during cold months is noteworthy: in the mid-future, the air temperature will still be below 0 °C during winter, but not anymore during late autumn nor early spring compared to the historical period. However, in the far-future, the daily mean temperature is projected to increase so much that it will barely reach 0 °C even during winter, changing drastically the hydrological features of Vallikallio catchment.

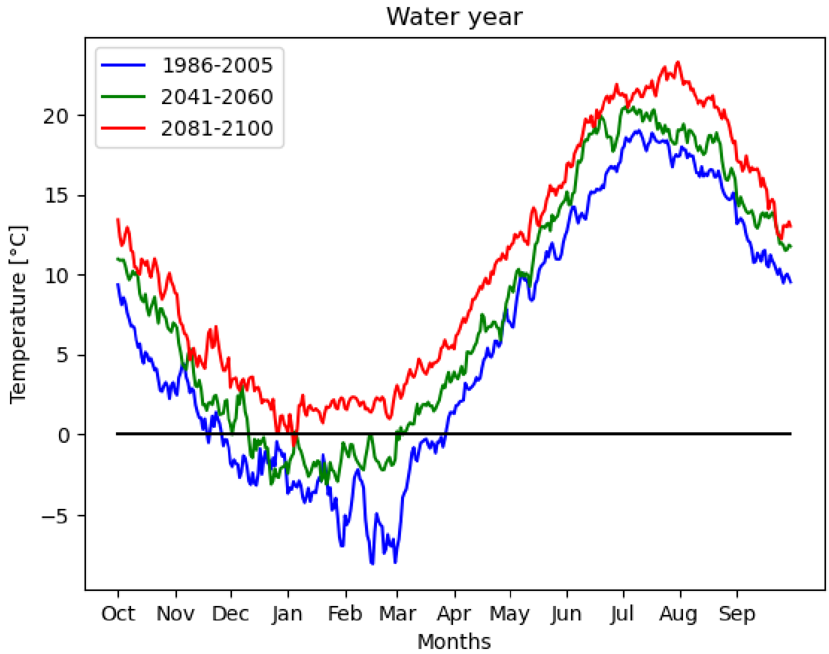

Figure 3: Daily mean surface air temperature over the water year. The blue, green and red lines represent respectively historical, mid- and far-future scenarios. The horizontal black line represents zero degrees Celsius.

The second simulation input that was chosen to show climate change impacts on the hydrology of Vallikallio catchment is the precipitation, which is shown as cumulative mean value within the water year in Figure 4. In the mid-future, the cumulative precipitation is projected to behave in a similar way with respect to the historical one, with a slight increase in the total amount. A more evident increase in precipitation is visible in the far-future period after the first weeks of the water year.

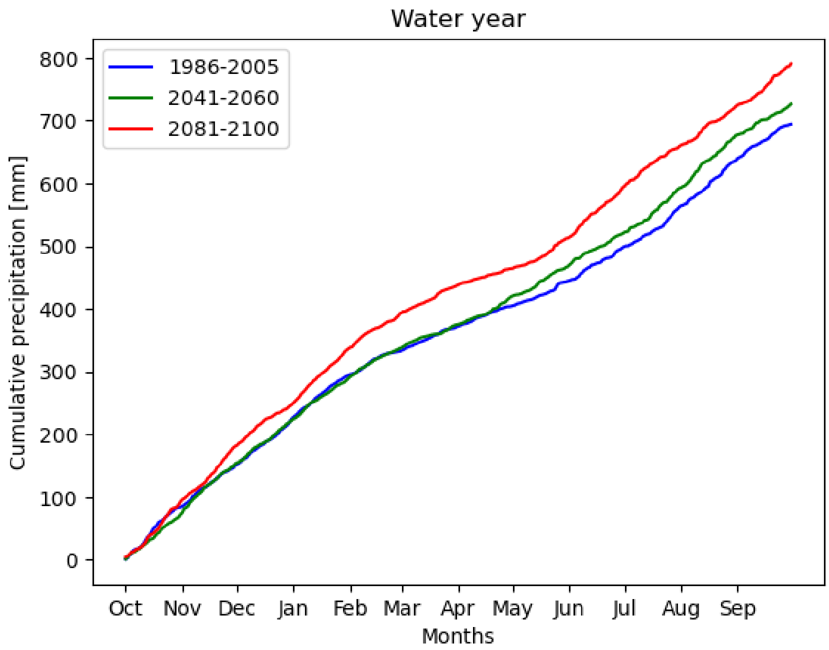

Figure 4: Mean cumulative precipitation over the water year. The blue, green and red lines represent respectively historical, mid- and far-future scenarios.

3. Methods

The methodology used in this study is illustrated in Figure 5, and it is described in detail in the following sub-sections.

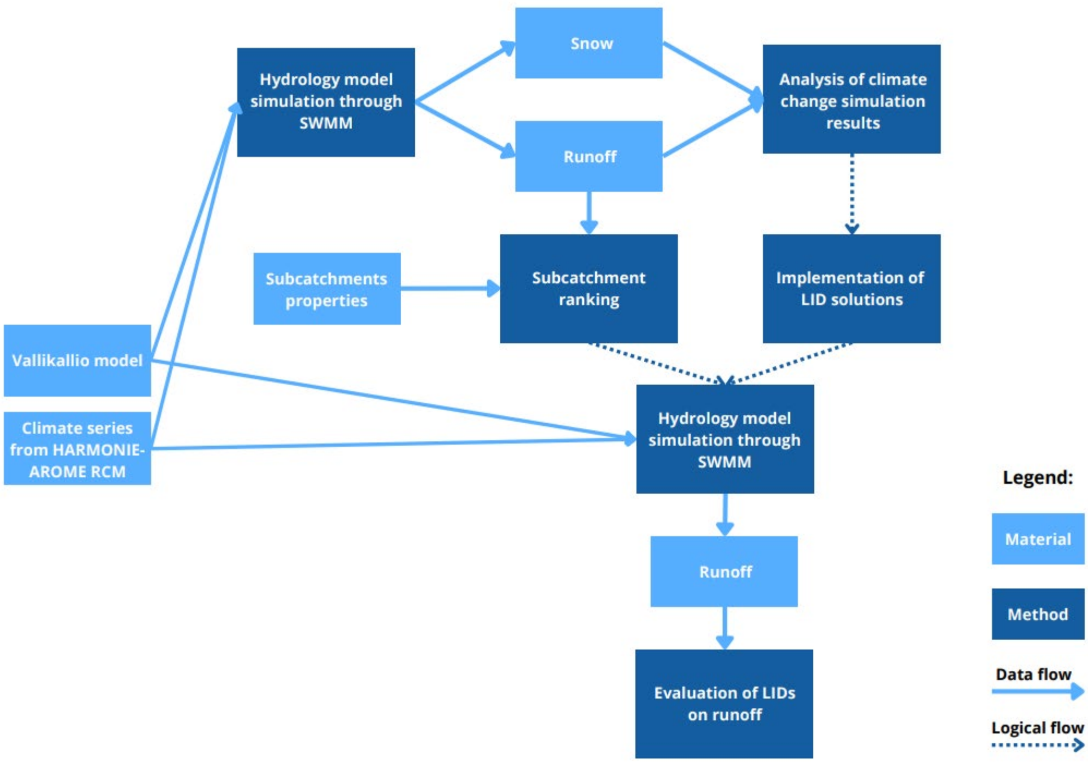

Figure 5: Flowchart representing all the methodological steps to perform the analyses.

3.1. Hydrology model simulation: SWMM

In order to perform the urban hydrology simulation, the SWMM software was used. It is a dynamic rainfall-runoff simulation model provided by the United States Environmental Protection Agency (U.S. EPA). It allows users to design and analyse stormwater management in urban areas, including different options of drainage system and stormwater control solutions. However, it is useful in describing non-urban areas and their drainage systems as well. SWMM provides the possibility to perform hydrologic, hydraulic and water quality simulations. Moreover, SWMM allows simulating performances of many LID solutions in runoff management and pollution removal (Storm Water Management Model (SWMM), 2022). All the hydrologic simulations were performed by using a warm-up period starting from the 1st January to the 30th September of the first available year of each time window.

Regarding the subcatchment object, SWMM allows to capture and retain rainfall and/or runoff coming from other subcatchments through LID controls, which are considered as properties of the subcatchment. There are eight different types of LIDs available in SWMM and, depending on the type, they can retain, infiltrate and/or evapotranspirate water. Table 2 lists layers and processes that characterize the LIDs available in SWMM. Bio-retention cell is a depression filled by vegetation. Surface and soil are required layers to model bio-retention cells, while storage and drain ones are optional. The LIDs with surface and soil layers can provide storage, infiltration and evaporation of rainfall or surface runoff coming from surrounding areas. Rain garden is one type of a bio-retention cell that cannot provide storage, because the storage layer is missing, as well as the subsurface drain option. Therefore, the rain garden is characterised by evapotranspiration and infiltration. Green roof may be considered as a bio-retention cell that lets rainfall in excess to flow out of the roof. It requires surface and soil layers, so it reduces runoff mostly through transpiration and attenuation, because it does not have a high infiltration capacity. Permeable pavement allows a very fast infiltration of rainfall or runoff through the surface to lower layers. Surface, pavement and storage are the required layers, while soil and drain may be included. Infiltration trench is a ditch that requires surface and storage layers and the presence of drain is optional. It provides storage and slows down the infiltration of runoff in the native soil. Rain barrel is simply a cistern that collects runoff from the roof and that gives the possibility to re-use or release collected rainwater during dry periods. Storage and drain layers are required. Roof disconnection discharges rainfall from the roof to pervious areas instead of the storm drain; it requires surface and drain layers. Vegetative swale is a depression characterised by sloping sides and covered by vegetation. The only layer of which it is composed is the surface one and is characterised by infiltration.

