Urban Resilience

The Optimization of Sustainable Urban Stormwater Management

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Urban Resilience: The Optimization of Sustainable Urban Stormwater Management

Image Source: Xicotencatl, 2013, https://commons.wikimedia.org/wiki/File:Water_Feature_UBC.jpg

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2.0 Abstract

With increasing urbanization and intensifying climate change impacts, an increasing amount of impermeable surfaces can result in surface stormwater runoff that overwhelms existing stormwater drainage systems. In response to the urgent need for sustainable cities, there has been a growing body of research on an increasingly popular urban planning initiative: sustainable urban stormwater management or ‘low impact development’. In this work, we expand on this discussion by investigating the stormwater resilience of the University of British Columbia’s Vancouver campus and the effectiveness of low impact development practices in increasing the resilience to climate change impacts. Specifically, the report examines various low impact development controls, including green roofs, rain gardens, and permeable pavements, evaluating their performance in managing stormwater runoff and reducing flood risk. The study used a rainfall-runoff analysis, employing a stormwater management model (SWMM 5.2.1) to simulate projected storm events under a moderate climate change scenario. The research findings indicate that a combination of permeable pavements and rain gardens are the most effective low impact development controls to enhance stormwater resilience. This supports existing research that low impact development can increase the infiltration of stormwater into the ground, thus reducing the volume of stormwater runoff and subsequent flooding events. This study concludes that low impact development is a promising urban planning initiative to enhance urban resilience to climate change impacts, and emphasizes the need for further research to optimize the design and implementation of low impact development controls.

Keywords: urban; resilience; climate change; low impact development; runoff

2.0 Introduction

2.1 Climate change and urban resilience

Climate change has a myriad of effects on the environment and urban environments are no exception. Impacts on a particular city are contextually dependent, since climate change interacts with regional landscapes and ecological processes such as hydrological cycles. However, climate impact projection models have indicated that we can generally expect to see a rise in sea level, increased weather severity, and changes in precipitation and air temperature (Hoegh-Guldberg et al., 2018). In addition to increased frequency of storm events and greater precipitation volume and intensity, climate change can compound with urbanization to intensify climate change impacts at local levels (Yang et al., 2021). For example, the urban heat island effect can increase local rain volumes, resulting in a phenomenon known as the urban rain island effect (Yang et al., 2021). At the same time, urbanization leads to a decrease in pervious surface areas (Fletcher et al., 2013). This results in increased impervious surface runoff which can overwhelm existing stormwater drainage systems, triggering urban floods (Eckart et al., 2017). Increases in urban floods are concerning, especially considering the projected growth of urbanization in this century, with an expected 60.4% of the world's population living in cities by 2030 (United Nations, 2018), and an expected world population of 8.5 billion by the same year (United Nations, n.d.). The urgency of this issue requires assessments of climate mitigation strategies such as sustainable urban stormwater management, to minimize the effects of climate change and urbanization on urban environments. This urgency is reflected in the literature, as there is growing attention to rainfall-runoff analyses and discourse on stormwater mitigation strategies (Yang et al., 2021).

With increasing rates of urbanization around the world, emphasis on sustainable development is coming to the forefront of urban planning initiatives. The United Nations' Sustainable Development Goals highlight this shift with the inclusion of 'sustainable cities and communities' (United Nations, n.d.). More recently, academic discussion is exploring the concept of resilience. Derived from ecological resilience theory, resilience can have different definitions between disciplines (Ernstson et al., 2010); This report will follow the definition of MacKinnon's resilience: "[the] capacity to deal with external sources of stress and maintain or recover normal functioning," (2015, p. 561). The concept of resilience has influenced urban planning to focus on the transformation of a city to use natural processes, instead of trying to change the physical environment to match the goals of development (Ernstson et al., 2010). An example of this lies with 'sponge cities' – these use a combination of traditional and green stormwater management approaches to reduce flood risks and store water for later use (Chan et al., 2022). Regardless of terms, there is a movement of urban planning initiatives toward using natural solutions and mimicking of natural hydrological cycles to increase urban resilience to climate change.

2.2 Low impact development as a tool for urban resilience

The integration of natural ecosystem processes into urban planning and designs can increase the resilience of urban environments to disturbance (Ernstson et al., 2010; Keeler et al., 2019). As such, there have been a series of movements and concepts introduced to urban stormwater management: best management practices (BMPs), integrated urban drainage system

(IUDS), low impact development (LID), and green infrastructure (GI) (Yang et al., 2021). While there are some slight differences in meanings, they all are similar in application – often using natural stormwater control techniques (e.g., bioswales, green roofs) as a way to manage stormwater (Yang et al., 2021). LID and GI are the most ‘current’ terms in the literature, often used interchangeably (Fletcher et al., 2015). For the purpose of this report, LID will be used as an umbrella term for sustainable urban stormwater management practices.

LID controls include practices such as green roofs, bioswales, bioretention cells (also known as rain gardens), rain cisterns, permeable pavement systems, etc., and are often used as a retrofit measure to improve stormwater infiltration and retention (Eckart et al., 2017). The key stormwater benefit includes the reduction in stormwater runoff volume, primarily by increasing water infiltration into the ground or retaining the water to slow down overground water flows (Eckart et al., 2017). As impervious runoff (runoff from impervious areas) can be up to 25 times greater than pervious runoff volumes from an equivalent area (Boyd et al., 1993), the greatest reductions in runoff are often seen where LID controls transition impervious surfaces to pervious or semi-pervious surfaces thereby reducing the risk of flash floods (Alexander et al., 2019; Shafique et al., 2018). Significant research has highlighted these positive impacts as LID controls have emerged as popular measures around the globe, with cities like London and Toronto successfully implementing LID initiatives (Yang et al., 2021). The increasing popularity of LID is further supported by the associated secondary benefits, including increases of green spaces, improvements in quality of life for residents, and increased biodiversity (Eckart et al., 2017).

2.3 Looking ahead: Low impact development at UBC

The University of British Columbia (UBC), with its main campus being in Vancouver, has developed action plans in an effort to become a more sustainable campus within an urban environment. Currently, the university is enacting an engagement project to facilitate collaborative planning, called Campus Vision 2050, which aims to expand on the pre-existing climate action plan. The current Climate Action Plan 2030 (UBC, n.d.) outlines their many goals, including decarbonization, waste minimization, and energy efficiency, within their overarching objective to respond to climate change with mitigation, adaptation, and increased resiliency. UBC’s (2017) Integrated Stormwater Management Plan further highlights resilience and recommends the implementation of LID controls on campus. Specifically, the plan aims to reduce stormwater runoff while maintaining water quality (UBC, 2017). While this plan references LID, there has not yet been an analysis of optimal LID selection and location on campus, nor an analysis on the direct effects on stormwater management. This research project aims to address this knowledge gap, by assessing the effects of LID controls on stormwater runoff using a simulated stormwater management model. It aims to answer the questions: Can LID improve the resiliency of UBC to climate change, by reducing stormwater runoff? And what combination of LID controls and LID locations result in the greatest improvements of stormwater resiliency?

