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Climate change adaptation using low impact development for stormwater management in a Nordic catchment

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Climate change is raising a need to adapt stormwater management systems to altered conditions. Low Impact Development (LID) controls are regarded as a promising solution for adaptation in urban areas. The main objective was to demonstrate how LID controls function in climate change adaptation. The analysis used air temperature and precipitation from regional climate model with RCP8.5 emission scenario as input to the Storm Water Management Model. Urban runoff and snow dynamics were simulated in historical, mid- and far-future periods. With the increase in mean air temperature, snow water equivalent reduces, which alters the seasonal runoff behavior in the future. To alleviate the climate change impacts, subcatchments generating high total runoff volumes were determined for LID implementation. Bioretention cells, permeable pavements and green roofs achieved runoff volume reduction in summer, while also having some impact on other seasons. Permeable pavements and bioretention cells behaved similarly throughout the year, but green roofs had a negligible runoff volume reduction in winter. This study highlights that LID adaptation design for summer flow events does not behave similarly in other seasons.

Introduction

Changes in air temperature and precipitation impact hydrological features. By the end of the century, the climate zone in southern Finland is projected to transition from its current state characterized by cold and snowy winters and relatively rainy, short, and cool summers to a climate featuring milder winters and longer, warmer summers with increased rainfall. (Jylhä *et al.* 2010). Due to climate change, the thermal winter is projected to become shorter, while the thermal summer to become longer across the entirety of Finland, because spring and summer will start earlier, and autumn and winter will start later compared with current conditions. Moreover, autumn is projected to become even longer, shortening the winter. Thus, in southern Finland, the future seasons are projected to resemble central Europe (Ruosteenoja *et al.* 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 melting in spring. In fact,

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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 snowpack and increasing the density and grain-size of snow (Rasmus *et al.* 2004). Therefore, due to rising temperature, snow accumulation in southern Finland will decrease significantly in winter, leading to snowmelt beginning already during winter. As a direct consequence, runoff and water levels will increase during winter, while runoff and snowmelt floods will decrease during spring. Thus, by the end of this century, permanent winter with air temperature below freezing threshold is projected to become exceptional in southern Finland, bringing notable changes in seasonal runoff dynamics (Veijalainen *et al.* 2010, Veijalainen 2012).

The complex urban areas, where hydrologic-hydraulic processes are strongly influenced by anthropogenic activities, are more vulnerable to climate change than rural areas. This is due to modification of natural areas into impervious surfaces like roofs and roads, which strongly alters the catchment hydrologic-hydraulic processes (Guan *et al.* 2015). The rainfall-runoff response time shortens, and less water remains in the catchment. Urbanization trend is expected to continue in the future, which further challenges the urban stormwater management under changing climate conditions. As the developed stormwater systems cannot handle this excessive hydraulic load, inflow to the stormwater system should be regulated (Kändler *et al.* 2021) by increasing water storage in the subcatchments.

Various water management solutions are available to reduce urban flooding risk and/or pollutant concentration (Fletcher *et al.* 2015, Kõiv-Vainik *et al.* 2022). Examples of such solutions include low impact development (LID) controls, which are designed to manage urban stormwater and bring urban hydrology closer to the pre-development conditions, dealing with both water quality and quantity. The peculiarity of LID controls is that they mimic processes involved in the natural water cycle (Khadka *et al.* 2021). By reducing the percentage of impervious surfaces within urban catchments, LIDs increase infiltration and evapotranspiration while reducing runoff volume, peak flow, and pollutant loads. Recently, LIDs have been used to reduce stress on urban stormwater infrastructure and increase resilience to climate change in urban catchments. Thus, they are regarded as promising methods for a more sustainable stormwater management (Eckart *et al.* 2017).

Many earlier modelling studies have focused on the hydrological functioning of LIDs. Qin *et al.* (2013) assessed the performance of LID designs for managing floods under different rainfall characteristics in China. They noted LID performance to be affected by the percentage of LID coverage, percentage of LID drainage area and the effective storage capacity. The LID scenarios evaluated in their study were found to be effective in flood reduction during intensive rainfall events, while they recommended to combine the scenarios with conventional flood control to remain effective also during longer rainfall events. Palla and Gnecco (2015) analyzed the capabilities 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 analyzed LID scenarios included green roofs and permeable pavements, the performance of which was evaluated through peak flow reduction, volume reduction, and hydrograph delay. Palla and Gnecco (2015) showed that volume reduction strictly depends on the catchment retention capability, which was modified by the characteristics of LIDs, such as void ratio and storage layer depth. Interestingly, they noted that the effectiveness of LID controls required a minimum land use conversion area, and they found a linear relationship between the effective impervious area reduction percentage and hydrological performance. Thus, reducing the imperviousness of the urban catchment was found to be a useful practice to transform the catchment close to the pre-development hydrological condition. Zahmatkesh *et al.* (2015) focused on the impacts of climate change on rainfall intensities and stormwater runoff volume and peak flows in New York City, United States. They showed that runoff volume increased with future climate scenarios because of increasing rainfall. According to the results, the application of LIDs decreased the long-term average runoff volume and peak flows. Among porous pave-