Table 2: Description of LID control layers and processes.

LID	Layer						Process		
Type	Surface	Pavement	Soil	Storage	Drain	Drainage Mat	Transpiration	Infiltration	Storage
Bio-retention cell	R	-	R	O	O	-	P	P	P
Rain garden	R	-	R	-	-	-	P	P	N
Green roof	R	-	R	-	-	R	P	N	N
Permeable pavement	R	R	O	R	O	-	N	P	P
Infiltration trench	R	-	-	R	O	-	N	P	P
Rain barrel	-	-	-	R	R	-	N	N	P
Roof disconnection	R	-	-	-	R	-	N	N	N
Vegetative swale	R	-	-	-	-	-	N	P	N

-	not included
N	not provided
O	optional
P	provided
R	required

SWMM allows to add LID solutions in one subcatchment in two different ways. The first option is to place one or more LID controls in an existing subcatchment. The LIDs may be different in the same subcatchment. If multiple LID solutions are placed, the only way they work is in parallel, which simplifies the runoff treatment because it cannot flow from one type of LID control to another in the same subcatchment. The second option is to place only one LID solution in a new subcatchment that has to be created for this purpose. In this way, LID controls work in series. (Rossman, 2015). In this study, the first option was chosen, because in the file that models Vallikallio catchment each subcatchment is defined with a specific tag according to the object that it represents. Therefore, one single LID solution was placed in a selected subcatchment.

In order to evaluate the impacts of LID solutions on the urban hydrology and see how differently they perform according to the layers they include, green roof, permeable pavement and bio-retention cell are the type of LID solutions that were chosen to realise a climate change adaptation of the urban catchment. As listed above in this section, these three type of LID solutions are characterised by different layers (see Table 2): green roof does not include storage as the others do, but it is the only one including a drainage mat; permeable pavement is the only type with pavement; bio-retention cell can occupy a very small fraction of the subcatchment with respect to the others. As described in Section 2.2, the subcatchment types are: vegetation, sand, rock, roof, pavers, walkway, road and parking lot. Thus, it was decided to place: green roof in roof subcatchments for treating direct rainfall; permeable pavement in both walkway and parking lot subcatchments, and bio-retention cell in parking lot subcatchments. Permeable pavement and bio-retention cell can treat both rainfall and runoff coming as inflow from the subcatchment that the LID is linked to.

3.2. Analysis of climate change simulation results

Besides air temperature and precipitation that are the input variables of the simulation, runoff and snow water equivalent are two of the simulation outputs that were chosen as variables to understand the impact of climate change on the hydrological features, both in the water year and seasonally.

In order to analyse the results of the simulations within the water year, for each variable, the 29th of February of each leap year was removed to have the length of all the years of each time window equalled 365 days. The data were ordered starting from the 1st of October to the 30th of September. Then, the mean value of each day of the year was computed for each time window. Regarding precipitation and runoff, their cumulative values were computed and visualized to perform the analyses. Thus, to appreciate the impacts of climate change on each variable, the average water year of each time window were compared.

To better understand how the changes occur during the year, the analysis of the variables was also performed for each season, with the exception of snow. The main focus of the seasonal analysis was on runoff, in order to understand how it is seasonally influenced by the changes in the input variables.

3.3. Subcatchments ranking

In order to use LID controls to mitigate the climate change impacts on the urban hydrology, it is crucial to decide where to place them. Therefore, all the subcatchments in Vallikallio catchment were ranked using to the following criteria: total runoff volume, subcatchments use and their area.

Because the aim of this study is to reduce the total volume runoff to the historical value, the first criterion chosen to rank the subcatchments is the total runoff of each subcatchment in the historical period. Thus, the Summary Report tool of SWMM was used to get a list of the total runoff in [mm] of each subcatchment. Then, in order to be able to compare the runoff from subcatchment with different extension, the second criterion was the area of subcatchments. Thus, the [mm] of total runoff from each subcatchment was multiplied by the area of the relative subcatchment, obtaining the list of the total runoff volume of each subcatchment. In this way, the total runoff generated by the different subcatchments are comparable to each other. Moreover, because green roof, permeable pavement and bio-retention cell were the chosen types of LID controls, the last criterion is the type of subcatchment according to their use. Thus, the subcatchments that were compatible to those LIDs and that were ranked were: roof, parking lot and walkway. Precisely, roofs were ranked in order to install green roofs; parking lots and walkways for permeable pavements and parking lots for bio-retention cells. In the end, subcatchments were ranked from the ones with the highest total runoff volume to the lowest, so that the most important subcatchments could be picked.

3.4. Implementation of LID solutions

After the subcatchment ranking, the next two steps were: to make the LIDs parameterization and to quantify the required amount of each LID type to be installed.

The LID parametrization is set up in two phases: the first phase (LID Control) is made on a per-unit-area criterion and aims to define the properties of layers of a LID type; the second phase (LID Usage) is used to set the dimensions of the LID solution according to the subcatchment occupied. Table 3 shows the parameters used to define the LID controls with the parameter values collected from literature (Krebs, Kuoppamäki, Kokkonen, & Koivusalo, 2016; Tuomela, 2017). All the LID controls belonging to the same category were defined with the same parameter values with few exceptions, meaning that the parameters remain almost constant in all the subcatchments devoted to the same LID solution. The only exceptions were the surface slope of permeable pavement and green roof, which was set to be equal to the subcatchment slope in which they were placed, and the seepage rate of permeable pavement and bio-retention cell, which was set equal to the hydraulic conductivity of the native soil to allow the infiltration from the system to the soil below. The LID Usage parameter values are listed in Table 4. The number of units per each subcatchment was set to 1 as discussed in Section 3.1. For both green roof and permeable pavement controls the LID coverage was assumed to be 100%, while the bio-retention cell covered about 13.3% of the total subcatchment area. The surface width of green roof and permeable pavement was set to be equal to the width of the subcatchment in which it was placed. The surface width of bio-retention cell it was set equal to zero, because this control spills any excess captured runoff over its berms. It was assumed that area occupied by a LID control is not initially saturated. The impervious area percentage of the subcatchment treated by bio-retention cells was set equal to 100, while for green roof and permeable pavement it was set to 0, because these LID solutions cover the entire subcatchment area.

According to the LID parameterisation scheme explained above, it was not possible to define one single green roof, permeable pavement and bio-retention cell that could fit all the subcatchments selected for each category, because some of the properties and parameters depended on the characteristics of the subcatchment. The subcatchment-specific parameterisation of each LID control was automized by PySWMM script considering the respective subcatchment properties.

Table 3: LID control parameters used for LID simulations.

Layer	Parameter	Unit of measure	Green roof	Permeable pavement	Bio-retention cell
Surface	Storage depth	mm	30	0	200
	Vegetative volume fraction	-	0.1	0	0.15
	Surface roughness	-	0.168	0.2	0.6
	Surface slope	%	*	*	0.5
Pavement	Thickness	mm	-	75	-
	Void ratio	-	-	0.24	-
	Impervious surface fraction	-	-	0	-
	Permeability	mm/h	-	360	-
	Clogging factor	-	-	**0	-
Soil	Thickness	mm	100	400	700
	Porosity	-	0.41	0.463	0.52
	Field capacity	-	0.29	0.094	0.15
	Wilting point	-	0.02	0.05	0.08
	Conductivity k	mm/h	37.9	114	119.4
	Conductivity slope	-	40	48	39.3
	Suction head	mm	61.3	49.53	48.26
Storage	Height	mm	-	300	300
	Void ratio	-	-	0.43	0.5
	Seepage rate	-	-	***4.21	***4.21
	Clogging factor	-	-	**0	**0
Drainage Mat	Thickness	mm	3.8	-	-
	Void fraction	-	0.41	-	-
	Surface roughness	-	0.01	-	-

* same as the subcatchment slope
** ignored
*** same as the hydraulic conductivity of the native soil

Table 4: LID usage parameters used for LID simulations.

Parameter	Unit of measure	Green roof	Permeable pavement	Bio-retention cell
N° of units	-	1	1	1
Area of subcatchment occupied	%	100	100	13.3
Surface width per unit	m	*	*	0
Area initially saturated	%	0	0	0
Impervious area treated	%	0	0	100

* same as the subcatchment width

Since summer is the season that has a very high total volume runoff and precipitation and the highest peak flows compared to the other seasons in each time window, the summer runoff volume was selected as the target value for designing LIDs. The target was to reduce the mid- and far-future volume runoff in the summer season to the historical value.

In order to understand how many square meters are required to obtain the reduction of runoff in summer, for each type of LID solution and in each future period, the same procedure was adopted for green roof, permeable pavement and bio-retention cell, which is the following. First of all, according to the ranking, each LID solution of interest was installed in the 15 most important subcatchments of the category devoted to that LID type, as a test. A new simulation was run for each LID scenario both in mid- and far-future time windows. So doing, it was possible to quantify the runoff reduction obtained in summer thanks to the introduction of LID solutions in the catchment by computing the difference between the total runoff volume of each future period before and after placing a certain LID in 15 subcatchments, in summer. After that, the total runoff volume reduced by a certain LID type in a certain future period can be normalised dividing the area of 15 subcatchments covered in total by that type of LID solution, obtaining a normalised LID impact. In order to quantify the total runoff volume that needs to be reduced in each future period, regardless of the type of LID solution, the difference between future total runoff volume and the historical one, in summer, was computed. In the end, the area required to place a certain LID solution was obtained by computing the ratio between the total volume runoff that is needed to be reduced in summer and the normalised impact of LID on the total volume runoff in summer. Thus,

$$\boldsymbol{A_{tot,i}} = \frac{\boldsymbol{V_f - V_h}}{\boldsymbol{(V_f - V_{f,i})/A_i}} \tag{1}$$

where $A_{tot,i}$ is the total area that needs to be covered by a LID type i [m^2], A_i is the total area covered by the 15 LIDs of type i in the experiments, V_f and V_h are the total runoff volume in the baseline case in the future and historical periods respectively [m^3], and $V_{f,i}$ is the total runoff volume in the 15 LIDs type i case in the future period [m^3].