3.0 Study Site and Data Summary

3.1 Study site

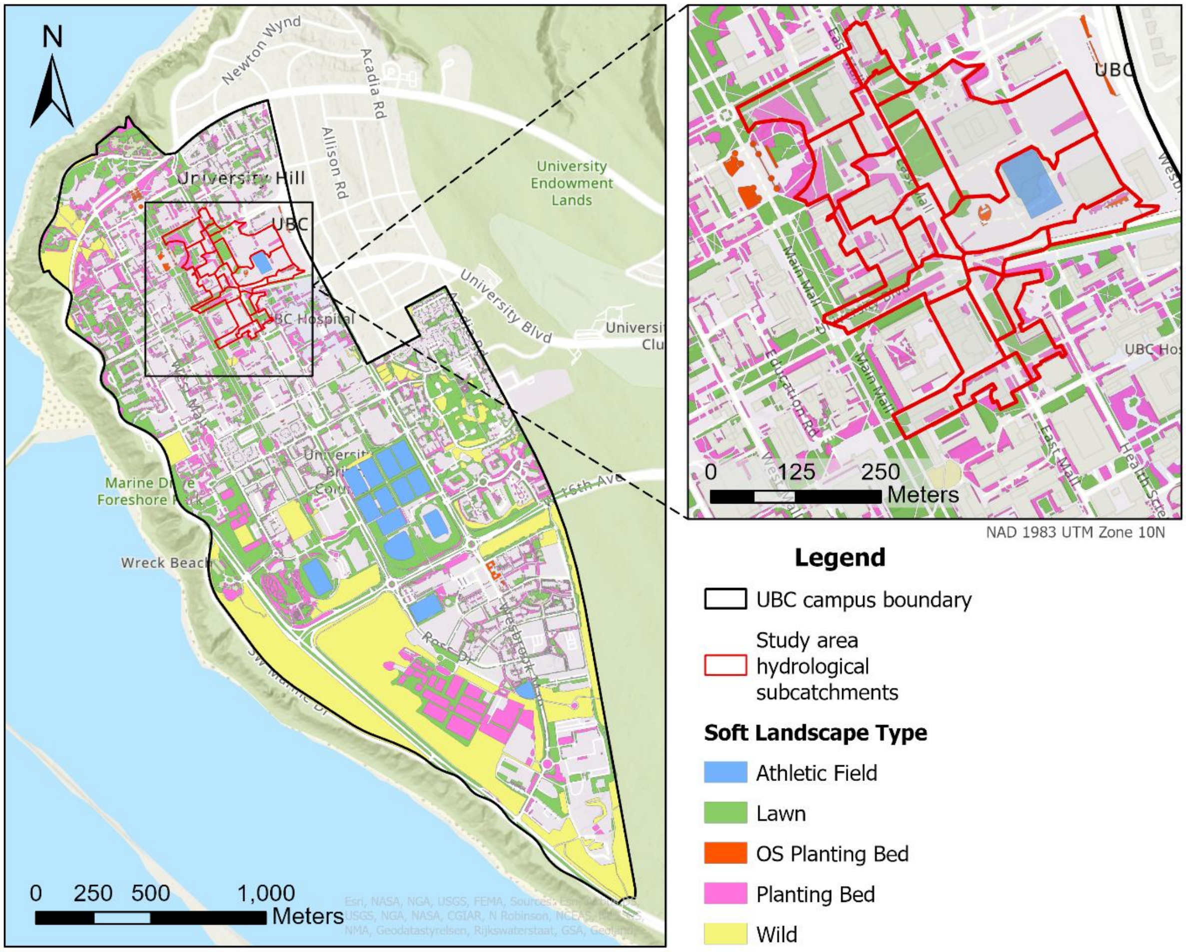

Figure 1. Study area of the University of British Columbia campus (outlined in black). Colours indicate areas of campus with soft landscape, separated by type (athletic fields, lawns, planting beds, wild grown). The map inset shows the hydrological subcatchments (outlined in red) used in the report's rainfall-runoff analysis.

The study area for the analysis involves 19 stormwater sub-catchments of the UBC campus. The subcatchments reside in the Northeastern section of campus, surrounding the intersection of East Mall and University Blvd (Figure 1). The native soils of the area are often heavy or silty clay, with a weak soil horizon A presenting risk of erosion (BC SIFT, 2018). Additionally, the soils belong to the Bose-Heron soil management group, meaning that the soils have low water-holding capacities and may need additional soil to improve drainage (Krzic et al., 2010). At the same time, the area has already seen substantial urbanization, with pervious surfaces being reduced to the soft landscapes seen in Figure 1. The native soil type in combination with the lack of pervious surface area signifies that the area is at risk of flooding due to reduced infiltration (Boyd et al., 1993). Current drainage infrastructure informed the delineation of the study area into hydrological subcatchments for the purpose of the rainfall-runoff analysis. LID controls in scenarios will be informed by the site conditions, such as area size, surrounding pervious and impervious surfaces, and existing land use.

The study area resides within the city of Vancouver, British Columbia, and exists on a peninsula on the Pacific Ocean coastline. As such, the climate of the study area is a moderate oceanic climate, often experiencing dry summers and wet winters. The biogeoclimatic (BEC) zone for the study area is CWHmm, meaning it is in the Coastal Western Hemlock zone, and the maritime subzone. Under climate change emissions scenarios, the average annual precipitation is expected to increase 6% from the historic average of 1350 mm/year (Shepherd et al., 2014). As well, the intensity of rainfall events is expected to grow (Figure 2), presenting a risk of increased flash floods (Alexander et al., 2019).

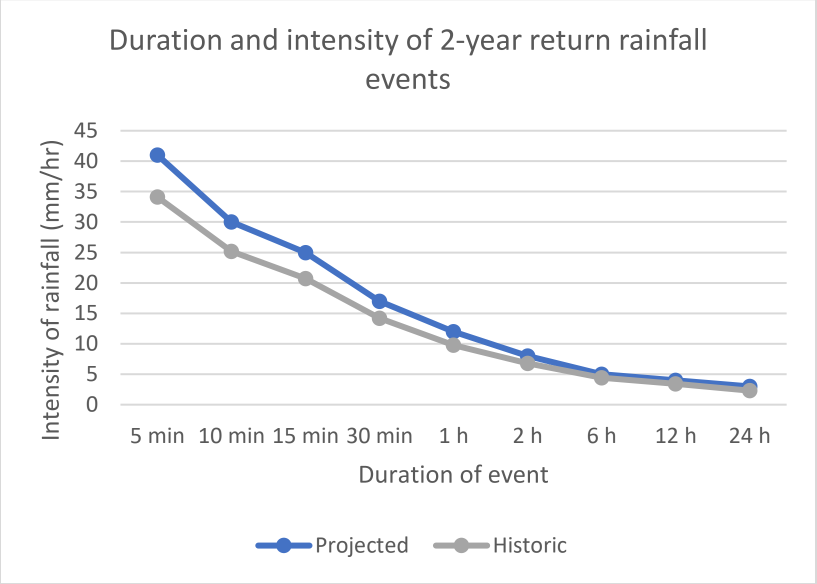

Figure 2. Duration and intensity of storm events for the University of British Columbia Vancouver campus located in Point Grey, Vancouver, BC. The intensity of rainfall (mm/hr) is expected to increase under moderate climate change scenarios for the area. Intensity of rainfall uses the median rates for 2-year return events, which are storms expected to occur once every two years. Data sourced from ClimateData.ca (Shepherd et al., 2014).

3.2 Data summary

Key datasets for this project have been summarized in Table 1. Aerial orthophotos were used to provide information for land cover and land use of the study area, and to validate spatial vector datasets provided by UBC's campus planning department. LiDAR-derived data, including a digital elevation model (DEM) were used to measure topographic information (e.g., elevation, slope, aspect) and to produce flow direction and flow accumulation rasters. Climate information, including projected precipitation, were used as parameters for the rainfall-runoff analysis. Further exploration of the uses of data are seen in section 2.3 below.

Table 1. Data summary table of notable datasets for the project analysis.

Data Name and Author	Data type	Date of publication or acquisition	Source and notes
Climate Change-Scaled IDF Data v3.30, Shepherd et al.	Climate variables	n.d., accessed September 2022	Precipitation, temperature under climate change scenarios (2011-2100) for the VANCOUVER UBC, BC weather station. Model projections created by employing the Clausius Clapeyron relationship to scale historical rainfall rates, using 26 CMIP6 global climate models. https://climatedata.ca/
UBCGeodata, [November 2016], Jeff Burton & Rachel Wiersma	Geospatial vector layers	November, 2016	The coordinate reference is ESPG:26910/UTM10N. Includes various geospatial layers that show features, roads, paths, and buildings on UBC campus. Some of the data collection occurred from 2008-2015, so this dataset may not represent current information for UBC campus. However, some layers such as the buildings layer are continually updated. https://hdl.handle.net/11272.1/AB2/S15BIR,
[University of British Columbia Vancouver Campus Lidar], 2021, University of British Columbia, Campus and Community Planning	LiDAR	June 23, 2021	Estimated horizontal accuracy of ± 0.30m and vertical accuracy of ± 0.15m. https://hdl.handle.net/11272.1/AB2/Y5KQNB
[Orthophotos, University of British Columbia Vancouver Campus], 2021, University of British Columbia, Campus and Community Planning	Orthophotos	April 14, 2021	10x10cm spatial resolution, captured by a Zeiss DMC 3 camera with a focal length of 92mm. The reference system is NAD 1983, and the projection is UTM Zone 10. The images are uncompressed 3 band TIFF with World Reference File, and a 3 band ECW with internal geotag. https://hdl.handle.net/11272.1/AB2/R731P3
UBC_Storm, University of British Columbia, Campus and Community Planning	Geospatial vector layers	February, 2022	Vector layers of UBC stormwater infrastructure including junctions, mains, manholes, nodes, stormwater detention features, end caps, outfalls, inlets, sump pumps, wells, and ditches. The reference system is NAD 1983 with a UTM Zone 10N projection. This resource was directly provided by Rachel Wiersma in UBC's department of Campus and Community Planning.