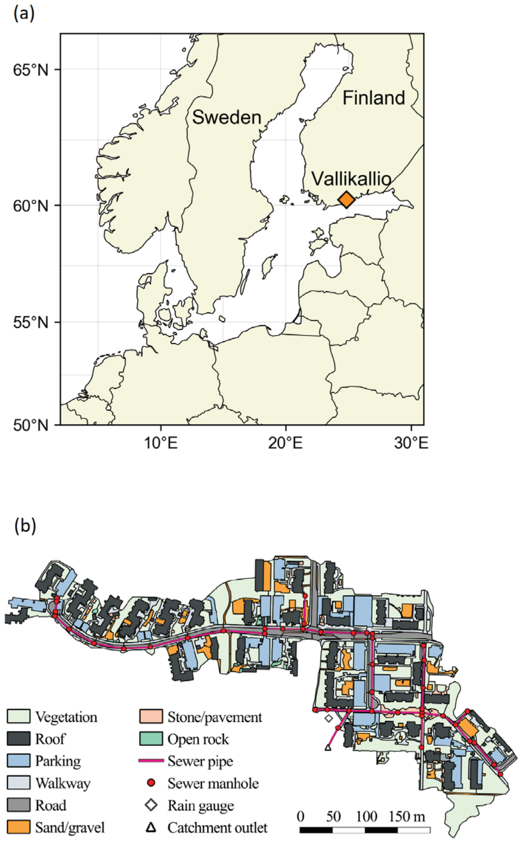

Fig 1. Study catchment (**a**) location and (**b**) layout.

ments, bioretention cells and rainwater harvesting, the pavements were noted to provide the highest peak flow reduction. Therefore, LIDs were also confirmed to be a promising climate change adaptation solution.

Tuomela *et al.* (2018) combined the evaluation of LID impact on stormwater quantity and pollutant load by modelling LID controls to assess their potential on runoff and pollution reduction in an urban catchment in southern Finland. Most of the stormwater load contribution originated from impermeable surfaces, such as parking lots, walkways, roads, and roofs. The role of bioretention cells and permeable pavements in controlling the loads was also investigated. LIDs were designed to reduce runoff volume by increasing infiltration and evapotranspiration, while also providing pollutant load removal. Similarly to Qin *et al.* (2013), a combination of different LID types proved to be a more effective management option than a LID scenario composed of single LID type.

The current study was motivated by the need to understand what requirements climate change imposes on urban stormwater management and how the undesirable impacts on urban catchments can be reduced through sustainable stormwater management. The main goal was to demonstrate how LID controls function in adaptation against impact of climate change. For this, a high-resolution climate model projection was used as an input to the Storm Water Management Model (SWMM, Rossman and Huber 2015), which was employed to simulate the hydrologic features in three time-windows (historical, mid- and far-future), and estimate urban runoff and snow dynamics. SWMM features were then exploited to model three LID scenarios to reduce the total runoff volume in an urban residential catchment in Southern Finland. The LID scenarios were green roofs, permeable pavements, and bioretention cells, which were designed to manage and adapt the catchment against summer increased runoff volumes under the extreme Representative Concentration Pathway (RCP) emission scenario RCP8.5. The goal was to assess how the LID scenarios perform seasonally during mid- and far-future periods, and to what extent it is possible to adapt to climate change impacts with sustainable stormwater management.

Material and methods

Site description

The analysis focused on a suburban area of Vallikallio in the city of Espoo, Finland (Fig. 1). The catchment's overall size is circa 110 000 m^2, of which the pervious area (47%) is primarily made up of vegetation and open non-vegetated sand or gravel. The 3–5 story residential buildings make up 36% of the impervious area, along with 26% of the pathways, 26% of the parking spaces, and 11% of the asphalted roadways. Sandy till is the predominant soil type with a low hydraulic conductivity (4.2 mm h^{-1}). Surface runoff is routed to separate stormwater sewer system located under roads. Sillanpää (2013) provides a more thorough explanation of the research catchment's features.

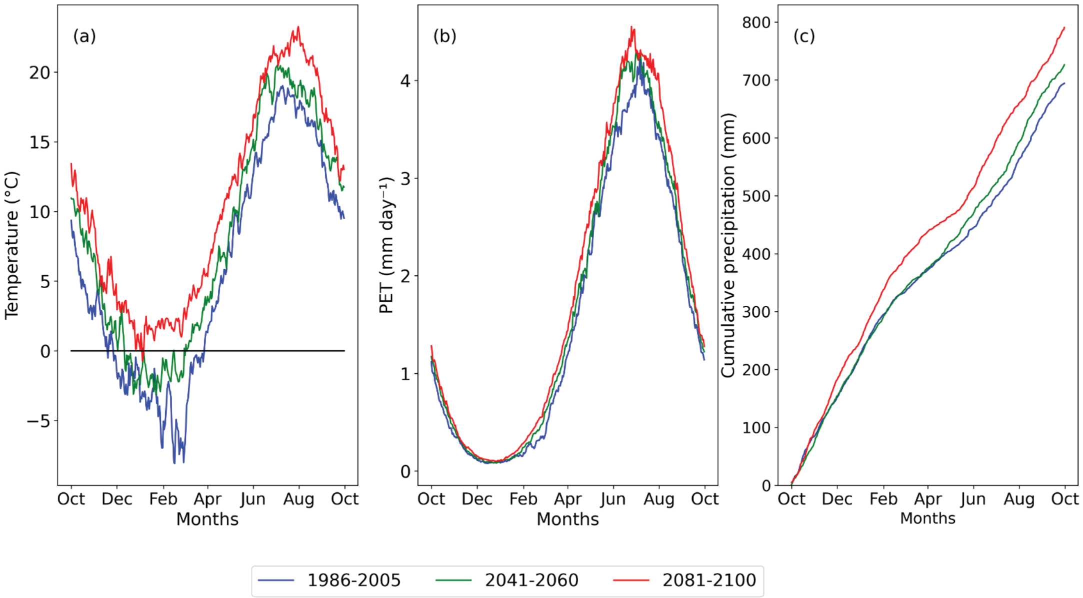

Fig 2. Daily plots of (**a**) mean air temperature, (**b**) potential evapotranspiration, and (**c**) mean cumulative precipitation, over the water year for the historical, mid-future, and far-future periods.