This simplifying approach, allowed to obtain the total area that is needed to be covered in the case of green roof, permeable pavement and bio-retention cell for both mid- and far-future periods. The required amount of square meters in each case was reached by summing up the area of the most important subcatchments according to the ranking previously performed. The required amount of each LID solution was placed in both future periods and new simulations were run.

The LID parameterization was performed in Python, using the package PySWMM, which allows the manipulation of SWMM through a coding interface. PySWMM was used to read into the model and interact with the simulation, setting the LID control and usage parameters in an automated way, (McDonnell, et al., 2016).

3.5. Evaluation of LIDs impact on runoff

The results of the simulations that include the required amount of LID solutions for each case were analysed in order to understand how the different types of LID solutions affect total runoff volume, number of runoff events, and peak runoff in mid- and far-future versus historical ones in each season, considering that the LID designs were based on reducing summer runoff volume.

The cumulative runoff was computed for each season, LID scenario and time window. The series were compared to see how differently the three LID controls perform in each season and what the runoff reduction is according to them.

SWMM includes the Statistics Report tool that computes statistical characteristics for each event and for the entire set of events of the simulation results. The reporting needs the following specifications: object category and name to analyse, the variable analysed, event time period’s length, event statistic to be analysed and specified event thresholds. In this study, the system was chosen as object category and the variable analysed was the runoff, because the total volume runoff is the variable of interest. It was decided to define an event based on the number of consecutive periods in which the variable is above the defined thresholds, so the event-dependent time period was chosen. The total statistic was selected and, in order to determine when a value can be included in an event or not, the event thresholds were set: 1 l/s as runoff flow; 114000 l as runoff volume, resulting from 1 mm times the total catchment area, and 3 h as separation time between the end of one event and the begin of the following one. According to the threshold values, the Statistics Report tool generated a table showing rank-ordered event periods that included the starting date, the duration and the magnitude of each event. The event date information further facilitated to quantify the number of total events occurring in each season. This analysis was performed for each LID scenario and in each time window in order to make a comparison of the evolution of the number of events. The number of runoff events in each scenario was divided by the years that compose the time window in order to deal with annual seasonal average number of events.

In order to see how the LID controls seasonally affect the peak runoff, the highest runoff value of each year was computed and ranked in each time window.

Assuming to deal with statistically independent sample of *n* observations, where n in this case is the size of the time windows (19 years), the standard error of the mean (SEM) of the historical, mid-future and far-future baseline scenarios was computed as the ratio between the standard deviation and the square root of *n*. This computation allows evaluating if there is a relevant difference between historical and future projections and between future baseline and LID scenarios.

4. Results

The first section of the results addresses at what extent climate change is projected to affect the urban hydrology of Vallikallio according to the RCP8.5 emission scenario. The second section presents the impacts of LID solutions that were chosen to mitigate the climate change effects on hydrology. As explained in Section 3.2, air temperature, cumulative precipitation and runoff and snow water equivalent are the variables that were selected among all to perform the analyses, both in the water year and seasonally. The behaviour of air temperature and cumulative precipitation were already viewed in Section 2.2.

4.1. Impact of climate change on hydrology

The combined change in air temperature and precipitation affects the hydrological response of the studied urban catchment in a clearly visible way, and the effects depend on the future period and the season. The two hydrological responses taken into account are runoff and snow water equivalent. In fact, the increase in the air temperature affects directly whether precipitation is falling in the form of rain or snow and the way snow accumulates and melts, which consequently has impacts on runoff.

Regarding snow, Figure 6 shows clearly how the snow water equivalent is going to change in the future periods compared to the historical one. Already in the mid-future time window, the snow water equivalent is projected to decrease by about 58%, even though the period of accumulation remains almost unchanged. However, in the far-future, the reduction is projected to be about 95%, resulting in almost zero snow in winter. Moreover, because of the projected far-future air temperature trend, the period of snow accumulation will be even shorter than the historical and mid-future time windows.

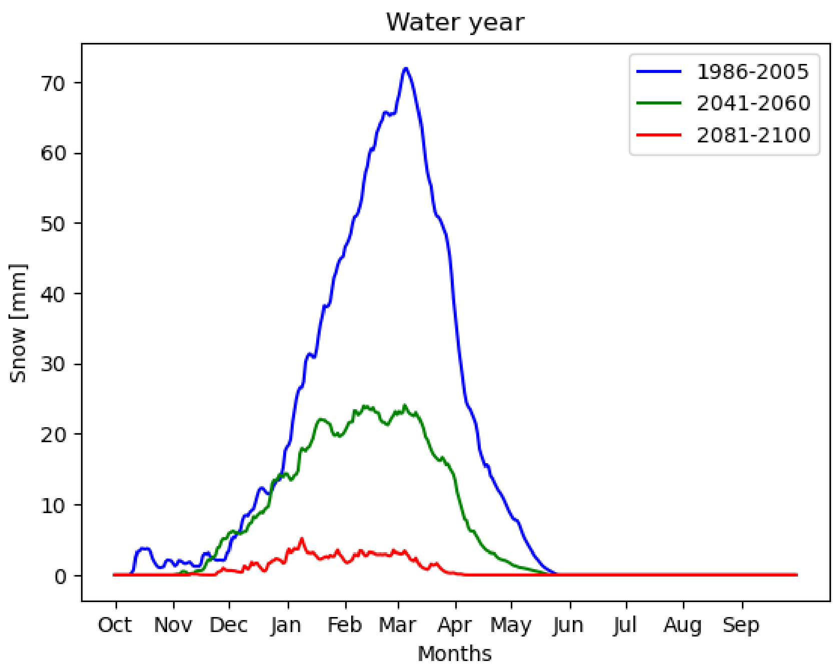

Figure 6: Mean snow water equivalent over the water year. The blue, green and red lines represent respectively historical, mid- and far-future scenarios.

Due to increasing trend in both air temperature and precipitation, and to decreasing snow, runoff is in general projected to increase in both future periods. As shown in Figure 7, the highest increment in runoff occurs in the far-future, which is consistent with temperature, precipitation and snow results combined together, while the mid-future runoff cumulates in a very similar way to the historical one until early winter and then it increases.

Beside the analysis of the variables within the water year, the seasonal analysis was also performed. The focus was mainly on the runoff, considering both the total volume and the peak flows in order to better understand the seasonal impact of climate change on the urban hydrology, thus to see when measures to mitigate climate change impacts are needed and at what extent.

Figure 10 and Figure 12 demonstrate the historical, mid- and far-future cumulative runoff in each season. In general, in summer and autumn, the change in runoff is driven by the increase in precipitation and the way they accumulate is almost the same. In summer, the mid-future runoff is cumulating in a similar way to the historical one until mid-July, and then it increases almost reaching the far-future total volume. Instead, the far-future runoff is projected to be higher than the historical one during the whole summer. The mid- and far-future increments are about 10% and 13%, respectively. In autumn, while the mid-future runoff is projected to slightly decrease (3%), the far-future is going to considerably diverge from the historical one starting from mid-autumn with an increment of around 25%. In winter and spring, the change in runoff is mainly driven by the increase in temperature, which determines snow accumulation and melting. Therefore, the trend of runoff and precipitation accumulation is not comparable anymore during these seasons. Moreover, the total runoff volume changes are significant compared to the other two seasons: in winter because of the large increase, while in spring because of the decreasing trend compared to the general increasing trend projected during the other seasons. Winter is the season characterized by the strongest climate change impacts on the hydrological features. Because of the reduction in the snow, caused by the increasing temperature of the air, the runoff is projected to increase by about 45% and 92% in mid- and far-future respectively. The moment in which the future cumulative runoff curves diverge from the historical one is already in the early-winter. In spring, the total runoff volume is projected to decrease in both future time windows: about 10% and 19% respectively during mid- and far-future. This opposite trend with respect to the other seasons can be explained because of the early snowmelt caused by climate change. This decreasing trend will be amplified by the use of LID solutions, as described in Section 5.2.

Figure 15 presents the ranked seasonal peak flows of each time window. It is clear that climate change is going to affect the maximum runoff values, as a consequence of the overall rising trend in runoff volume. In fact, the peak flows are projected to increase in each season in both future periods, even during spring that is projected to have a reduction in the total runoff volume. In Figure 15d, there is a historical peak flow that is unusually high and caused by an extreme rainfall event that occurred in the spring of 1988.

The results clearly show that climate change is projected to affect the hydrology of Vallikallio catchment, so that the stormwater management will need to be adapted to the future scenario. According to the results, it was assessed that in summer the total runoff volume is the second highest after autumn and the volumes are projected to increase in the future, as well as the peak flows. Figure 8 shows the ranked peak flows of each season, during the historical period, and it is clear how in summer there are the highest peak flows. In the next Section, LIDs were introduced to mitigate the effect of climate change by reducing the future total runoff volume back to the historical summer level.