3.3 Obtaining and pre-processing data

This research largely follows the methodologies of Alexander et al. (2019) and Frias & Maniquiz-Redillas (2021), depending primarily on the following factors from the study area: 1) topographic conditions 2) soil type 3) current drainage infrastructure 4) land use & land cover and 5) rainfall data. For each data type, pre-processing of data includes ensuring projections are consistent and reprojecting into UTM Zone 10N if required.

1) *Topographic conditions*
   A DEM was produced using LiDAR data and R software (Murray, 2022) to obtain topographic information including elevation, slope, and aspect (Xu et al., 2021a). The

DEM was primed for hydrological analysis using tools from WhiteboxTools (Lindsay, 2014) and used to produce flow accumulation and flow direction rasters.

2) *Soil composition*
   Soil composition for the study area is downloaded from Soilweb as a shapefile. PlanetScope satellite imagery of 3m x 3m spatial resolution and orthophotos of a 10cm x 10cm spatial resolution were used in ArcGIS Pro to identify areas that may exhibit different soil properties than the region's dominant native soil. As soils have different seepage and water holding capacities depending on their geophysical properties (Guan et al., 2016; Ren et al., 2020), the soils were used to determine variations in water infiltration rates (mm/hr).
3) *Current drainage infrastructure*
   Current drainage infrastructure was provided by UBC and includes information pertaining to subcatchments, drains, manholes, water mains, outlets, and stormwater detention features. The drainage infrastructure was used to determine parameter inputs for the rainfall-runoff analysis model.
4) *Land use & land cover*
   Land use was provided by the University of British Columbia (UBC) as a shapefile, with land cover obtained through PlanetScope satellite imagery and aerial orthophotos. A land cover classification of the study area was performed with classes based on permeability of surfaces (impervious, semi-pervious, pervious) (Shrestha et al., 2021). The land cover classes enabled the verification of permeability of subcatchments provided by UBC's drainage infrastructure dataset.
5) *Rainfall data*
   Projected rainfall data under climate change scenarios was obtained from ClimateData.ca (Shepherd et al., 2014). The rainfall data is associated with different storm return events and durations and includes 2-year, 25-year, and 100-year return events with storm durations of 10 minutes and 24 hours.

4.0 Methods

4.1 Rainfall-runoff analysis

The United States Environmental Protection Agency's (EPA) Storm Water Management Model (SWMM) 5.2.1 was used to estimate stormwater runoff of the study area under different precipitation intensities. SWMM is a rainfall-runoff spatial simulation model that uses subcatchments to route precipitation and subsequent runoff through a spatially defined area (Rossman & Simon, 2022). SWMM allows for the estimation of flow rate, depth, and water quality, and is often used for urban planning and analysis of drainage systems (Rossman & Simon, 2022). Five factors were inputted into the SWMM model to assess runoff volumes and flood risks of the current study area under climate change scenarios: topographic conditions, soil infiltration rates, current drainage infrastructure, land cover & land use, and rainfall data. The simulation was then repeated using the LID controls within the SWMM model, representing different campus designs or layouts, to assess runoff volumes and flood risks with potential LID installations. Supported LID controls within the SWMM model include: bio-retention cells, rain gardens, green roofs, infiltration trenches, continuous permeable pavement systems, rain barrels, rooftop disconnection, and vegetative swales (Rossman & Simon, 2022). The LID controls used in the model layouts are outlined in Table 2.

Table 2. LID controls used in each SWMM model layout. Layout 1 represents the current UBC campus, with no additional LID controls implemented beyond what currently exists.

Layout	*Permeable pavement system*	*Green roof*	*Bio-retention cell*
1			
2	✓		
3		✓	
4			✓
5	✓		✓
6	✓	✓	✓

4.2 Resiliency analysis

As an emerging concept, there is currently no commonly used stormwater resiliency metric or method for quantification. As such, the study area's overall resiliency to flooding is quantified using the runoff coefficient, the ratio of total runoff to total precipitation, produced by the SWMM rainfall-runoff analysis. The runoff coefficient acts as a proxy for resilience as it represents how much water in a sub-catchment cannot infiltrate into the ground or the stormwater system, in comparison to how much water the sub-catchment receives.

Comparison of resiliency

In this communication, we compare LID controls to assess their relative effectiveness in increasing climate change resilience. Each LID model layout was simulated under six different climate-projected rainfall scenarios: 2-year, 25-year, and 100-year return storm events, with each return event being tested twice using durations of 10 minutes and 24 hours (Figure 3). This variety of rainfall scenarios enables the assessment of UBC's resilience to both storms of differing magnitudes and intensities, which previous research has found to be correlated to runoff volumes and flood risk (Hettiarachchi et al., 2018; Shafique et al., 2018). The overall resiliency of the study area to climate change scenarios and potential flooding events was then compared across simulations and layouts. The aim of the comparison was to identify the optimal potential LID controls which can increase the resiliency of the study area to climate change effects. Optimal locations and types of LID practices were determined by the SWMM simulations and corresponding runoff coefficients. As optimality of LID practices is inherently tied to spatial locations (Liu et al., 2016; Xing et al., 2016), a map was produced in AcrGIS Pro showing recommended LID controls and locations for decision-making and planning processes.

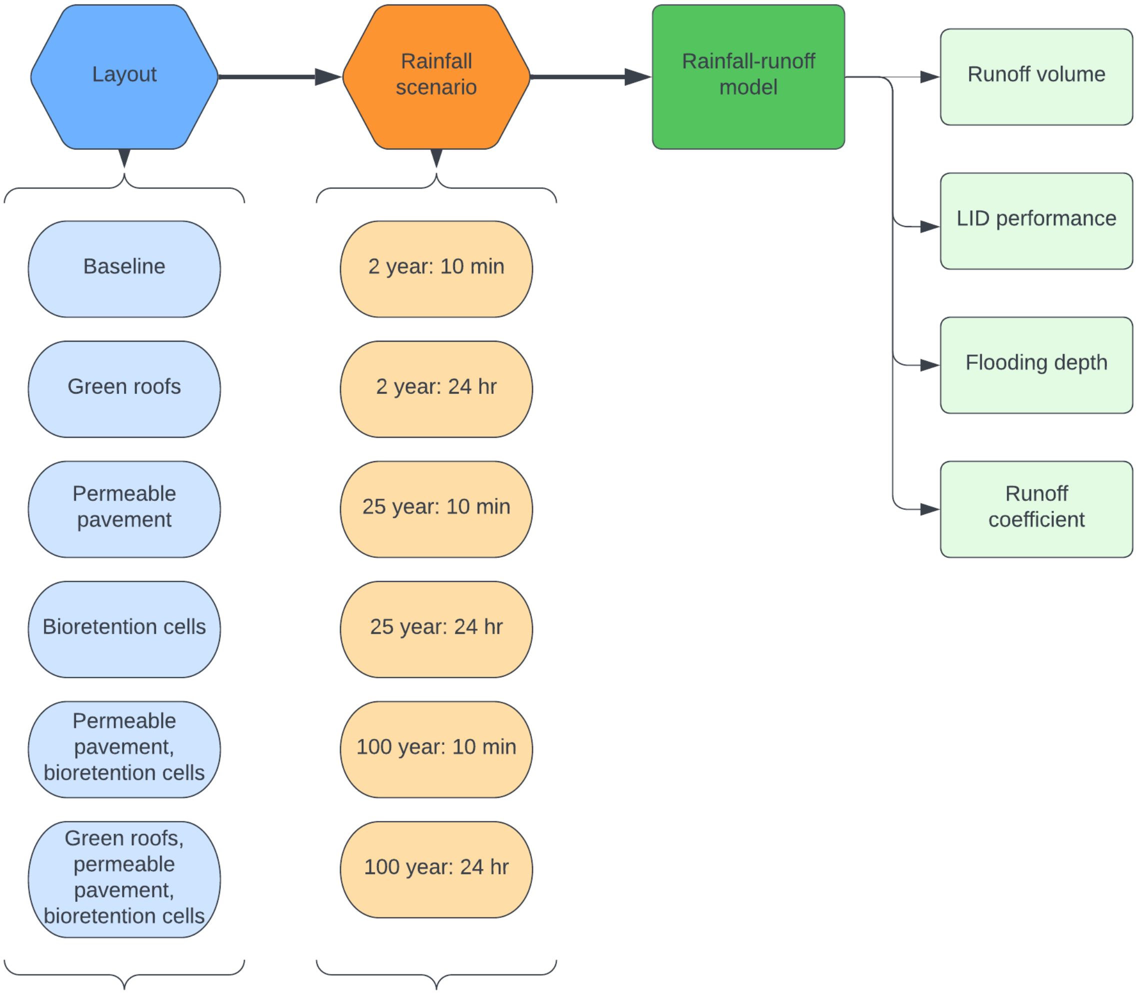

Figure 3. Workflow of the SWMM model simulations for the assessment of UBC's stormwater management resiliency and the identification of potential LID practices to increase resiliency to climate change effects. Layouts include UBC's baseline current storm infrastructure, as well as five additional layouts which include either a single LID control or a combination of LID controls (seen in blue). Each layout is simulated under six different rainfall scenarios (seen in orange), with 2-year, 25-year, and 100-year return events of two different durations: 10 minutes and 24 hours. The combined LID layout and rainfall scenario was simulated in the SWMM rainfall-runoff model, producing output variables (seen in green). These include total runoff volume (mm), LID performance (total infiltration in mm), flood depth (mm), and the runoff coefficient (ratio of total runoff volume to total received precipitation).