The climate of the region is influenced by the proximity of the Gulf of Finland. The four seasons can be clearly distinguished, and the winters are snow-affected. The annual mean air temperature is 4.5°C and precipitation 700 mm. The coldest month is February with an average temperature of 4.4°C, with a high variability from –14.0°C to +1.4°C. July has the warmest mean temperature at 18.0°C and a much narrower variability from 14.7 to 22.0°C, while August typically has the highest precipitation amounts, and April experiences the lowest amounts.

Climate data

High-resolution convection permitting climate simulations from the HARMONIE-Climate (Lind *et al.* 2023, Bengtsson *et al.* 2017) Regional Climate Model (RCM) was chosen to investigate climate change adaptation using LID solutions. The RCM was forced by the EC-EARTH (Hazeleger *et al.* 2012) Global Climate Model (GCM) using the pessimistic emission scenario RCP8.5. Although it is considered less plausible than alternative scenarios (RCP4.5 and RCP6.0), it provides useful insights on how urban hydrology responds to quite extreme warming levels in the future. This worst-case scenario climate simulations include three time-periods: 1) the historical period from 1986 to 2005; 2) mid-future from 2041 to 2060; and 3) the far-future from 2081 to 2100. The near-surface temperature and precipitation information was extracted from the climate simulations as drivers of hydrologic-hydraulic processes in an urban catchment. This data has a high temporal resolution of one hour, which is assumed to be sufficient for the LID adaptation assessment in an urban catchment. A more detailed description of the raw climate data processing methodology can be found in Tamm *et al.* (2023). Figure 2 illustrates the mean annual dynamics of future air temperature, potential evapotranspiration, and precipitation for historical period and two future periods according to the climate projection. The daily mean air temperature is systematically increasing in both future periods during the water year, according to the RCP8.5 scenario. The mean temperature increase during cold months (December to March) is noteworthy: in the mid-future, the mean air temperature will still be mostly below 0°C during winter season, but not 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 that it will barely reach the freezing point even during winter, inducing strong alterations in the study catchment hydrological features. Potential evapotranspiration is projected to increase in both future periods within the water year, but not in the cold season (November to February), as shown in Fig. 2b. The projected increases in cold air temperatures are reflected in the evapotranspiration demand much less than increases in warm temperatures. Precipitation is shown as cumulative mean value within the water year in Fig. 2c. In the mid-future, the cumulative precipitation is projected to behave in a comparable way with respect to the historical one, with a slight increase in the total amount. A more notable increase in precipitation is visible in the far-future period, when the highest changes occur in the end of autumn and winter. The average annual precipitation amount is projected to increase approximately 100 mm by the end of the century.

Stormwater management model

The stormwater management model (SWMM) was first created in 1971 as a design model focused on simulating individual storm events with short modelling times. Over the years, it has witnessed considerable upgrades. Today, it has evolved into a widely used dynamic rainfall-runoff routing simulation model that can also perform long-term simulations for water quantity and quality (Rossman 2010).

The Vallikallio catchment (Fig. 1b) was discretized into eight surfaces with uniform surface characteristics, which were adapted from Tuomela *et al.* (2019). The subcatchment types in Vallikallio urban catchment were vegetation, sand, rock, roof, pavers, walkway, road, and parking lot. As a result, the Vallikallio study catchment was discretized into 610 homogenous subcatchments that either drained to another subcatchment as surface runoff or to the subterranean stormwater network. The subcatchments were all linked together through 44 junctions and 43 conduits, forming the whole underground stormwater network. Koivusalo *et al.* (2022) improved the model by calibrating it using snow and flow data from the period 2001 to 2006 obtained from Sillanpää (2013). According to the calibration results against the measured flow, the hourly all-year Nash Sutcliffe Efficiency NSE (Nash and Sutcliffe 1970) score was 0.52 and 0.66 for the calibration (2005–2006) and validation period (2001–2005), respectively. The corresponding modified Kling-Gupta Efficiency (KGE', Gupta *et al.* 2009, Kling *et al.* 2012) values were 0.63 and 0.69 for the calibration and validation, respectively.

The impact of climate change on an urban stormwater catchment was investigated by continuous simulations of the 19-year periods and comparing the main hydrological variables between historical and future periods. This study uses a computation time step of 1 hour for dry weather and 5 minutes for wet weather as it was found to be suitable in terms of simulation time and model accuracy. The routing time step of 5 seconds was used in computing flow routing in the stormwater network. The input variables of air temperature and precipitation from the climate model were extracted to drive the urban hydrological processes in the SWMM throughout the seasons and years. Outlet runoff and snow water equivalent were chosen as simulation output variables. The impact of climate change on the hydrological features was demonstrated as mean daily values over the water year (from 1 October to 30 September) as well as seasonally.