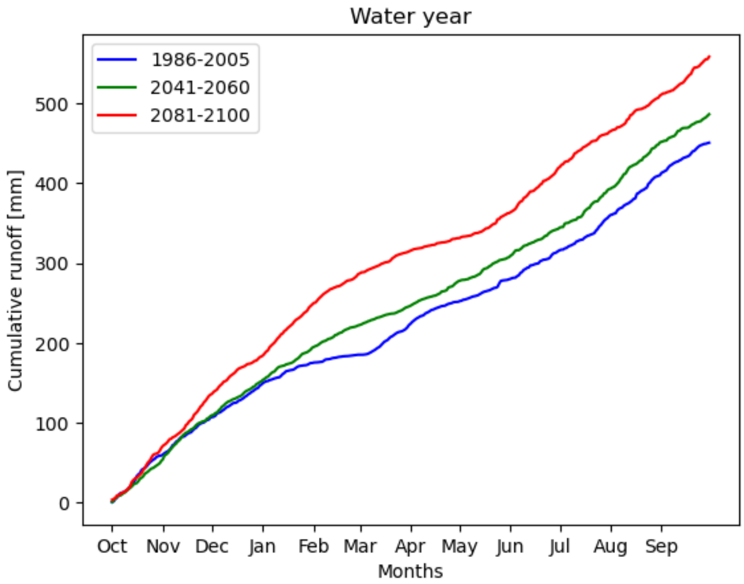

Figure 7: Mean cumulative runoff over the water year. The blue, green and red lines represent historical, mid- and far-future scenarios, respectively.

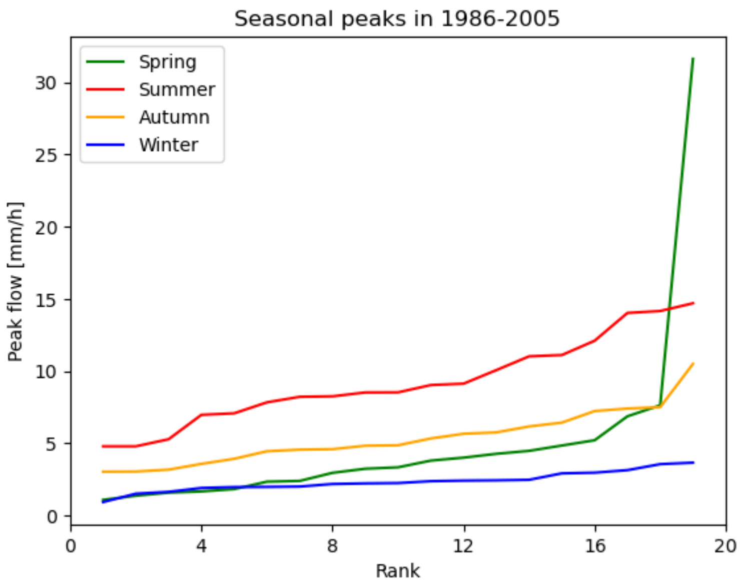

Figure 8: Ranked seasonal peak flows during the historical time window. The green, red, orange and blue lines represent peaks in spring, summer, autumn and winter, respectively.

4.2. Impact of LIDs on hydrology

The impacts of LID controls on the urban hydrology were evaluated by analysing the cumulative runoff, the number of total runoff events and the peak flows in each season and time window for three different LID scenarios: green roofs, permeable pavements and bio-retention cells. According to the method previously described in Section 3.4, the LID solutions were placed in the most important subcatchments according to their ranking, depending on the type of LID control and the required future runoff volume reduction in summer. Table 5 shows that bio-retention cell scenario required the lowest LID coverage even though the number of subcatchments involved were slightly higher than permeable pavement scenarios, while green roof scenario was the highest one, in both future periods.

Table 5: Number of LID units and area coverage required to reach the total runoff volume reduction to the historical value in summer, for each LID scenario and future period. R is the total area required to be covered by a LID type; A is the total available area that can be covered by a LID type; T is the total catchment area.

LID scenario	Future period	N° units	Area required [m2]	*R/A* [%]	*R/T* [%]
Green roof	Mid	14	11526.7	53.1	10
	Far	20	14607.1	67.5	12.7
Permeable pavement	Mid	7	5616.6	17.4	4.9
	Far	10	6898.7	21.2	6
Bio-retention cell	Mid	10	978	6.5	0.8
	Far	13	1229.2	8.4	1.1

Figure 9 shows the location of the green roofs and the difference in their number between mid- and far-future periods, reflecting the higher runoff volume that will be needed to be reduced in the far-future because of climate change compared to the mid-future. By using Equation 1, the area needed to reduce the total runoff volume was computed for the future periods: 53% of the total area was occupied by roofs in the mid-future period, while 67% of roofs would be needed to be covered by green roofs in the far-future to achieve the same goal. Figure 10a demonstrates how the summer total runoff in both future periods becomes reduced to the historical amount. After placing the green roofs in the mid-future summer, runoff seems to accumulate in a very similar way to the historical period one, while the far-future cumulative runoff is still higher for most of the season, even if the total volume is the same as the historical value. In autumn (Figure 10b), in the mid-future, the volume runoff is projected to slightly decrease compared to the historical volume; by placing green roofs, the runoff will be further reduced. In the far-future period, runoff will be reduced even if it will not reach the historical total volume, because the LID design was made for the summer season. Then, in both future periods, the reduction is not significant, because the green roof scenario falls in the respective error band. Regarding winter (Figure 10c), green roofs do not affect the runoff, because they attenuate runoff through transpiration, which does not characterise cold weather. In each future winter period, the runoff accumulation in the baseline and green roof scenarios almost overlap each other, both falling in the error band. During spring (Figure 10d, Figure 12d), the total runoff is projected to decrease in both future periods and the reduction will be amplified by the introduction of LID controls.

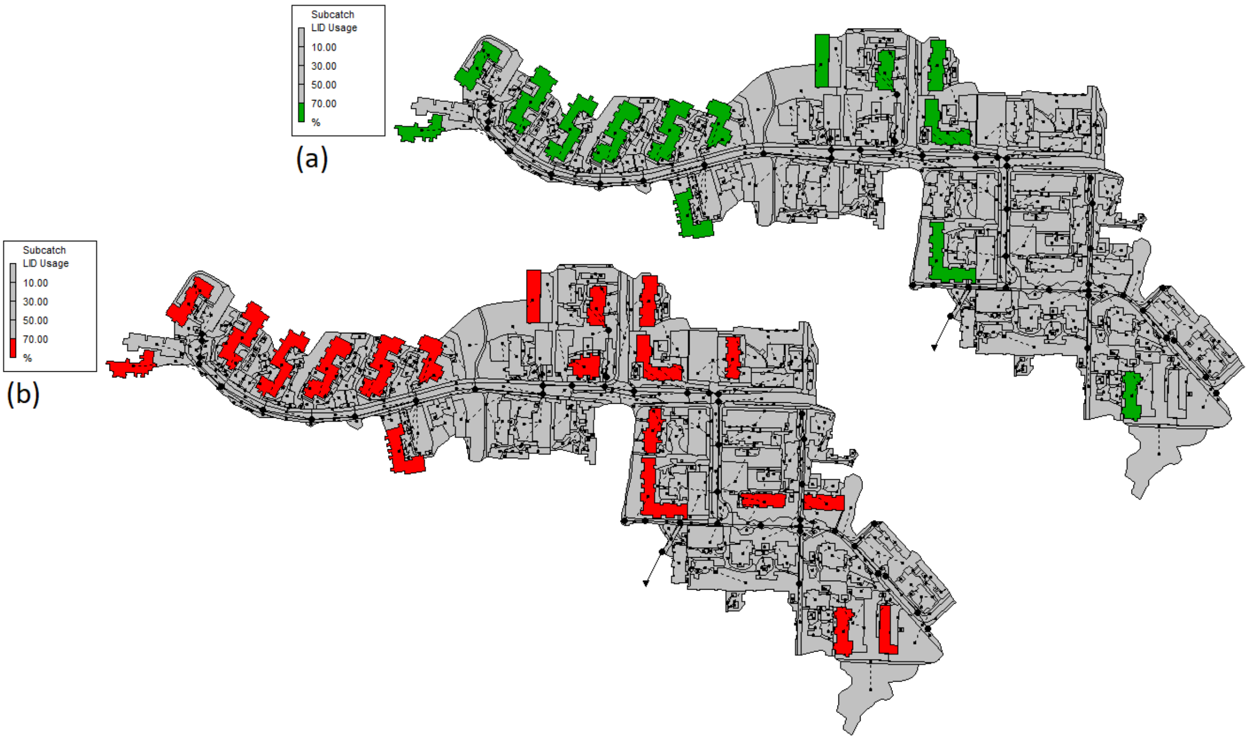

Figure 9: Vallikallio catchment – Green roofs placed in roofs in the mid-future (a) and in the far-future (b). The legend indicates the percentage of a subcatchment covered by green roof (100%).