5.0 Results

5.1 Rainfall-runoff analysis

Table 3. Average runoff coefficients (ratio of total runoff to total received precipitation) for each model simulation across all subcatchments, with lower runoff coefficients indicating greater resilience to flooding. Layout indicates LID layout in the model simulation. Baseline = current infrastructure; GR = green roofs; PP = permeable pavement; BR = bioretention cells; BRPP = bioretention cells, permeable pavement; BRPPGR = bioretention cells, permeable pavement, green roofs.

LAYOUT	2YR 10 MINS	2YR 24HRS	25YR 10 MINS	25YR 24HRS	100YR 10 MINS	100YR 24HRS
BASELINE	0.86	0.76	0.94	0.76	0.97	0.76
GR	0.85	0.75	0.94	0.76	0.97	0.77
PP	0.64	0.54	0.71	0.55	0.74	0.55
BR	0.83	0.73	0.91	0.74	0.94	0.74
BRPP	0.62	0.53	0.70	0.53	0.72	0.53
BRPPGR	0.62	0.52	0.70	0.53	0.72	0.53

Table 3 displays the average runoff coefficient for the entirety of the study area (19 subcatchments) for all 36 model simulations. Across all rainfall scenarios, layouts that include LID controls generally have lower runoff coefficients than the baseline layout. Three layouts consistently have the lowest runoff coefficients for each rainfall scenario: PP (permeable pavements), BRPP (bioretention cells and permeable pavements), and BRPPGR (bioretention cells, permeable pavements, and green roofs).

Table 4. For each LID layout, the reduction in average runoff coefficients (ratio of total runoff to total received precipitation) from the baseline infrastructure is shown. GR = green roofs; PP = permeable pavement; BR = bioretention cells; BRPP = bioretention cells, permeable pavement; BRPPGR = bioretention cells, permeable pavement, green roofs.

LAYOUT	2YR 10 MINS	2YR 24HRS	25YR 10 MINS	25YR 24HRS	100YR 10 MINS	100YR 24HRS
GR	0.00	0.01	0.00	0.00	0.00	-0.01
PP	0.22	0.21	0.23	0.21	0.23	0.21
BR	0.03	0.02	0.03	0.02	0.03	0.02
BRPP	0.23	0.23	0.24	0.23	0.24	0.23
BRPPGR	0.24	0.24	0.24	0.23	0.25	0.23

Table 4 presents the reductions in average runoff coefficients from the baseline layout, for each LID layout and rainfall scenario. All except one model simulation for LID layouts saw a reduction in runoff coefficients, with an average reduction of 0.14 across all simulations. PP, BRPP, and BRPPGR saw the greatest reductions, with average reductions being 0.22, 0.23, and 0.24 respectively. However, for one GR (green roofs) simulation, the average runoff coefficient was increased by 0.01 from the baseline, occurring under a rainfall scenario of a 100-year return event storm with a duration of 24 hours.

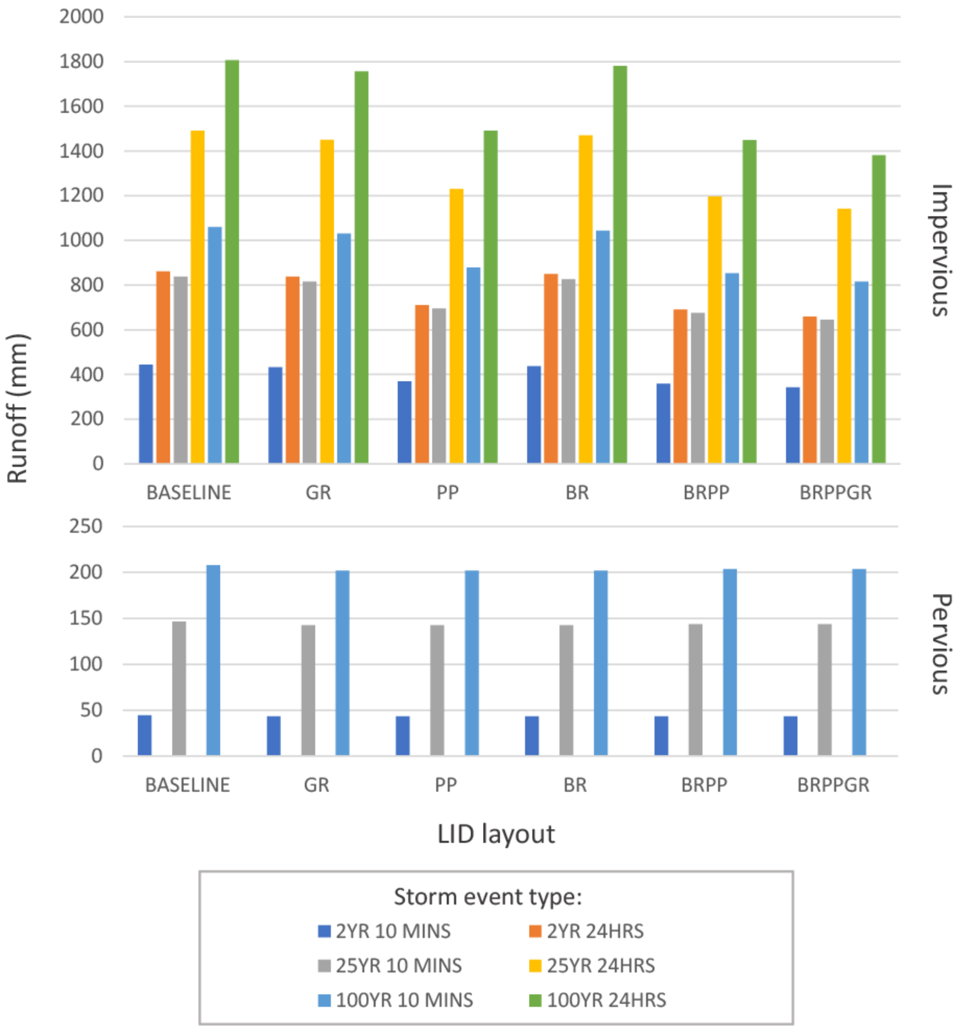

Figure 4. Total runoff (mm) across LID layouts, differentiated by rainfall scenario (storm event type). Top graph shows total impervious runoff (mm), with the bottom graph showing total pervious runoff (mm). LID layouts include: Baseline = current infrastructure; GR = green roofs; PP = permeable pavement; BR = bioretention cells; BRPP = bioretention cells, permeable pavement; BRPPGR = bioretention cells, permeable pavement, green roofs. Storm event type represents the rainfall scenario, with the year indicating the return event (2-year, 25-year, 100-year) and the time indicating the duration of the storm (10 minutes and 24 hours).

Figure 4 displays the total impervious and pervious runoff volumes for each model simulation. Generally, the total runoff increases with increasing magnitude storms, with 100-year return events having the greatest total runoff. However, there is a difference between 10 minute and 24 hour rainfall events, as pervious runoff only occurs during 10 minute storms. This is despite the total runoff (pervious and impervious) of 10 minute storms being less than the total runoff of 24 hour storms.