SWMM allows to install diverse types of LID controls in a subcatchment (Rossman and Huber 2015) and simulate their impact on runoff generation and losses via evaporation, infiltration, and storage. In this study, the selected LID tools were green roof, permeable pavement, and bioretention cell, which were structured to have layers that provide runoff reduction through different processes. Green roof enhances evapotranspiration losses and includes a drainage mat, which leads to a limited detention impact. Permeable pavement increases infiltration capacity through reduced impermeability. Bioretention cell can occupy a small fraction of the subcatchment with enhanced detention and losses of infiltration and evapotranspiration. In this study, green roofs were placed in roof subcatchments for managing direct rainfall; permeable pavements were placed in both walkway and parking lot subcatchments, whereas bioretention cells were placed only in parking lot subcatchments. Permeable pavement and bioretention cell can treat both rainfall and runoff coming as inflow from the upstream subcatchment to which the LID is connected.

SWMM includes tools to define flow events and compute statistical characteristics of the events. The flow event analysis needs specifications, such as the length of the event time and specified event thresholds. The length of an event was defined based on the time the variable is above the defined thresholds. The flow event thresholds were set as: 0.001 m^3 s^{-1} as runoff flow, 114 m^3 as runoff volume resulting from 1 mm multiplied with the total catchment area, and 3 h as separation time between the end of one event and the beginning of the following event. The flow event information facilitated quantification of the number of total runoff events occurring in each season. This analysis was performed for each LID scenario and in each time-period to make a comparison of the number of flow events.

Calculations and statistics

The placement logic of the LID controls in the subcatchments was as follows. The hydrological impacts of all the subcatchments in Vallikallio were grouped and ranked in terms of runoff generated from a subcatchment, its area, and its land use. Because the aim was to control the total runoff volume, the first criterion chosen to compute was the magnitude of runoff produced by each subcatchment in the historical period. To compare the runoff from subcatchments with different areal extents, the total runoff (m) from each subcatchment was multiplied by the area (m^2) of the subcatchment, obtaining the list of the total runoff volume (m^3) of each subcatchment. The second criterion was the subcatchment type according to its compatibility to the analyzed LIDs. These included the following subcatchment types: roofs, parking lots and walkways. Roofs were ranked to install green roofs, parking lots and walkways for permeable pavements, and parking lots for bioretention cells. Finally, all the subcatchments with LID potential were ranked from the highest total runoff volume to the lowest, so that the most influential subcatchments were identified.

The LID parametrization was set up in two phases: in the first phase (LID Control) the properties of the layers of a LID type were fixed and in the second phase (LID Usage) the dimensions of the LID solution were set according to the subcatchment occupied. The parameters used to define the LID controls were adopted from the literature (Table 1) (Krebs *et al.* 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 bioretention 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 (Table 2) were chosen as follows. For both green roof and permeable pavement controls the LID coverage was assumed to be 100%, while the bioretention cell covered 13.3% of the total subcatchment area. The surface width of the 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 bioretention cell was set equal to zero, because this control spills any excess captured runoff over its berms. It was assumed that the area occupied by a LID control is not initially saturated. The impervious area percentage of the subcatchment treated by bioretention 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 parameterization scheme explained above, it was not possible to define one single green roof, permeable pavement and bioretention 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 parameterization of each LID control was automated with PySWMM (McDonnell *et al.* 2020) considering the respective subcatchment properties.

In the simulations of the LID impacts on hydrology, the summer runoff volume was selected as the target value for designing LIDs. Summer is the season with high precipitation intensities, and it has the highest peak flows compared to the other seasons. The target was to use as many LIDs as needed to reduce runoff volume in the mid- and far-future summer season back to the value of the historical summer season. 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 following procedure was adopted for green roof, permeable pavement, and bioretention cell. According to the ranking of the subcatchments, each LID solution of interest was installed in the 15 most influencing subcatchments of the category devoted to that LID type. A simulation was run for the three LID scenarios both in mid- and far-future

Table 1. LID control parameters used for LID simulations.

Layer	Parameter	Unit	Green roof	Permeable pavement	Bioretention 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^{-1}	–	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^{-1}	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 2. LID usage parameters used for LID simulations.

Parameter	Unit	Green roof	Permeable pavement	Bioretention 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

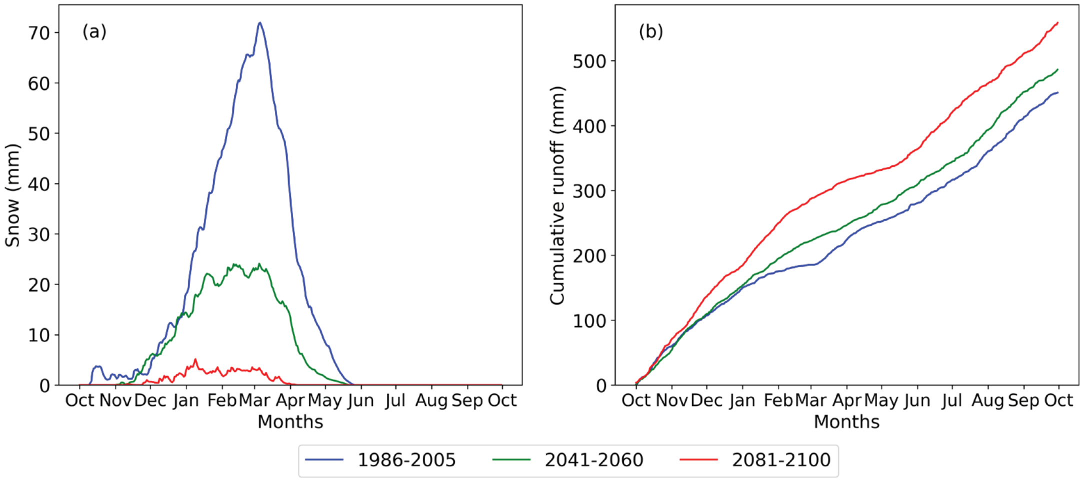

Fig 3. Daily plots of (**a**) mean snow water equivalent and (**b**) mean cumulative runoff over the water year for the historical, mid-future, and far-future periods.