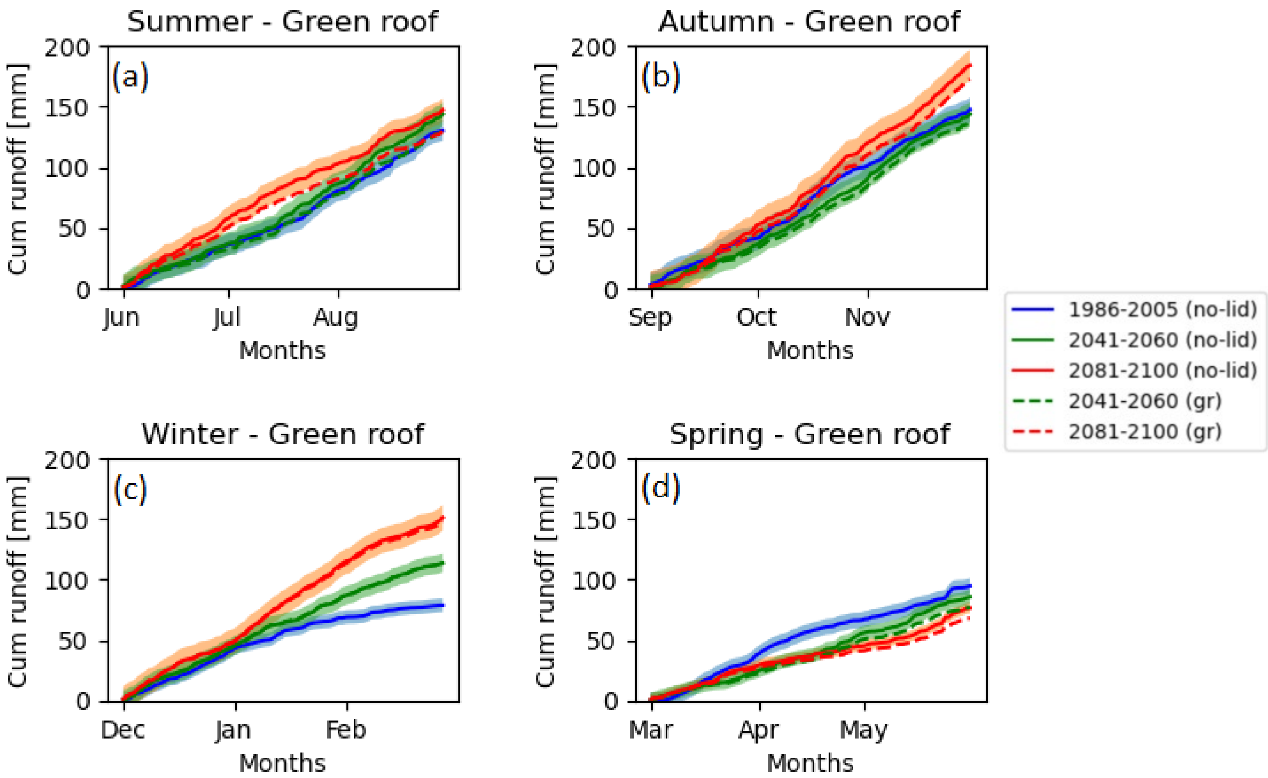

Figure 10: Seasonal effect of green roofs on the cumulative runoff for each future period. The blue, green and red colours refer to the historical, mid-future and far-future time windows, respectively. The solid and dashed lines refer to baseline (no-lid) and green roof (gr) LID scenarios. The coloured bands represent the standard error of the mean (SEM) of the historical, mid-future and far-future baseline scenarios.

Figure 11 illustrates the placing of the permeable pavements and the difference in their number between mid- and far-future periods. As explained in Section 3.3, the subcatchments chosen to place permeable pavements were both parking lots and walkways. Nevertheless, according to the subcatchment ranking, in the mid-future the required area needed to be covered by permeable pavements was satisfied by parking lots, while in the far-future also a walkway was included, according to the hierarchy of subcatchments devoted to install permeable pavements. The permeable pavement area from the total area of parking lots and walkways in Vallikallio was 17% in the mid-future and 21% in the far-future. Figure 12 shows the impact of permeable pavements and bio-retention cells on runoff in each season and time window. The runoff reduction performed by these two LID controls is similar. In fact, the cumulative runoff controlled by permeable pavements and bio-retention cells are almost overlapping in each season and future period. In general, these two LID controls produce higher runoff volume reduction than the reduction performed by green roofs and the biggest difference occurs in winter. In fact, during this season, the curves representing the cumulative runoff controlled by permeable pavements and bio-retention cells are outside the error band of both future baseline scenarios. As described in Section 3.1 and Table 2, permeable pavements and bio-retention cells are characterized by a storage layer, providing both infiltration and storage compared to green roofs, which mainly provide runoff reduction through transpiration, which is limited during cold months.

Figure 11: Vallikallio catchment – Permeable pavements placed in parking lots and walkways in the mid-future (a) and in the far-future (b). The legend indicates the percentage of a subcatchment covered by permeable pavements (100%).

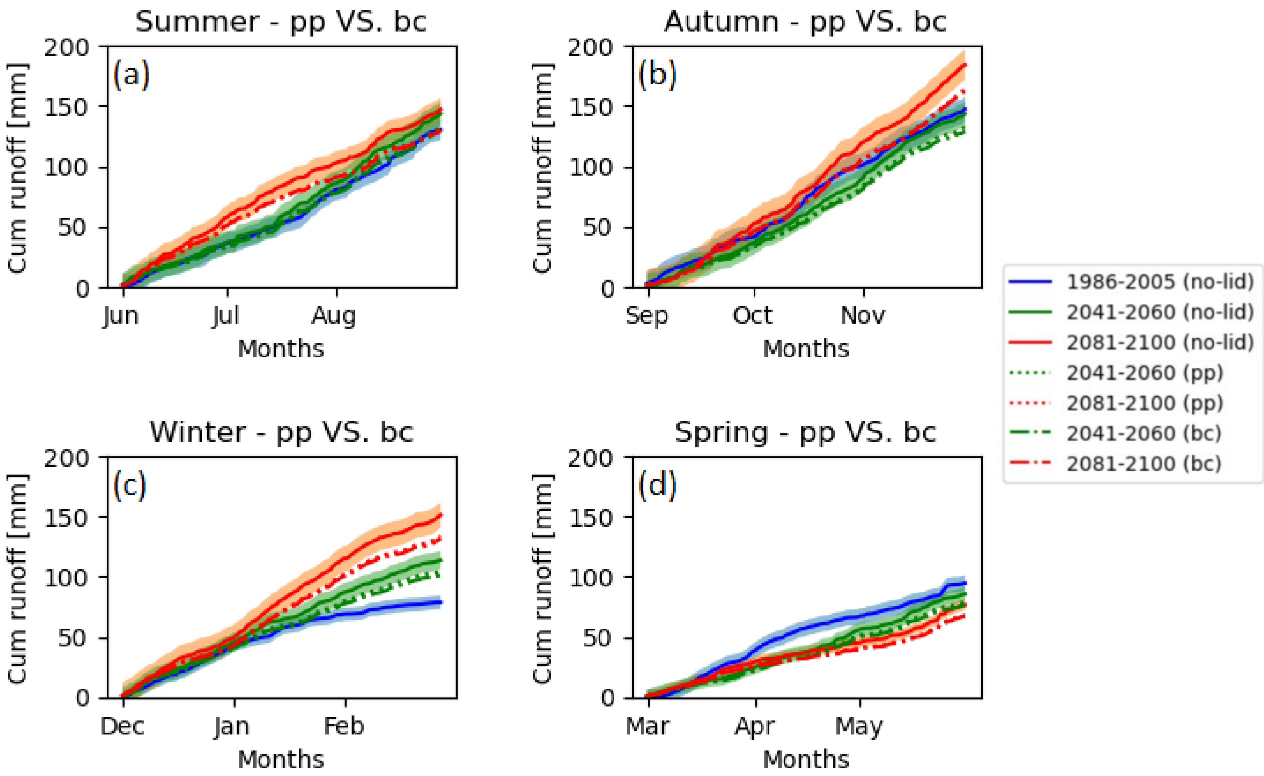

Figure 12: Seasonal effect of permeable pavements and bio-retention cells on cumulative runoff in each future period. The blue, green and red colours refer to the historical, mid-future and far-future time windows, respectively. The solid, dotted and dash-dot lines refer to baseline (no-lid), permeable pavement (pp) and bio-retention cell (bc) LID scenarios. The coloured bands represent the standard error of the mean (SEM) of the historical, mid-future and far-future baseline scenarios.

Figure 13 shows the location of the bio-retention cells and the difference in their number between mid- and far-future periods, according to the higher runoff volume that will be needed to be reduced in the far-future compared to the mid-future. The area needed to reduce the total runoff volume in the mid-future period was about 6% of the total parking lots area, while in the far-future the 8% of parking lots would be needed to be covered to achieve the same goal.

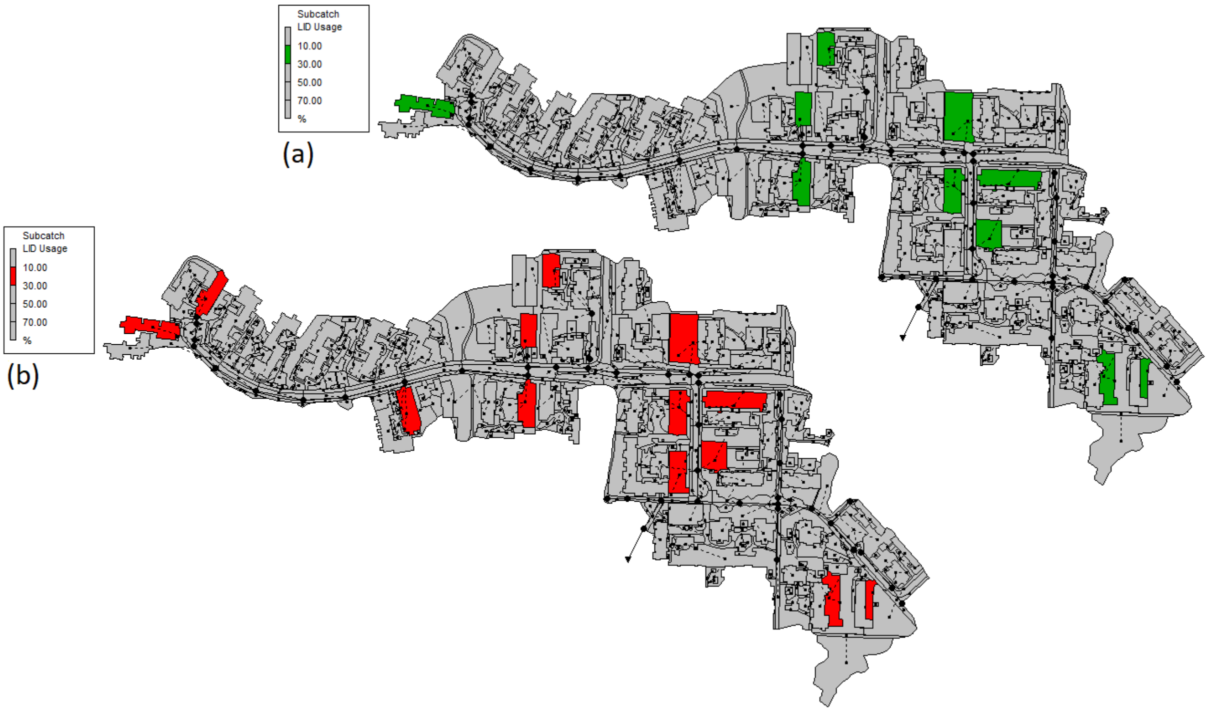

Figure 13: Vallikallio catchment - Bio-retention cells placed in parking lots in the mid-future (a) and in the far-future (b). The legend indicates the percentage of a subcatchment covered by bio-retention cell (13.3%).