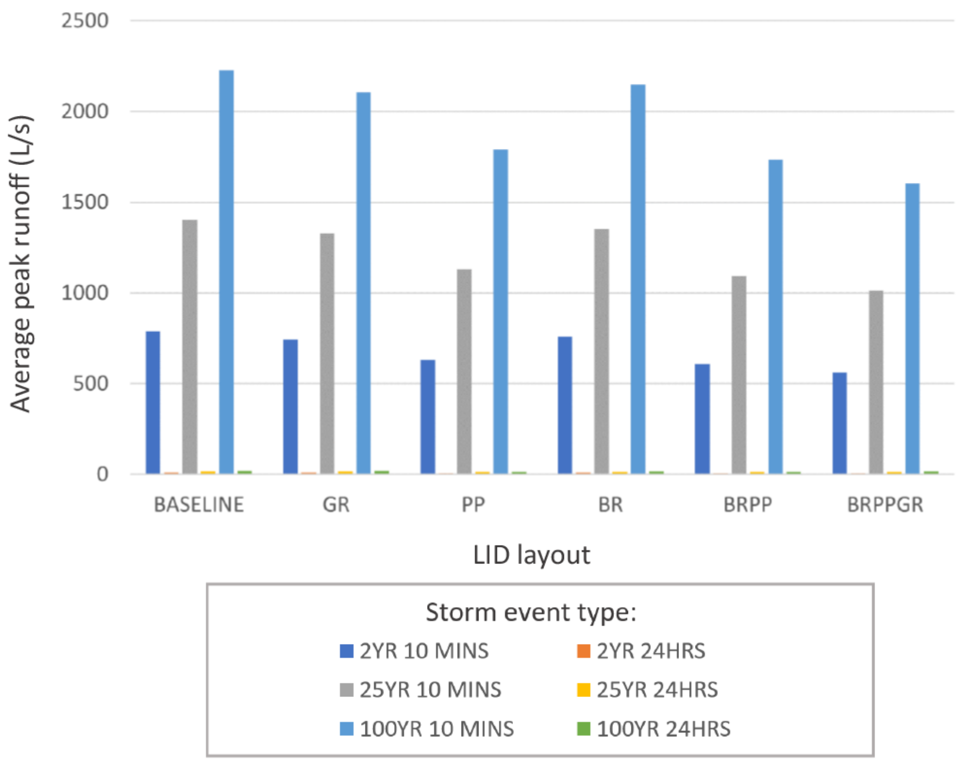

Figure 4. Average peak flow runoff (L/s) for LID layouts differentiated by storm event type. LID layouts include: Baseline = current infrastructure; GR = green roofs; PP = permeable pavement; BR = bioretention cells; BRPP = bioretention cells, permeable pavement; BRPPGR = bioretention cells, permeable pavement, green roofs. Storm event type represents the rainfall scenario, with the year indicating the return event (2-year, 25-year, 100-year) and the time indicating the duration of the storm (10 minutes and 24 hours).

Similarly to total runoff, peak runoff (the maximum flow rate of all runoff in L/s) demonstrates a relationship to the storm duration or intensity. Figure 5 displays the average peak runoff across subcatchments for each model simulation, where the peak runoff is approximately 207 times larger for 10 minute storms than 24 hour storms. The largest peak runoff values occur with the baseline layout, and increases from 788.31 L/s (2-year return event, 10 minute duration) to 2228.75 L/s (100-year return event, 10 minute duration). The lowest peak runoffs occur under the BRPP and BRPPGR layouts, although these see the same increases between storm magnitudes as the baseline however to a lesser degree; BRPPGR has an average peak runoff of 562.20 L/s during 2-year, 10 minute storms, and 1604.97 L/s during 100-year, 24 hour storms.

Table 5. Total number of flooded nodes (stormwater drains, manholes, and junctions) across all SWMM model simulations. Layout indicates LID layout in the model simulation. Baseline = current infrastructure; GR = green roofs; PP = permeable pavement; BR = bioretention cells; BRPP = bioretention cells, permeable pavement; BRPPGR = bioretention cells, permeable pavement, green roofs. Columns represent rainfall scenario, with the year indicating the return event (2-year, 25-year, 100-year) and the time indicating the duration of the storm (10 minutes and 24 hours).

LAYOUT	2YR 10 MINS	2YR 24 HRS	25YR 10 MINS	25YR 24 HRS	100YR 10 MINS	100YR 24 HRS
BASELINE	60	4	92	4	100	4
GR	57	4	90	4	97	4
PP	42	4	82	4	97	4
BR	58	4	92	4	98	4
BRPP	32	4	82	4	95	4
BRPPGR	29	4	77	4	94	4

In addition to runoff variables, the SWMM model output includes the number of flooded nodes (stormwater drains, manholes, and junctions) within each simulation. Table 5 shows the total number of flooded nodes for each layout and rainfall scenario. LID layouts see fewer flooded nodes than the BL layout, however this difference is less significant with higher magnitude storms; 100-year events see minimal differences in flooded nodes across layouts, while 2-year events show substantial differences. Regardless of the storm magnitude, all 24 hour storms report the same four flooded nodes.

5.2 Optimization of LID for UBC campus

The reduction in runoff coefficients varied amongst LID layouts. PP, BRPP, and BRPPGR saw the greatest reductions, with BRPP and BRPPGR having only slightly higher reductions than PP (see Table 4). However, differences between BRPP and BRPPGR are minimal with the addition of green roofs only contributing a maximum additional 0.01 runoff coefficient reduction. Additionally, for the 24 hour storms, BRPPGR saw greater average peak flows than BRPP. The BRPP layout and corresponding LID implementation is displayed in Figure 6, and represents the optimal layout based on the rainfall-runoff analysis results.

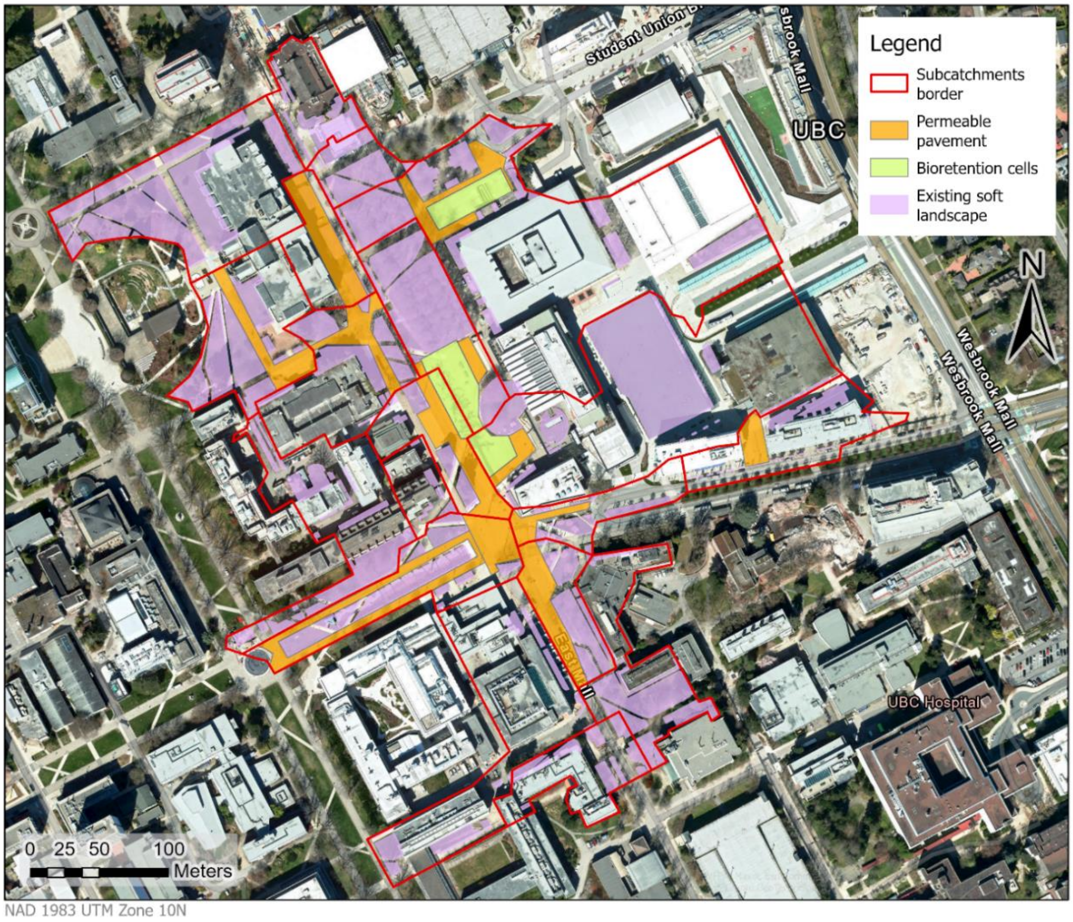

Figure 6. Recommended BRPP (current infrastructure + bioretention cells and permeable pavements) LID layout for UBC campus. Subcatchments are outlined in red, with permeable pavements being orange, bioretention cells being yellow, and existing soft landscape features being purple. Recommendation for layout is based on the performance of LID controls in SWMM rainfall-runoff analysis.