time-windows. The runoff reduction in summer season was computed as the difference between the total runoff volume of each future period before and after placing the LIDs. Thereafter, the runoff reduction per unit LID area was defined as the reduction divided by the area of 15 subcatchments covered by the LID control. To quantify the total runoff volume that needs to be reduced in each future period, the difference between future total runoff volume and the historical one was computed. In the end, the area required to place a certain LID solution was obtained by computing the ratio between the total runoff volume that is needed to be reduced and the unit reduction.

Results

Urban hydrology projection to future

The study catchment, located in southern Finland, is sensitive to climate warming as air temperature frequently fluctuates around the freezing point, affecting the form of precipitation. As a result, changes in snow water equivalent (SWE) and winter-spring runoff dynamics are the main hydrological responses to climate change as seen in Fig. 3, which shows their daily mean patterns in historical and two future time periods. Notable changes are already simulated in the mid-future time-window: the mean SWE is projected to decrease by 58%. Interestingly, the mean snow cover duration remains almost unchanged (Fig. 3a). In the far-future, the SWE reduction is projected to be about 95%, resulting almost no snow during an average winter, and the snow cover period is projected to be notably shorter compared to the other two time-windows. Increasing air temperature and precipitation with decreasing SWE leads to an overall runoff increase and changing pattern. Fig. 3b illustrates how runoff in the mid-future is projected to accumulate similarly to the historical period until later winter, when more precipitation is projected to fall as rainfall and snow to melt earlier, increasing the runoff. The highest runoff increase is projected to occur by the end of the century, consistently reflecting higher air temperature, increased precipitation and changed snowmelt amounts.

The climate change impacts on runoff were analyzed for each season to assess the catchment hydrological behavior with and without LIDs under changing climate. In Fig. 4, the climate change impact without any mitigation measures demonstrates contrasting changes in seasonal runoff. In summer and autumn, the change in runoff is driven mainly by the increase in precipitation. The mid-future runoff accumulation in summer overlaps almost identically with the historical one until mid-July, when it starts to

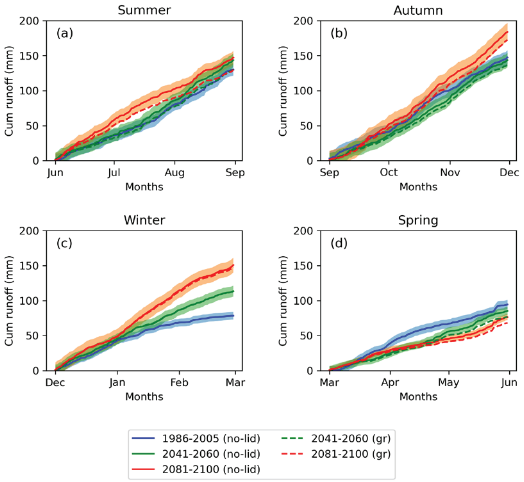

Fig 4. Seasonal impacts of climate change (no-lid) and green roofs (gr) on cumulative runoff in each future period. The coloured bands represent the variability (standard deviation) of the mean of the historical, mid-future, and far-future (no-lid) scenarios.

increase and almost reaches the far-future total runoff. The far-future runoff is projected to be consistently higher than the historical one during all the summer months. The average increases in the cumulative summer runoff for the mid- and far-future are about 10% and 13%, respectively. The changes in autumn runoff between the future periods are less consistent. While the mid-future runoff shows a slight decrease (3%), the far-future is considerably larger (about 25%) than in the historical period. In winter and spring, the change in runoff with no LIDs is mainly explained by the increase in temperature, which affects snow accumulation and melting. Due to notable changes in snow conditions, the runoff and precipitation accumulations deviate during these seasons. Winter is the season characterized by the strongest climate warming impacts on the hydrological behavior. Because of the snow reduction, the total winter runoff is projected to increase approximately 45% and 92% in the mid- and far-future period, respectively. This affects spring runoff generation: in this season, the total runoff volume shows a clear opposite trend compared to other seasons as it is projected to decrease in mid- and far-future about 10% and 19%, respectively.

The results clearly show that climate change is projected to strongly affect the seasonal hydrology of the Vallikallio study catchment. The inconsistent seasonal changes challenge the stormwater management systems and indicates the need for adaptation measures against varying changes in the future runoff. The LIDs capability in alleviating climate change impacts on urban runoff regime was next analyzed.

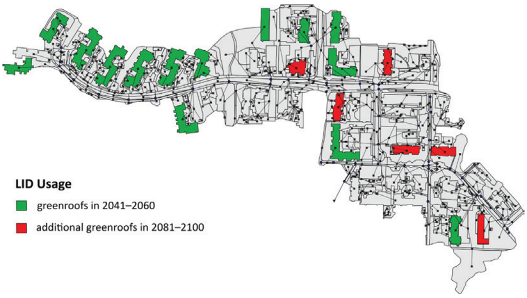

Fig 5. Green roof placement in the mid-future (2041–2060) and far-future (2081–2100).