After studying the LID impacts on the total runoff volume, the number of events for each time window and LID scenario were compared to each other. Regardless of the future period and the season taken into account, permeable pavements and bio-retention cells reduce in a similar way not only the total runoff volume, but also the number of runoff events, as shown in Figure 14. Again, green roofs are performing in a different way compared to the other two LID controls. Even if green roofs provide a lower reduction in the total runoff volume in autumn, winter and spring, they perform a higher reduction in the number of runoff events in all the seasons. The only exception is the mid-future winter scenario, during which the green roofs are projected to slightly increase the number of events compared to the other lid mid-future scenarios and to the green roof far-future winter scenario;

however, the reduction is not significant, considering that it is included in the error bar of the mid-future baseline scenario. In fact, knowing that green roofs reduce the runoff through transpiration and attenuation by infiltration through its layers, in cold conditions such as the historical or mid-future winters, green roofs cannot provide runoff reduction because of lack of transpiration, resulting in more runoff and larger number of events. However, during other seasons and far-future winter, there will be the climatic conditions that allow transpiration through the surface layer of green roofs and rainfall will be able to infiltrate through the lower layers, delaying the rainfall flow over green roofs, resulting in reduced number of runoff events. Nevertheless, the impact of LID solutions in changing the number of events is not significant compared to the climate change impacts on runoff volume, in particular during winter and spring. The increasing and decreasing trend of total runoff volume in winter and spring, respectively, is reflected in the number of events. The strongest change occurs in winter, because the rising temperature and precipitation will affect snow accumulation and melt, causing more frequent runoff events already during winter, while decreasing them in spring.

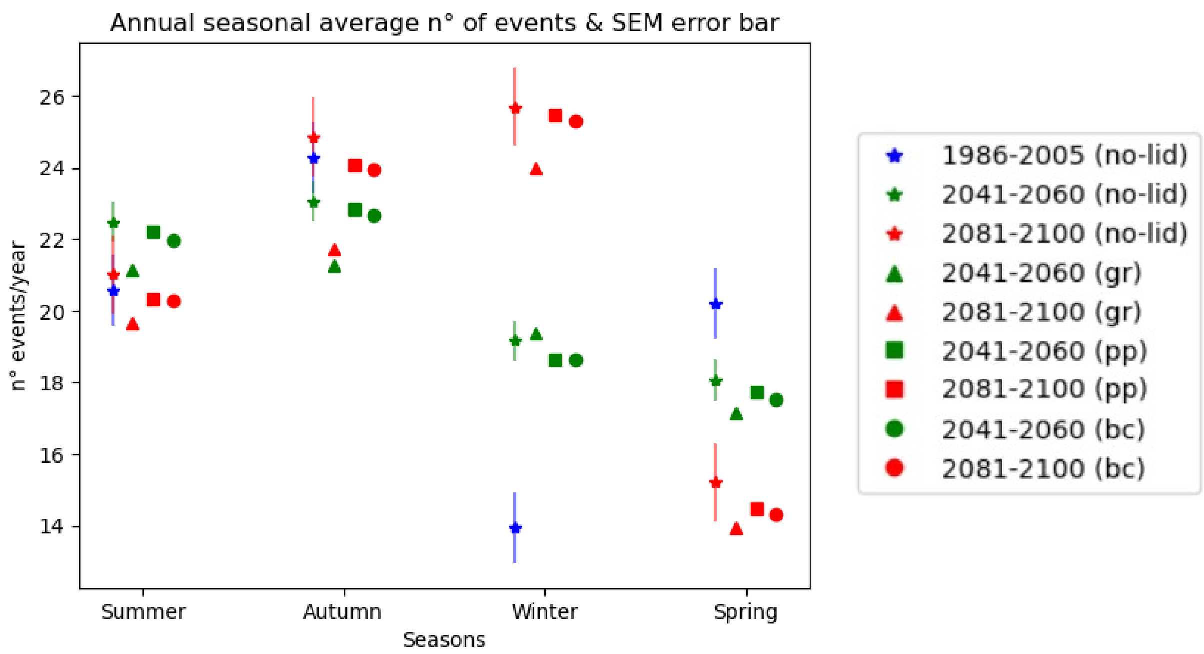

Figure 14: Annual seasonal average number of total volume runoff events. The blue, green and red colours refer to the historical, mid-future and far-future time windows, respectively. The star, triangle, square and circle refer to baseline (no-lid), green roof (gr), permeable pavement (pp) and bio-retention cell (bc) LID scenarios, respectively. The coloured bars represent the standard error of the mean (SEM) of the historical, mid-future and far-future baseline scenarios.

The LID impact on the peak flows is illustrated in Figure 15. LID controls provide a reduction in the peak flows that are projected to occur in the future. However, the impacts of LID controls on the peak flows is lower than the climate change effect. None of the LID scenarios is sufficient to reduce the peak flows to the historical summer level. This reflects the fact that the LID implementation was based on the total runoff volume in summer instead of the peak flows. Thus, according to the goal of the stormwater management, the LID implementation can be based on total volume or peak flows, implementing different scenarios and yielding different results.

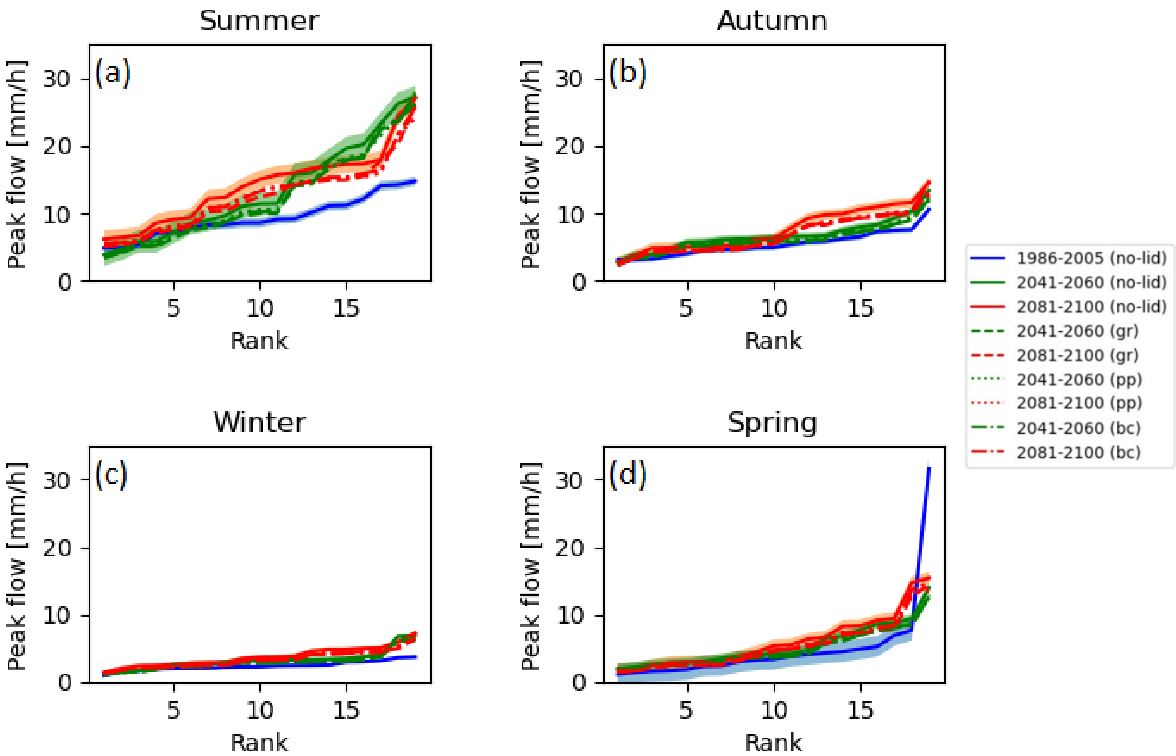

Figure 15: Ranked seasonal annual peak flows in each time window for each LID scenario. The blue, green and red colours refer to the historical, mid-future and far-future time windows, respectively. The solid, dashed, dotted and dash-dot lines refer to baseline (no-lid), green roof (gr), permeable pavement (pp) and bio-retention cell (bc) LID scenarios, respectively. The coloured bands represent the standard error of the mean (SEM) of the historical, mid-future and far-future baseline scenarios.