Figure 7 provides a more in-depth look at the current infrastructure, showing the runoff coefficients for each subcatchment under all six rainfall scenarios. There is little difference in runoff coefficients between the three 24 hour storm events. However, there is a clear distinction between the corresponding runoff coefficients for storm durations, as the maps on the left (10 minute durations) show substantially increased runoff coefficients compared with the maps on the right (24 hour durations). For 2-year storm events, the 10 minute storm had an average increase of 0.10 in the runoff coefficient in comparison to the 24 hour storm. The 25-year 10 minute storm had an average increase of 0.18 compared with the 25-year 24 hour runoff coefficient. While the 100-year 10 minute storm saw the largest increase in runoff coefficients with an average increase of 0.20 compared with the 100-year 24 hour storm.

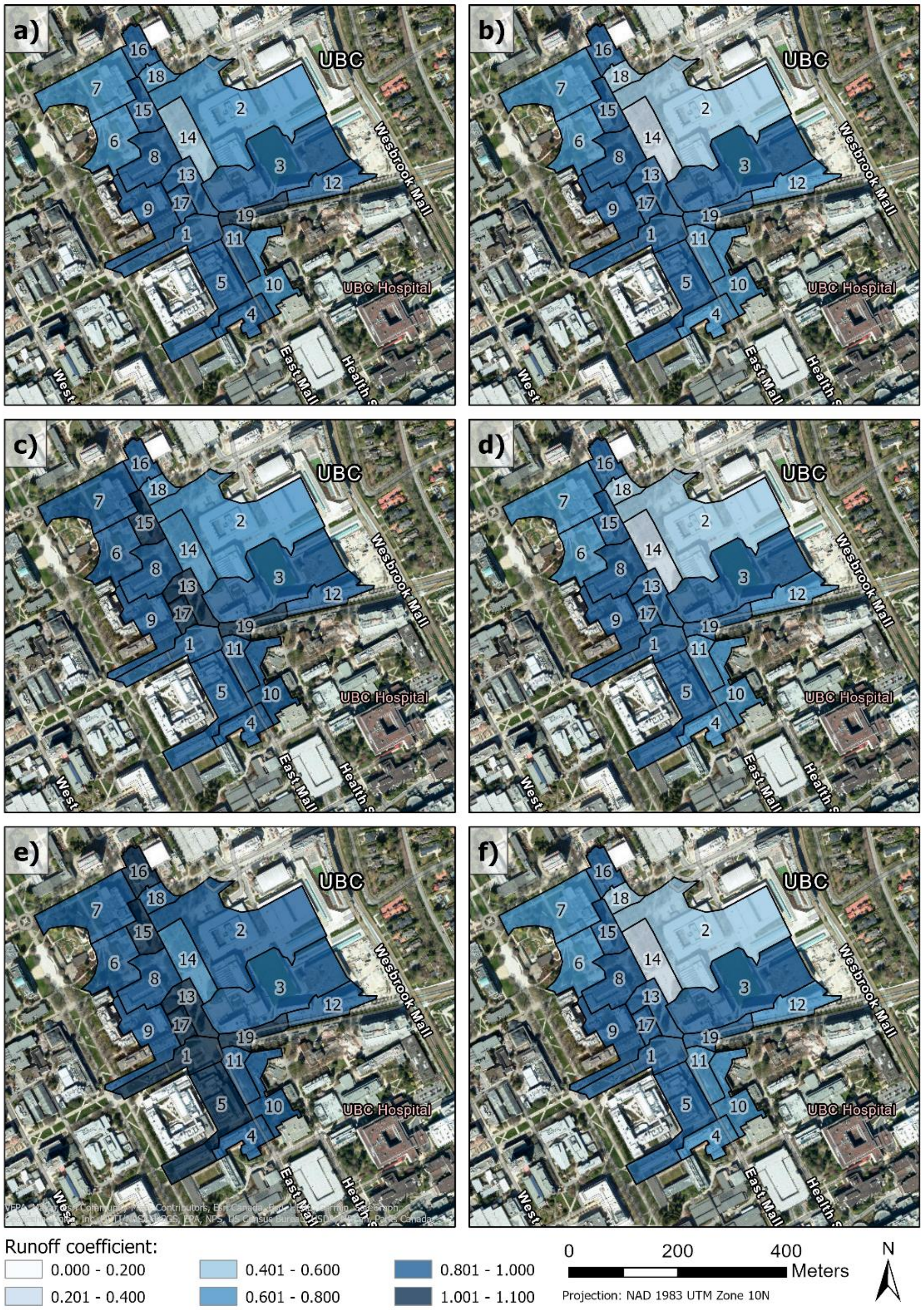

Figure 7. Runoff coefficients (ratio of total runoff to total received precipitation) produced by rainfall-runoff analysis for baseline/current infrastructure layout of UBC campus. Each panel represents a different storm event: a) 2-year return event, 10 minute duration; b) 2-year return event, 24 hour duration; c) 25-year return event, 10 minute duration; d) 25-year return event, 24 hour duration; e) 100-year return event, 10 minute duration; f) 100-year return event, 24 hour duration. For each subcatchment (numbered on the maps), runoff coefficients are represented by the colour with the darkest blue being the greatest runoff coefficients and the lightest blue being the lowest runoff coefficients (preferable).

Two subcatchments, 15 and 19, consistently had the highest runoff coefficients, each having an average runoff coefficient of 0.99 across rainfall scenarios. Subcatchment 19 had the largest runoff coefficient in 10 minute storms, whilst subcatchment 15 had the highest runoff coefficient in 24 hour storms. In contrast, subcatchment 14 had the lowest runoff coefficient in every rainfall scenario, with an average of 0.52 across simulations. Subcatchments 2 and 18 follow, with average runoff coefficients of 0.65 and 0.58 respectively. Of the 19 subcatchments, only three have an average runoff coefficient less than 0.75, with a total of eight subcatchments with runoff coefficients greater than 0.90.

Similarly to the baseline layout, BRPP runoff coefficients were largely the same for the three 24 hour storms, with slight increases with storm magnitude. There is also the same differentiation between 10 minute and 24 hour duration rainfall events, as the shorter storms show increased runoff coefficients compared to the longer storm events.

However, the runoff coefficients vary substantially between subcatchments. Across all rainfall scenarios, subcatchments 13 and 14 consistently have the lowest runoff coefficients, with an average of 0.15 and 0.14 respectively. In fact, there were three simulations in which subcatchment 14 had a runoff coefficient of 0.00, which were the three 24 hour storms. On the contrary, subcatchments 5 and 17 have the largest runoff coefficients in every rainfall scenario, averaging out to 0.96 and 0.93 respectively. Subcatchments 4 and 9, while not as high, also have consistently large runoff coefficients. All four subcatchments (4, 5, 9, and 17) have runoff coefficients greater than 1.01 in the 100-year 10 minute duration storm event, with subcatchment 17 also having a runoff coefficient greater than 1.01 in the 25-year 10 minute duration storm.

Compared to the baseline layout (see Figure 7), the BRPP layout shown in Figure 8 displays lower runoff coefficients in all rainfall scenarios. Only three BRPP subcatchments have average runoff coefficients (across rainfall scenarios) larger than 0.90 in comparison to the baseline's eight subcatchments. 11 of 19 BRPP subcatchments have average runoff coefficients less than 0.75 (compared to the baseline's three), and five of those have coefficients less than 0.30.