Simulation of LIDs under changing climate

The LID controls chosen as adaptation measures were green roofs, permeable pavements, and bioretention cells, which were placed to the most influential subcatchments in SWMM according to the ranking of their impact on runoff as described in the material and methods section. The number of LID units and area coverage required to reach the total runoff volume reduction to the historical value in summer is highly dependent on the LID type (Table 3). Bioretention cell scenario needed the lowest LID areal coverage to reduce the mean summer runoff to historical level, while green roof scenario required the highest coverage. While the required green roof or permeable pavement area for the required runoff volume reduction is not large compared to the total study catchment area (5–13%), it is relatively large from the LIDs potential area (17–68%).

Figure 5 shows the required number and the placement location of green roofs in mid- and far-future periods, reflecting a higher runoff volume to be reduced in the far-future compared to the mid-future.

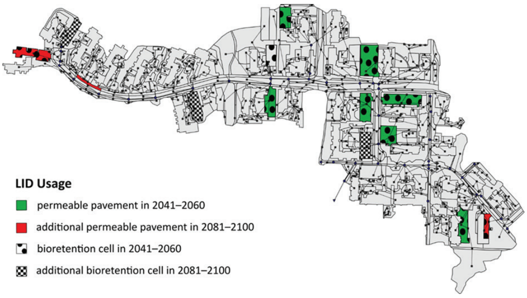

Fig 6. Permeable pavements placed in parking lots and walkways, and bioretention cells placed in parking lots in the mid-future (2041–2060) and far-future (2081–2100).

The fractional area needed to reduce the total summer runoff volume was computed to be 53% and 67% for the mid-future and far-future periods, respectively. Green roofs were able to reduce the summer total runoff in both future periods to the historical amount according to the design criterion (Fig. 4a). Even though the total volume of summer runoff looks similar in the mid- and far-future, the green roof area needed to reduce the runoff to the design level is larger in the far-future (Table 3). The autumn runoff (Fig. 4b) in the mid-future is projected to slightly decrease compared to the historical volume. The placing of green roofs further reduces the autumn runoff volume. In the far-future period, green-roofs will reduce mean autumn runoff to some extent. However, the historical total volume is not reached in autumn, because the LID design was made for the summer season. Regarding winter (Fig. 4c), the runoff accumulation in the historical scenario and both future green roof scenarios are nearly overlapping and falling in the variability band within the simulation periods. During spring (Fig. 4d), when the total runoff is projected to decrease in both future periods due to climate change, the reduction will be amplified by the introduction of LID controls.

Figure 6 illustrates the results from the permeable pavements scenario with the preferable placement location and the difference in their number between mid- and far-future. As described earlier, the suitable subcatchment types chosen to place permeable pavements were parking lots and walkways. According to the subcatchment ranking, the required area needed to be covered by permeable pavements in the mid-future was satisfied only by parking lots, while walkway was included in the far-future, according to the ranking 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. The location of the bioretention cells was similar to permeable pavements (Fig. 6), because both of these LIDs were allowed to be placed in the parking area catchment. The area of bioretention cells 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 8% of parking lots would be required to achieve the same goal.

Figure 7 shows the impact of permeable pavements and bioretention cells on runoff for each season and time-period. The runoff reduction by these two LID controls is similar. In fact, the cumulative runoff controlled by permeable pavements and bioretention cells are almost overlapping in each season and future period.

Table 3. 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	No. of units	Area required (m^2)	R/A (%)	R/T (%)
Green roof	Mid	14	11 527	53.1	10.0
	Far	20	14 607	67.5	12.7
Permeable pavement	Mid	7	5617	17.4	4.9
	Far	10	6800	21.2	6.0
Bioretention cell	Mid	10	978	6.5	0.8
	Far	13	1229	8.4	1.1

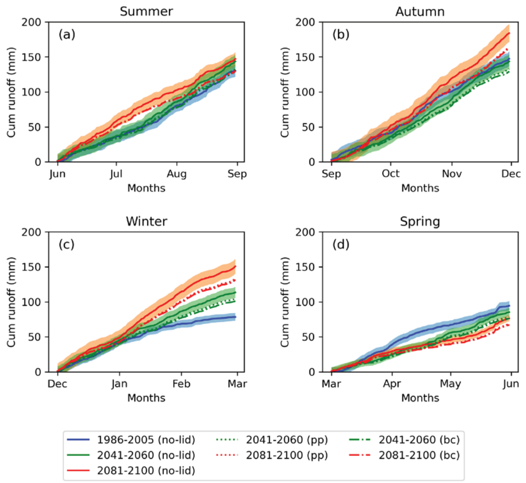

Fig 7. Seasonal impacts of climate change (no-lid), permeable pavements (pp), and bioretention cells (bc) on cumulative runoff in each future period. The coloured bands represent the variability (standard deviation) of the mean of the historical, mid-future, and far-future (no-lid) scenarios.

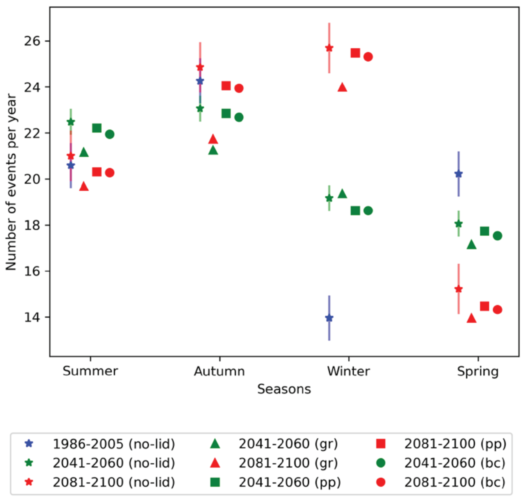

Fig 8. Seasonal impacts of climate change (no-lid), green roofs (gr), permeable pavements (pp), and bioretention cells (bc) on average number of flow events per year in each future period. The coloured bars represent the variability (standard deviation) of the mean of the historical, mid-future, and far-future (no-lid) scenarios.