5. Discussion

5.1. Climate change and urban hydrology

In Finland, temperature and precipitation are expected to increase by the end of the century (Jylhä, et al., 2010). Moreover, in southern Finland, it has been estimated that the far-future air temperature will rarely be below freezing point (Veijalainen, 2012). In this study, the input data showed that both air temperature and precipitation are projected to increase on average, in both future periods. However, the strongest increment will occur in the far-future, during which on average the air temperature will barely reach 0 °C, driving notable changes in the hydrologic response of the urban catchment.

Because of change in air temperature, snow water equivalent is projected to decrease in the mid-future by 58%, while in the far-future by 95%, resulting in almost zero snow in winter. Moreover, also the snow accumulation period is projected to significantly decrease compared to the historical and mid-future periods, because of the stronger rising air temperature trend. In accordance to these results, Rasmus et al. (2004) suggested that snow cover in southern Finland is more sensible to rising temperature than other regions. In particular, according to the simulation results of their study, snowpack formation in the far-future will occur about two weeks later than the present, while snowmelt will occur about two weeks earlier. Moreover, the snow water equivalent is projected to decrease.

Large changes in seasonal runoff volume and dynamics are projected to occur. Due to the rising temperature trend, the snow accumulation and melt dynamics are projected to change, affecting both the total runoff volume and its number of events, above all during winter and spring (Veijalainen, Lotsari, Alho, Vehviläinen, & Käyhkö, 2010; Veijalainen, 2012). As Figure 10 and Figure 12 illustrate, the strongest increase in runoff volume occurs in winter, while in spring the discharge is projected to decrease. By analysing the number of runoff events (Figure 14), it was clear that the most significant change in that number occurs in winter, followed by spring. In fact, because the cold seasons are projected to become warmer, the number of events will be significantly higher during winter and lower during spring than the historical ones. This impact of climate change exaggerates the urbanization one, as assessed by Sillanpää (2013). In fact, snowmelt starts earlier and it is separated into a higher number of runoff events with a shorter duration.

5.2. LID stormwater management

In this study, it was assessed that even though LID scenarios provide a small reduction of peak flows, none of the scenarios was enough to reduce their magnitude to the historical value, because they were implemented to provide total runoff reduction in summer. As Figure 15 illustrates, the peak flow reduction provided by the LID scenarios is not sufficient to bring peak flows value close to the historical values. Thus, a higher LID coverage would be needed to achieve that reduction. However, during the other seasons, the LID coverage increment should not be that high. Thus, according to the goal that one wants to achieve through LID controls, the LID coverage may vary significantly.

Table 5 lists the number of LID units and area coverage for each LID scenario and future period required to reach the total runoff volume reduction to the historical value in summer. It is clear that bio-retention cell scenario requires the lowest LID coverage compared to the other two scenarios, to reach the same goal in both future periods. According to the estimation of additional investment cost compared to the conventional impervious surface by Khadka et al. (2021), the additional cost per square meter for bio-retention cell is higher than the other two LID types. Nevertheless, because bio-retention cells require less LID coverage, this LID scenario would be the most convenient to provide a climate change adaptation solution of the urban catchment of Vallikallio.

It is known that LID solutions are a sustainable alternative to conventional stormwater management. They can potentially provide and maintain the pre-development runoff volume by decreasing the impervious area, improving infiltration, storage and evapotranspiration within the urban catchment (Eckart, McPhee, & Bolisetti, 2017; Palla & Gnecco, 2015). The scope of this study was not to restore the runoff to its pre-development conditions. Nevertheless, as Table 5 shows, there is still a certain available percentage of area that may be devoted to LID controls, for each of the LID scenario, in both future periods. Thus, with a further analysis the urbanization impact on Vallikallio catchment could be included, evaluating if both climate change and urbanization impacts could be mitigated.

The subcatchment ranking process (Section 3.3) was performed according to the historical total runoff volume. However, the subcatchment ranking was performed in each time window in order to understand if climate change would have affected the ranking. Thus, the subcatchment ranking of the three time windows were compared and it was assessed that there are not significant changes in the hierarchy of the subcatchment because of climate change.

5.3. Limitations and future works

This study demonstrates how the results of a climate model can be expanded to an analysis of urban hydrological processes and stormwater management. The focus of modelling is limited to single scenario and a restricted location in the northern Europe.

One of study limitations regards the area extent. In fact, it was assessed that the area extent and landscape characteristics influence the hydrological catchment response to climate change impacts (Teutschbein, Grabs, Laudon, Karlsen, & Bishop, 2018). The study area is a small suburban one (about 11.4 ha), which is part of the urban Leppävaara district in the city of Espoo. It would be interesting to enlarge the area, considering the entire district and see how the extent and the location of mitigation solution may change. Moreover, applying the same methodology of this study on a larger scale and/or on different sites may help to understand better the response of urban catchments to climate change.

Another limit of this study is the choice of the future scenarios. As explained in Section 2.2, the single future high emission scenario RCP8.5 was chosen to perform the simulation and the analyses. An improvement to this study would be performed by using stabilization scenarios, such as RCP4.5 and/or RCP6.0. In fact, they may be considered the most realistic ones according to the current mitigation/adaptation scenario and/or to the one that is going to be adopted in the near-future. It would be relevant to compare the climate change impacts and their possible adaptation solutions according to different radiative forcing scenarios.

Moreover, the study was based on a single regional climate model, HARMONIE-AROME, and a single global climate model, EC-Earth. In order to quantify and present uncertainties involved in the climate projections, a comparison of results obtained by using different climate models should be performed.

Another limit of this study regards the length of time windows used to perform the simulations and analyses. Weather conditions may vary significantly from year to year. This is the reason why a normal period of 30 years is usually used to make climate statistics and analyses. In fact, on one hand, this standardised length of a normal period allows exceptional years not to affect the averages. On the other hand, it is short enough to group years characterised by the same climate statistics. As explained in Section 2.2, each time window that was considered in this study is composed by 19 years instead of 30, because the availability of data was of 20 years for each time period. Nevertheless, because of the warming up period that goes from the 1st of January to the 30th of September of all the first years of the periods, and because of the choice of performing all the analyses according to the water year (1st October – 30th September), the years available in each time window were 19.

A further improvement regards the LID scenarios. To perform this study, it was decided that each LID scenario would be composed of a single type of LID control, because the scope was to understand how the required amount of a certain type of LID would perform in each season, according to the total runoff volume reduction to the summer historical level. However, it would be interesting to apply the same methodology with other LID scenarios. One could be covering the most important subcatchment by following the exact order of the subcatchment ranking. Another interesting LID scenario would be to select the subcatchment to cover with a certain LID type taking also into account the losses by evaporation and infiltration in the design. In fact, a combination of different LID types would be more effective than a LID scenario composed of one LID type, because it would be possible to include the entire spectrum of storm events due to their different layers and mechanisms through which they work (Qin, Li, & Fu, 2013).

The scope of this study was not on restoring the runoff regime to its pre-development conditions. Nevertheless, as Table 5 shows, there is still a certain available percentage of area that may be devoted to LID controls, for each of the LID scenario, in both future periods. Thus, with a further analysis the urbanization impact on Vallikallio catchment could be included, evaluating if both climate change and urbanization impacts could be mitigated.

6. Conclusions

This study was motivated by climate change impacts on urban hydrology and by the consequent need to adapt urban catchments through sustainable stormwater management systems. The two main objectives were to investigate climate change impacts on urban hydrology and to understand how to adapt an urban catchment through LID solutions.

In order to achieve the first goal of the study, the hydrologic features of Vallikallio catchment were simulated through SWMM, over three time windows: historical, mid- and far-future. In this way, it was possible to compare the simulation results within the water year and seasonally, focusing on total runoff and snow water equivalent. Air temperature and precipitation were also analysed, to understand how their behaviour affects runoff and snow water equivalent dynamics. In fact, it was assessed that both air temperature and precipitation are projected to increase on average, in both future periods. However, the strongest increment will occur in the far-future, during which on average the air temperature will barely reach 0 °C, driving notable changes in the hydrologic response of the urban catchment. In the mid-future, snow water equivalent is projected to decrease by 58%, while in the far-future by 95%, resulting in almost zero snow in winter. Moreover, the snow accumulation period is projected to significantly decrease compared to the historical and mid-future periods, because of the stronger rising air temperature trend. As a consequence to the combined changes in air temperature, precipitation and snow, the runoff is projected to increase in both future periods during almost the entire water year, especially in the far-future. In summer and autumn, the change in runoff is mainly driven by the increase in precipitation. In summer, total runoff volume increment is about 10% in mid-future and 13% in far-future. In autumn, the total runoff volume is projected to slightly decrease by 3% in mid-future, while increase by 25% in the far-future period. In winter and spring, the total runoff volume change is mostly influenced by the rising air temperature, which determines snow accumulation and melting, anticipating it already in winter, causing opposite trends of runoff during these seasons. In mid-future, total runoff volume is projected to increase by 45% in winter and decrease by 10% in spring; while in far-future, total runoff volume will increase by 92% in winter and decrease by 19% in spring. Climate change is going to affect peak flows as a consequence of the overall rising trend in runoff volume. In fact, peak flows are projected to increase in each season in both future periods, even during spring that is projected to have a reduction in the total runoff volume. After the analysis regarding the impacts of climate change on hydrology, it was decided to mitigate their effect on runoff, reducing its total volume to the summer historical value.