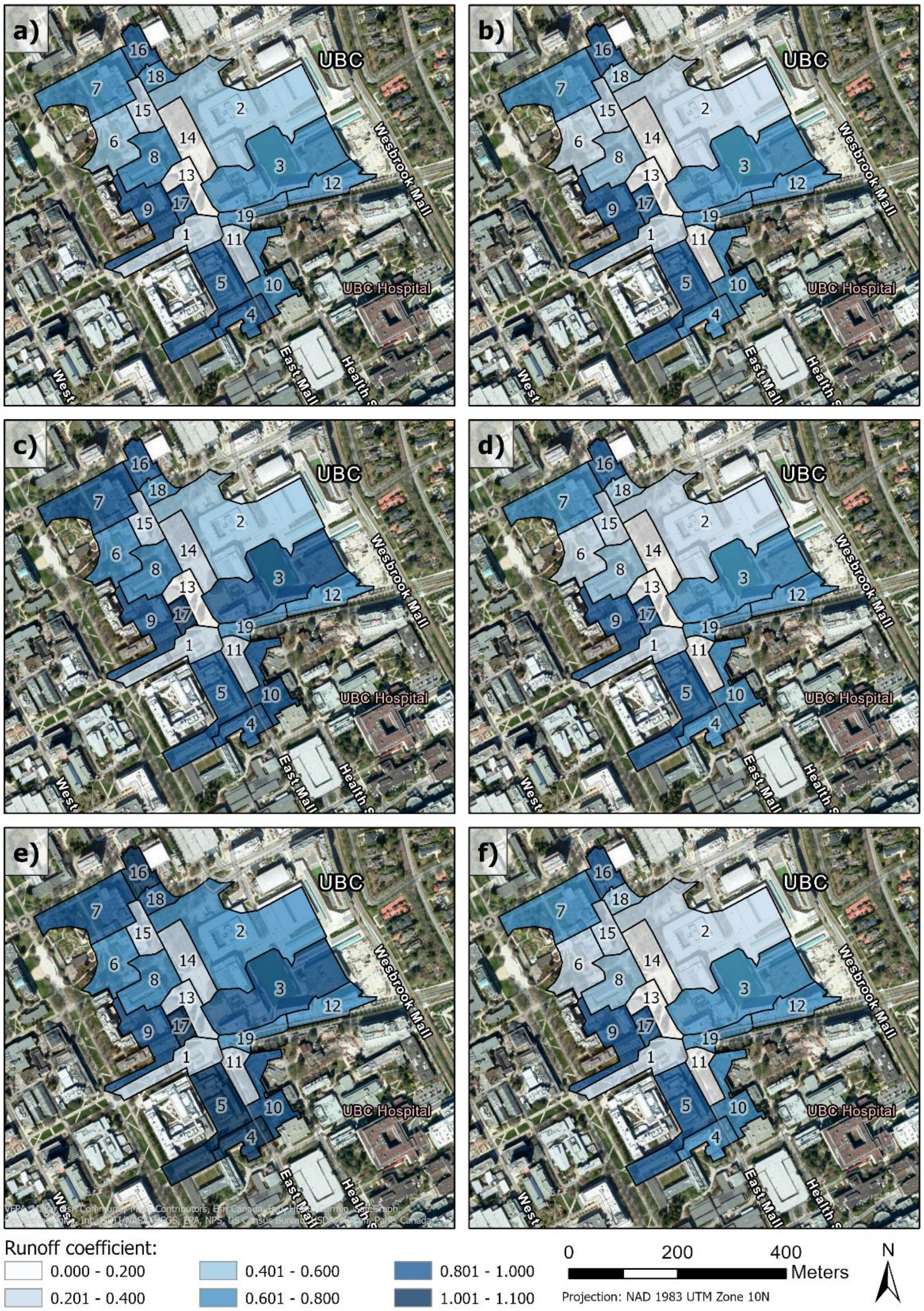

Figure 8. Runoff coefficients (ratio of total runoff to total received precipitation) produced by rainfall-runoff analysis for the BRPP layout (current infrastructure + bioretention cells and permeable pavements) of UBC campus study area subcatchments. Each panel represents a different storm event: a) 2-year return event, 10 minute duration; b) 2-year return event, 24 hour duration; c) 25-year return event, 10 minute duration; d) 25-year return event, 24 hour duration; e) 100-year return event, 10 minute duration; f) 100-year return event, 24 hour duration. For each subcatchment (numbered on the maps), runoff coefficients are represented by the colour with the darkest blue being the greatest runoff coefficients and the lightest blue being the lowest runoff coefficients (preferable).

6.0 Discussion

6.1 Overview

In this analysis, we sought to use a rainfall-runoff analysis to address the questions: Can low impact development or LID controls increase the stormwater resilience of UBC's campus, and which LID controls enhance the resilience most effectively? To answer these questions, the analysis primarily focused on the runoff coefficient, total runoff volumes, and peak flows obtained from SWMM model simulations. Overall, the research reveals that LID controls can reduce the runoff coefficient (see Table 4) by increasing ground and system infiltration thus reducing stormwater surface runoff. In doing so, LID can effectively increase the resilience of UBC's campus to climate change impacts. However, LID performance varies with storm events as shorter, more intense storms are still able to overwhelm the stormwater system. Additionally, LID performance varies with the type of LID, with some LID controls, such as permeable pavements, being more effective than others. Although, a combination of LID controls further reduces stormwater runoff and the risk of flooding over one LID control type alone. This supports previous research findings that the integration of LID can mitigate flooding in urban areas (Eckart et al., 2017; Hu et al., 2019; Hua et al., 2020). Regardless, no LID layout was found to be sufficient as every simulation output reported flooded nodes. It is recommended that UBC further investigate stormwater management retrofit practices to become resilient against climate change impacts.

6.2 Reductions in runoff

Previous research has outlined LID as a tool to reduce large volumes of runoff and mitigate flooding (Eckart et al., 2017; Hu et al., 2019). The analysis builds on this research, finding that generally, LID is effective at reducing the runoff coefficient from UBC's current infrastructure (Tables 3 & 4). That said, the type of LID control (infiltration or flow reduction) had a significant effect on their performances and corresponding runoff coefficients. For this analysis, the green roofs acted as a flow velocity reduction LID control, whilst permeable pavements acted as an infiltration LID control, and bioretention cells accomplished both infiltration and flow reduction (Eckart et al., 2017). Of the LID practices, permeable pavements had the lowest average runoff coefficients in contrast to both green roofs and bioretention cells (Table 3). However, the optimal reduction of runoff coefficients was seen with both the scenarios that contain a combination of LID controls (Table 4). Samouei & Özger (2020) similarly found a combination approach to be more effective in reducing runoff volumes, though claiming that reductions in runoff is linearly correlated with an increase in pervious surface area. In this study, it is unclear whether the increased performance of the LID combinations is simply due to a greater surface area that has been converted from impervious to pervious, or due to the presence of different types of LID controls (infiltration or flow reduction).

The study area is a subsection of an urbanized university campus (Figure 1) thus it is unsurprising that there is a much higher degree of impervious runoff than pervious runoff (Figure 4). Different LID controls had varying effectiveness at reducing the impervious runoff; green roofs and bioretention cells alone performed poorly, signifying that they should not be considered as single LIDs for this subsection of campus. Although impervious runoff is affected by LID controls, pervious runoff seems to be determined by the storm duration or intensity, as all layouts saw insignificant differences in pervious runoff volumes (Figure 4). This is expected, as pervious runoff has been shown to be more closely related to storm intensity than to stormwater infrastructure (Boyd et al., 1993; Guan et al., 2016).

6.3 LID impact on peak flows

As with runoff, LID controls can positively impact peak flow rates. The model simulations revealed that the three LID layouts which include permeable pavements are effective at reducing the maximum flow rate of runoff by up to approximately 624 L/s (under a 100-year return event) (Figure 5). This suggests that permeable pavements are most effectual for increasing the resilience of UBC's campus to high peak flows and, consequently, flash floods (Alexander et al., 2019). However, the inclusion of green roofs had a negative effect on peak flows during 24 hour storm events. The negligible performance of green roofs is unexpected, but is likely due to green roofs acting to reduce flow as opposed to storage of significant amounts of water (Eckart et al., 2017; Samouei & Özger, 2020). Particularly with extensive green roofs, the water holding capacity is minimal, and unless pipe infrastructure is updated at the green roof outflow, they are likely to have an insignificant effect on the capacity of water infrastructure to handle storm events (Eckart et al., 2017). The results are in contrast to much of the literature, as many studies have reported green roofs capable of peak flow attenuation (Berardi et al., 2014; Shafique et al., 2018), however, some researchers are calling for further analysis; Sims et al. suggest that the effectiveness of green roofs as it pertains to flow rate is related specifically to green roof design specifications surrounding soil geophysical properties like capacity and existing moisture levels (2019). This suggests that for potential green roofs on UBC's campus to be effective, their design would need to incorporate greater storage capacities than those associated with extensive green roofs as well as careful consideration for the soil or media utilized.

In conjunction with LID design specifications, the average peak flow rate of runoff volumes is correlated with the magnitude, duration, and intensity of the storm. Figure 5 displays the significant difference in peak runoff flows, with 10 minute storms exhibiting approximately 207 times the peak runoff rate of 24 hour storms. At the same time, there is a linear relationship between storm magnitude and average peak flows, with the 100-year larger magnitude events having significantly higher peak flows than the lower magnitude, 2-year return events. Although the LID layouts see lower peak flows than the baseline, the results suggest storm intensity and magnitude are more significant for average peak runoff flows than the LID implementation. This is consistent with the literature which poses that shorter duration storms with more intense rainfall can easily overwhelm stormwater infrastructure, producing peaky flows and flash floods (Hettiarachchi et al., 2018; Shafique et al., 2018).