This reflects the similar locations of the LIDs in the subcatchments, even though bioretention cell covered a smaller fraction of the subcatchment. In general, these two LID controls produce higher runoff volume reduction than green roofs (Fig. 4), and the biggest difference occurs in winter. During the winter season (Fig. 7c), the curves representing the cumulative runoff controlled by permeable pavements and bioretention cells are outside the yearly variability ranges of both future scenarios without LIDs. As described in the material and methods section, permeable pavements and bioretention cells are characterized by a storage layer, providing both infiltration and storage capacity compared to green roofs, which mainly provide runoff reduction through evapotranspiration that is limited during cold winter months.

In studying the LID impacts on the total runoff volume, the number of flow events for each time-window and LID scenario were also compared (Fig. 8). For both future periods and all seasons, permeable pavements and bioretention cells showed similar reduction not only in total runoff volume, but also in the number of flow events. Again, green roofs are performing in a different way compared to the other two LID controls. Even though green roofs provide a lower reduction in the total runoff volume in autumn, winter, and spring, they induce a higher reduction in the number of flow events for all the seasons. This is because green roofs retain the water for a longer time due to the drainage mat, which delays the water coming from the roof. Because of this process, the flow events in the outlet get longer and less frequent while still satisfying the established event criteria. The only exception is the mid-future winter scenario, when 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. Knowing that green roofs reduce the runoff through evapotranspiration, and attenuate runoff by detention, in cold conditions such as the historical or mid-future winters, green roofs provide limited runoff reduction because the lack of evapotranspiration due to low temperatures. This likely explains the larger number of events in mid-future winter despite green roofs. However, during other seasons and far-future winter, the shift in the climatic conditions changes detention and probably allows more evapotranspiration too, which results in a reduced number of flow events. The impact of LID solutions in changing the number of flow events is not as clear as climate change, which alters the number of events notably during the winter and spring seasons. A clear increasing and decreasing trend of total runoff volume in winter and spring, respectively, is evident. The strongest change occurs in winter, because the rising temperature and liquid precipitation will affect snow accumulation and melting, causing more frequent flow events already during winter, while decreasing them in spring.

Discussion

The future climate conditions challenge urban stormwater management in cold regions. The future projections in temperature and precipitation are in line with previously reported changes for Finland with coarser climate models (Jylhä *et al.* 2010). By the end of the century, mean daily air temperature in southern Finland will rarely drop below freezing point under the highest emission scenario (Veijalainen 2012). The projected changes in air temperature and precipitation drive notable changes in urban catchment hydrology. Snow water equivalent is projected to decrease in the future, resulting in the occurrence of some winters without any snow and with short intermittent snow-cover periods. According to Rasmus *et al.* (2004), snow cover in southern Finland is more sensitive to rising temperature than other regions: in the far-future period, snowpack formation will occur about two weeks later than in the historical period, while snowmelt in the study catchment will occur about two weeks earlier. Due to the increasing temperature trend, and changes in snow accumulation and melting processes, distinct changes in seasonal runoff volume and patterns are projected to occur. As in the current urban stormwater study, Veijalainen *et al.* (2010) reported that climate change impact on total runoff volume and flooding risk in Finnish rivers are also to be most affected during winter and spring.

Simulating the number of flow events under changing climate (Fig. 8) pointed out the clearest impact on the number of winter events, followed by spring. Because the cold seasons are projected to become warmer, the increasing fraction of liquid precipitation raises the number of winter flow events, while the reduction in snowmelt drives the decrease in the number of spring flow events. This tendency of increasing mixed and liquid precipitation during winter and spring is already taking place in Finland, as found by Luomaranta *et al.* (2019), who analyzed snow cover trends in Finland. Sillanpää (2013) measured winter flow events in urban catchments and showed how urban construction leads to a higher number of flow events. Thus, climate change further exaggerates the urbanization impact on the occurrence of flow events.

LID solutions can potentially restore and maintain the pre-development runoff regime by decreasing the impervious area, and increasing infiltration, storage, and evapotranspiration within an urban catchment (Palla and Gnecco 2015, Eckart *et al.* 2017, Khadka *et al.* 2021). The results reveal that restoration or maintaining the current hydrological regime is by far more difficult to achieve with the changing climate. Depending on the rate of warming and wetting in the future, some of LIDs capacity will be needed to just alleviate the changes without the possibility for restoration to pre-development conditions. After the climate change adaptation with LIDs, a portion of potential LID areas remain in both future periods (Table 3). Thus, with more extensive LID designs, the urban catchment could be adapted, to some extent, to climate change and urbanization impacts.

Another main finding is on how the impact of LIDs on the hydrological regime varies between seasons. Climate warming in cold regions shows the strongest hydrological impacts in winter and spring, while LIDs are typically designed for the summer or autumn season by focusing on management of the stormwater system against flooding risks. While bioretention cell and permeable pavement show comparable performance due to their hydrological-hydraulic similarity, green roofs have limited runoff reduction capability during the cold months. Thus, according to the results of this study, the choice of a LID solution is important when they are expected to function throughout the seasons.