To achieve the second objective of this study, SWMM was used to model different LID scenarios in order to assess if it is possible to mitigate climate change effects on the urban hydrology in both future periods. Green roofs, permeable pavements and bio-retention cells were chosen among all the LIDs because they are composed of different layers that confer on them different mechanisms, such as evapotranspiration, infiltration and storage, through which they provide runoff reduction. It was decided to place green roofs on rooftops, permeable pavements on parking lots and walkways, both covering 100% of the subcatchment area; bio-retention cells on parking lots, covering 13.3% of the total subcatchment area. After choosing the three LID scenarios, the subcatchment ranking was performed to detect locations, where LIDs reduce the highest volumes of runoff. Then, the total area needed to be covered by each LID scenario was computed to achieve the total runoff volume reduction in summer. Thus, a certain amount of subcatchments were selected according to their ranking in order to place LIDs and the simulations were run again in both future periods for each LID scenario. In mid-future, the share from the total catchment area needed to be covered, in order to achieve the total runoff volume reduction in summer, is about 10% by green roofs, 4.9% by permeable pavements and 0.8% by bio-retention cells; while in the far-future, the percentage required will be higher: 12.7%, 6% and 1.1% for green roofs, permeable pavements and bio-retention cells respectively. Thus, bio-retention cell scenario is the one that requires the lowest area coverage in both future periods. Regarding the differences in the performance of the LID scenarios, considering that they all achieve the goal established, in general green roofs perform a lower reduction of runoff volume during the other seasons, while permeable pavements and bio-retention cells perform in a very similar way during the whole year. However, the biggest difference occurs in winter. Green roofs can provide runoff reduction through evapotranspiration and attenuation, but in winter the weather is still too cold to allow transpiration, even though climate change is projected to increase temperature. Another interesting result regards spring, because even in the baseline scenario, without LID controls, the total runoff volume is projected to decrease in the future. Thus, after placing all the LID scenarios, the total runoff volume is projected to decrease even more. Regarding peak flows, it was assessed that none of the studied scenarios was enough to reduce their magnitude to the historical value, because they were implemented to provide total runoff reduction. According to these designs, the impact of climate change on peak flows is greater than the studied LID impacts. The last observations regard the number of runoff events. Due to the LID scenarios, the number of events decreases compared to the baseline scenario of the same future period, but the reduction is not enough to be close to the historical number of events.

References

Barrett, M. E. (2005). Performance comparison of structural stormwater best management practices. *Water Environment Research, 77*(1), 78-86. doi:10.2175/106143005X41654

Bengtsson, L., Andrae, U., Aspelien, T., Batrak, Y., Calvo, J., de Rooy, W., . . . al., e. (2017). The HARMONIE-AROME Model Configuration in the ALADIN-HIRLAM NWP System. *Monthly Weather Review, 145*(5), 1919-1935. doi:10.1175/MWR-D-16-0417.1

Berggren, K., Olofsson, M., Viklander, M., & Svensson, G. (2012). Hydraulic impacts on urban drainage systems due to changes in rainfall caused by climate change. *Journal of Hydrologic Engineering, 17*(1), 92-98. doi:10.1061/%28ASCE%29HE.1943-5584.0000406

Climate elements. (2022). Retrieved from Finnish Meteorological Institute: https://en.ilmatieteenlaitos.fi/climate-elements

Eckart, K., McPhee, Z., & Bolisetti, T. (2017). Performance and implementation of low impact development-A review. *Science of the Toral Environment, 607*, 413-432. doi:10.1016/j.scitotenv.2017.06.254

Jylhä, K., Ruosteenoja, K., Räisänen, J., Venäläinen, A., Tuomenvirta, H., Ruokolainen, L., . . . Seitola, T. (2010). *The changing climate in Finland: estimates for adaptation studies. ACCLIM project report 2009.*

Jylhä, K., Tuomenvirta, H., Ruosteenoja, K., Niemi-Hugaerts, H., Keisu, K., & Karhu, J. A. (2010). Observed and projected future shifts of climatic zones in Europe and their use to visualize climate change information. *Weather, Climate, and Society, 2*(2), 148-167. doi:10.1175/2010WCAS1010.1

Khadka, A., Kokkonen, T., Koivusalo, H., Niemi, T. J., Leskinen, P., & Körber, J.-H. (2021). Stormflow against streamflow-Can LID-provided storage capacity ensure performance efficiency and maintenance of pre-development flow regime? *Journal of Hydrology, 602*, 126768. doi:10.1016/j.jhydrol.2021.126768

Khadka, A., Kokkonen, T., Niemi, T. J., Lähde, E., Sillanpää, N., & Koivusalo, H. (2020). Towards natural water cycle in urban areas: Modelling stormwater management designs. *Urban Water Journal, 17*(7), 587-597. doi:10.1080/1573062X.2019.1700285

Koivusalo, H., Tamm, O., Di Natale, C. M., Dubovik, M., Wendling, L., & Warsta, L. (2022). Warming winters at the edge of snow-affected conditions in an urban area. *Nordic Hydrological Conference.* Tallinn.

Krebs, G., Kuoppamäki, K., Kokkonen, T., & Koivusalo, H. (2016). Simulation of green roof test bed runoff. *Hydrological processes, 30*(2), 250-262. doi:10.1002/hyp.10605

McDonnell, B. E., Wu, J., Peña-Castellanos, G., Roberts, S., Mullapudi, A., & Li, J. (2016). Retrieved from PySWMM: https://pyswmm.readthedocs.io/en/stable/overview.html

Metsäranta, N., Kotola, J., & Nurminen, J. (2005). Effects of urbanization on runoff water quantity and quality: Experiences from test catchments in Southern Finland. *International Journal of River Basin Management, 3*(3), 229-234. doi:10.1080/15715124.2005.9635263

Okkonen, J., & Bjørn, K. (2010). A conceptual and statistical approach for the analysis of climate impact on ground water table fluctuation patterns in cold conditions. *Journal of Hydrology, 388*(1-2), 1-12. doi:10.1016/j.jhydrol.2010.02.015

Palla, A., & Gnecco, I. (2015). Hydrologic modeling of Low Impact Development systems at the urban catchment scale. *Journal of Hydrology, 528*, 361-368. doi:10.1016/j.jhydrol.2015.06.050

Pang, X., Gu, Y., Launiainen, S., & Guan, M. (2022). Urban hydrological responses to climate change and urbanization in cold climates. *Science of The Total Environment, 817*, 153066. doi:10.1016/j.scitotenv.2022.153066

Qin, H.-p., Li, Z.-x., & Fu, G. (2013). The effects of low impact development on urban flooding under different rainfall characteristics. *129*, 577-585. doi:10.1016/j.jenvman.2013.08.026

Rao, N. S., Easton, Z. M., Schneiderman, E. M., Zion, M. S., Lee, D. R., & Steenhuis, T. S. (2009). Modeling watershed-scale effectiveness of agricultural best management practices to reduce phosphorus loading. *Journal of Environmental Management, 90*(3), 1385-1395. doi:10.1016/j.jenvman.2008.08.011

Rasmus, S., Räisänen, J., & Lehning, M. (2004). Estimating snow conditions in Finland in the late 21st century using the SNOWPACK model with regional climate scenario data as input. *Annals of Glaciology, 38*, 238-244. doi:10.3189/172756404781814843

Rossman, L. A. (2015). *Storm Water Management Model User's Manual Version 5.1.* Cincinnati, Ohio: U.S. Environmental Protection Agency.

Ruosteenoja, K., Räisänen, J., & Pirinen, P. (2011). Projected changes in thermal seasons and the growing season in Finland. *International Journal of Climatology, 31*(10), 1473-1487. doi:10.1002/joc.2171

Seasons in Finland. (2022). Retrieved from Finnish Meteorological Institute: https://en.ilmatieteenlaitos.fi/seasons-in-finland

Sillanpää, N. (2013). Effects of suburban development on runoff generation and water quality.

Storm Water Management Model (SWMM). (2022). Retrieved from U.S. Environmental Protection Agency: https://www.epa.gov/water-research/storm-water-management-model-swmm

Tamm, O. (2022). Bias corrected air temperature and precipitation series from HARMONIE-AROME (historical and RCP8.5 future periods).

Teutschbein, C., Grabs, T., Laudon, H., Karlsen, R. H., & Bishop, K. (2018). Simulating streamflow in ungauged basins under a changing climate: The importance of landscape characteristics. *Journal of Hydrology, 561*, 160-178. doi:10.1016/j.jhydrol.2018.03.060

Tuomela, C. (2017). Modelling source area contributions of stormwater pollutants for stormwater quality management.

Tuomela, C., Sillanpää, N., & Koivusalo, H. (2019). Assessment of stormwater pollutant loads and source area contributions with storm water management model (SWMM). *Journal of Environmental Management, 233*, 719-727. doi:10.1016/j.jenvman.2018.12.061

Veijalainen, N. (2012). Estimation of climate change impacts on hydrology and floods in Finland.

Veijalainen, N., Lotsari, E., Alho, P., Vehviläinen, B., & Käyhkö, J. (2010). National scale asssessment of climate change impacts on flooding in Finland. *Journal of Hydrology, 391*(3-4), 333-350. doi:10.1016/j.jhydrol.2010.07.035

Yu, J., Yu, H., & Xu, L. (2013). Performance evaluation of various stormwater best management practices. *Environmental Science and Polluntion Research, 20*(9), 6160-6171. doi:10.1007/s11356-013-1655-4

Zahmatkesh, Z., Burian, S. J., Karamouz, M. F., Tavakol-Davani, H., & Goharian, E. (2015). Low-Impact Development Practices to mitigate climate change effects on urban stormwater runoff: Case study of New York city. *Journal of Irrigation and Drainage Engineering, 141*(1), 04014043. doi: 10.1061/(ASCE)IR.1943-4774.0000770