6.4 Flood risk

As flooding is closely related to runoff volumes and peak runoff flows (Alexander et al., 2019), it is unsurprising that there is a definite distinction between the 10 minute and 24 hour storms. While every 24 hour storm reported a total of four flooded nodes, 10 minute storms reported up to 100 flooded nodes (100-year return event). This reinforces the previous conclusion that the intensity and magnitude of storms is more significant than LID type when it comes to flooding, again reinforcing existing research (Hettiarachchi et al., 2018; Shafique et al., 2018).

As with runoff and peak flows, the total flooded nodes do not depend solely on storm intensity, still varying substantially between LID layouts. The baseline current infrastructure reported the greatest number of flooded nodes for all storm events while, again, the three layouts including permeable pavement performed best with the least flooding (Table 5). This suggests that LID controls can reduce the flood risk of UBC campus. However, LID controls were ineffective at reducing the flooding during 24 hour storms, suggesting that greater stormwater infrastructure improvements than seen in these models might be critical for improving stormwater resilience.

6.5 Optimization of low impact development for UBC campus

LID controls were selected based on the subcatchment and the LID control requirements. Seven subcatchments (3, 5, 9, 10, 16, 17, and 18) were not deemed suitable for the installation of green roofs, permeable pavements, or bioretention cells, as in some cases, buildings and other infrastructure has already been developed. In other cases, if the aerial photography showed the buildings having reasonably open and flat roofs, extensive green roofs were selected as a potential LID control. Though it is unknown if the buildings have the structural capacity or accessibility to successfully implement a green roof. In other subcatchments where there is a greater amount of open space available, permeable pavements were chosen to replace pre-existing paths and walkways. If a particularly large area was available (> 100 m^2), there was the potential to replace the pavements with bioretention cells. Of the three LID controls implemented in these model scenarios, permeable pavements were deemed suitable most frequently.

All three layouts including permeable pavement would be suitable for UBC campus, as they saw the greatest reductions in runoff coefficients, runoff volumes, peak flows, and flooded nodes. Yet, the two combination scenarios performed more effectively than permeable pavement alone. For example, for a 10 minute, 2-year return event, the combination of LID controls further reduced the number of flooded nodes by 10 and 13 compared to permeable pavements as a single LID. Performances between the two combination scenarios were almost indistinguishable, suggesting that either would increase UBC's campus resilience to climate change. However, since the two are virtually equal in their effects, it seems as if the addition of green roofs may be unnecessary. Thus, in the interest of cost effectiveness and conserving university resources, the optimal infrastructure layout for UBC campus would be the simpler of the two, which combines permeable pavements and bioretention cells and is shown in Figure 6.

In contrast to the current infrastructure, the inclusion of permeable pavement and bioretention cells has a positive impact on runoff volumes and flood risks. The baseline layout subcatchments generally reported substantially higher runoff coefficients than the optimal layout (Figures 7 & 8). Of particular concern are subcatchments 5, 15, and 19, as they reported the greatest runoff coefficients. Although subcatchments 5 and 19 were not deemed suitable for LID controls, subcatchment 19 still saw a reduced runoff coefficient under the optimal layout. This is likely owing to LID installations further upstream reducing the subcatchment's received runoff; LID has been known to positively affect downstream and surrounding subcatchments (Alexander et al., 2019). Subcatchment 15, which had the second highest runoff coefficient with current infrastructure, had permeable pavements implemented in the combined LID layout. The results were impressive, as using the LID layout resulted in the subcatchment seeing the second greatest improvement in runoff coefficients, decreasing from 0.99 to 0.28. This is promising as it indicates that proper planning of LID implementation can have significant positive impacts on high-flood-risk areas.

6.6 Further research for low impact development

The research reveals improvements could be made for the optimization of LID in urban areas. For instance, further analysis could aim to answer whether the degree of imperviousness or the type of LID controls included (infiltration or flow reduction) is the dominant factor in reducing stormwater runoff. And further, if the dominant factor changes depending on the environmental and geophysical context. In doing so, efforts to increase stormwater resilience can be tailored to the goals of the stormwater management, as certain LID controls will either increase infiltration, reduce flow, and/or increase perviousness. This means that depending on the dominant factor, some LID controls will be more appropriate than others. Further, as the potential impact of LID is contingent on design specifications, further modelling of variations in the design of LID controls would enable the identification of the influential design parameters. This could useful for informing planning projects of the necessary designs to ensure optimal performances of LID. Additionally, since high intensity storms have the ability to overwhelm stormwater systems, urban hydrological modelling should continue to be used for research into mitigation of large peak flows and flash flooding.

6.7 Limitations and challenges

Limitations of the stormwater infrastructure dataset may have affected the accuracy of the analysis results. UBC provided geospatial data for a variety of the stormwater infrastructure components, including water mains or pipes, drains, end caps, manholes, storage detention tanks, and subcatchment information. However, the geospatial data was incomplete. 13.38% of the pipes did not have an associated pipe diameter, which has significant implications for the infrastructure's water holding capacity. Additionally, only 9.89% of drains in the infrastructure network were directly connected to the pipes and 56.06% of drains were within 5m of pipes, meaning it was uncertain which pipes the drain inflows were transported to. Similarly, no information was provided concerning the capacity of the storage tanks. Due to this, logical assumptions had to be made to ensure the infrastructure data met the model input requirements. In the cases of pipes not having a diameter, the surrounding pipes and their corresponding diameters were used. For instance, if a pipe had no pipe diameter information and the connecting pipes had a diameter of 300 cm, then the assumption was that the original pipe would also have a diameter of 300 cm. For the drains, an assumption was made following hydrological standards, that typically drains will be at a higher elevation than the receiving pipe and drains will likely flow to the nearest pipes (Nix, 1994). In the case of the capacity of the storage tanks, the depth of the storage tanks were determined by the inlet elevation and the outlet elevation, as the depth of the storage tank must be at least as deep as the difference in elevations. While these assumptions mitigated the inconsistencies in the data, these assumptions may have resulted in some inaccuracies in the model stormwater infrastructure and thus the model outputs. However, regardless of the potential errors with the baseline infrastructure, the model still allows for comparisons of the relative impact of LID scenarios under climate change effects even whilst the absolute performance is unknown.

6.8 Recommendations for UBC

The results of the model scenarios show that UBC campus could be improved by incorporating LID controls into campus planning initiatives. As a starting point for UBC campus planning, if the aim of the installation of LID controls is to reduce peak flow volumes, the extensive green roofs used in this analysis should not be considered. For increasing infiltration and reducing runoff, bioretention cells perform best. However, if the issue is that impervious surface runoff is particularly high, then permeable pavements are most recommended. For UBC campus, the best option for the reduction of surface runoff is a combination of both permeable pavements and bioretention cells.

A combination of bioretention cells and permeable pavement systems could be most effective for increasing the resilience of campus. However, under a moderate climate change emissions scenario, even the incorporation of LID controls may not be enough to adequately prevent flooding. This is particularly apparent with 100 year storm events, as the model showed that the effectiveness of LID controls decreases with increasing storm return. Previous research has indicated the importance of modelling LID controls under differing storm events; as climate change impacts further intensify, precipitation is expected to display different temporal patterns with extreme peaks in rainfall rates (Hettiarachchi et al., 2018). Prior to further campus planning, UBC should investigate the proposed layout under different temporal patterns in precipitation, to assess the resilience to both peaky and steady storms. It is recommended that a more robust stormwater infrastructure analysis be completed in order to ensure that the campus can adequately handle the more intense storm events that may occur more frequently with increased climate change effects.

7.0 Conclusion

In this report, we aimed to answer the questions:

- Can low impact development or LID controls increase the stormwater resilience of UBC's campus?
- Which LID controls enhance the resilience most effectively?

A rainfall-runoff analysis was used to answer these questions. In response to the first, the results show that LID can increase the resilience of the UBC campus to climate change, by reducing impervious runoff and peak runoff flows. In answer to the second question, the findings indicate that performance of LIDs for increasing resilience was varied. As a single LID control, permeable pavements are most effective for UBC campus. Yet the greatest reductions in runoff can be achieved using a combination of permeable pavements and bioretention cells. However, the results indicate that intense storms are likely to overwhelm UBC's infrastructure, even with the implementation of LID controls. Further investigation into mitigation efforts for flash flooding and peak flows would be beneficial for UBC's resilience to the peaky storms expected with climate change. Overall, the research indicates that more sustainable stormwater management can mitigate the combined effects of urbanization and climate change which has promising implications for urban environments. Urban planning should continue to adopt low impact development as an innovative and successful approach to combatting climate change impacts.

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