The most typical use of LIDs is the decentralized management of stormwater at a mesoscale (Xu *et al.* 2023) to alleviate the increasing hydraulic stress from climate change (Tamm *et al.* 2023) and urbanization (Sillanpää and Koivusalo 2015). Even though changes in maximum flow due to climate change are important as they relate to flooding risk, the current study demonstrated how the results of a climate model can be expanded to a seasonal analysis of urban hydrological processes and stormwater management. The modelling was limited to a single location in northern Europe and a single climate scenario. The use of multiple urban areas combined with several climate projections would be an extension of this study. The use of an ensemble of scenarios (Veijalainen *et al.* 2010) would provide a more reliable view on the variability and uncertainty of the future urban hydrological regime. While the snow depths may be negligible in the future average winter conditions, variability in snow conditions assures that occurrence of snowy winter conditions hardly disappears. The use of hourly average rainfall values in continuous simulation limits the description of short-term rainfall-runoff dynamics in the stormwater network including LIDs, where the critical response time can be in the order of minutes rather than hours (Ntelekos *et al.* 2008, Smith *et al.* 2002). Because of this limitation, the focus was not on LID impacts on short term rainfall events and peak flows, but rather on the analysis of LID impacts on overall seasonal changes in volume and the number of events.

The current study outlined a transparent approach for evaluating how to adapt stormwater management to changing climatic conditions. Earlier studies have shown SWMM as a flexible tool for various stormwater management scenario assessments (Guan *et al.* 2015, Jato-Espino *et al.* 2019, Khadka *et al.* 2021). It should be noted that one of the prerequisites for the LID simulations is the parametrization of an urban catchment at a high resolution (Krebs *et al.* 2014) that supports the classification of homogeneous urban surface types and placement of LIDs at the roof, parking area, and street on a subcatchment level. The magnitude of simulated hydrological impact of LIDs under changing climate forcing depends on the selection of LID type and model parameters. Several studies on performance of SWMM LID module against measurements have been made for green roofs (Hamouz and Muthanna 2019, Krebs *et al.* 2016). Lisenbee *et al.* (2022) assessed the SWMM bioretention cell module against observations. Specific studies about the permeable pavement submodel were not found, but the description of permeable pavement resembles the SWMM parameterization of pervious areas in general. Conclusion from existing model comparisons against measurements is that SWMM is shown to be sufficient for simulation of LIDs under changing conditions, such as the simulations in this study.

The parameter values in this study were adopted from earlier studies (Krebs *et al.* 2016, Tuomela 2017). Green roof studies (Krebs *et al.* 2016, Hamouz and Muthanna 2019) pointed out sensitivity of green roof simulation by SWMM to substrate porosity values. Krebs *et al.* (2013) studied sensitivity of SWMM model parameters to urban surface parameters and noted depression storage to be a key parameter. These findings suggest that model parameters controlling storage capacity have a large impact on simulated runoff, which is a relevant piece of information for designing LIDs. The model results are also sensitive to the soil type of the area. In the current simulations, sandy till was conductive enough to simulate permeable pavement and bioretention cell without subsurface drainage, which led to increased infiltration and decreased stormwater discharge from the area. When a less conductive soil type is present, the permeable pavement and bioretention cell structures require use of subsurface drainage connected to the storm sewer network, which reduces infiltration losses and decreases the impact of LIDs on stormwater discharge volumes. Recognizing the fact that model parameters are site specific and change when calibrated against data from new sites (e.g. Abdalla *et al.* 2022), the simulation results of future simulations with one single parameterization should be treated with caution.

Conclusions

This study investigated the needs and possible solutions for adapting stormwater management to climate change impacts. Climate change is projected to have strong impacts on wintertime hydrological processes in northern cities. The availability of high-resolution climate models makes it possible to explore climate change impacts in urban areas at scales meaningful for stormwater management. The current RCP8.5 scenario leads to an average decrease of 58% in mid-future snow water equivalent and 95% in far-future, resulting on average, in almost no permanent snow cover in winter. Because of changes in air temperature, precipitation and snow processes, runoff is projected to increase in future periods during most of the year, except in the spring. Summer total runoff volume increase is about 10% and 13% in the mid-future and far-future periods, respectively. In winter and spring, the total runoff volume change is mostly influenced by the rising air temperature, which controls snow accumulation and melting dynamics. Mid-future total runoff volume is projected to increase by 45% in winter and decrease by 10% in spring, while in the far-future, total runoff volume will increase by 92% in winter and decrease by 19% in spring.

SWMM was used to model different LID scenarios and assess to what extent urban catchment can be adapted to alleviate climate change impacts on future hydrology. Green roofs, permeable pavements and bioretention cells were chosen as LID controls due to their runoff retention mechanisms, such as evapotranspiration, infiltration, and storage. Bioretention cell scenario was the one requiring the lowest area coverage while green roofs required the largest area but performed a lower reduction of runoff volume in the future periods. The biggest difference between LID controls' performance was evident in the winter season. Green roofs provide runoff reduction through evapotranspiration and attenuation, but winter weather now and in the future does not allow significant evapotranspiration, even though air temperature is projected to increase notably due to climate change. In spring, the total runoff volume without LID controls is projected to decrease in the future and after placing the LID controls, the total runoff volume is projected to decrease even more. The selected LID scenarios influence the number of flow events in the future periods compared to the baseline scenario without any LIDs, but their impact is not enough to restore the historical number of events. The most striking result from Vallikallio was the demonstration of unexpected behavior of LIDs during the cold seasons, when climate warming leads to strong changes in snow accumulation and melting cycles.

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